Biobased Chemistry and Technology

Thesis Biobased Chemistry and Technology

Application of RID to farm located conversion systems for agricultural on-farm products and residues

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Preface

My interest in the conversion of agricultural products has been encouraged by a Biobased Economy evening in 2015 where a presentation was given by Johan Sanders. In his presentation, he told about the biorefinery of grass and the enormous amount of potential it could have for the agricultural industry. At that time, I asked myself why this had not been implemented yet when there were so many possibilities. Some years passed but the idea of biorefinery kept getting my interest. In my final year of my master, I decided to do something with biorefinery and went to Ton van Boxtel with an idea for my master thesis involving biorefinery. From that point till now a lot of work has been put in this thesis that is lying before you.

I would like to give special thanks to Ton van Boxtel for his support, flexibility and regular feedback sessions that were always convivial. Special thanks to Elinor Scott who was always very willing to help me when I got stuck with difficult chemical matters. Also special thanks to Henk ter Stege who supplied me with a lot of practical information about processing methods and machinery that was very valuable for the model that was developed.

Summary

Accompanied with the production and harvest of agricultural products a wide variety of waste streams is created. These waste streams are partially left at the field or are temporarily stored as compost or manure on the farm to be spread on the field as fertilizer in the spring again. Examples are sugar beet leaves and tops that are left on the field or livestock manure stored on the farm. Leaving the wastes on the field or storing them on the farm results in avoidable emissions. The waste streams can now be seen as a liability or in some cases even a cost component for the farm. Although these streams can be seen as waste, they have the potential for conversion into feed, materials or chemicals, it is therefore better to call them agricultural residues.

These residues can be processed by conversion systems into potential semi-finished products or end-products that are more useful or even profitable. Examples are chemicals to sell as a valuable farm product and fertilizers that can be stored and spread at the appropriate moment.

Pre-processing or full processing of agricultural products and residues seem to be the result of tradition, intuitive thinking or is opportunity driven. In the literature, systematic analysis of the processing of agricultural materials to biobased products seems not to be present. In order to perform a good analysis, it is essential not to continue from the current situation but to restart with an open mind and to take all possibilities into consideration. The reflective interactive design (RID) method offers the opportunity to perform the analysis from scratch, this design approach is based on the 'Structured Design' method of Van den Kroonenberg.

At the moment the different routes for converting biomass into different semi-finished products or end products are known. Dröge & van Drimmelen, Schwandt Infographics, and Wageningen University made an interactive routemap which visualizes these routes with conversion methods, semi-finished products and end products for a variety of starting products. Although the conversion routes are known, these systems for processing are not available or not (yet) implemented. The cause of this unavailability is the lack of information that describes the potential of different conversion routes. Farmers have no insight into the potential of conversion routes and are not able to decide whether to invest in a conversion system on the farm.

The aim of this research is to apply RID to farm located conversion systems. The farmer's process of selection is centre stage.

Possible ways of conversion have to be determined and the potential of a complete conversion system has to be measured. The potential of conversion systems will be quantified by a calculation tool. The calculation tool gives a source of information/first impression of the possibilities and potential of a variety of conversion routes.

A biobased problem for farm located conversion was approached, therefore the steps of RID were reconfigured to make the method fit this sort of problem. This research was limited to the first and second phase. A manual on RID has been used to execute the different steps in RID. Phase 1 was used to define the needs of the farmer, the focus was primarily on the farmer. The needs of the farmer were translated into a calculation tool in phase 2, the focus shifted to the calculation tool in this phase. Principally the steps in phase 2 were translated into the calculation tool where RID was used to structure the development. This research is in the exploration phase and RID was executed for the first time. The steps were therefore not elaborately executed.

From a wide variety of possible products and residues, fresh grass was finally chosen as the product to be considered for this research. The calculation tool was developed for a limited number of paths

for conversion. As a starting point, the interactive routemap was used to define the routes that were programmed. These routes and products were evaluated with an expert on process technology and an expert on chemistry to eliminate some routes and/or end products that would definitely not have any potential for a farm located conversion system. The model will calculate water use, energy use, investments, production costs, net revenues, profit, return on investment for all the possible conversion routes. These numbers were defined as the key functions of the calculation tool.

All information was modelled into a program and calculations were made. Only routes that made a profit and had a return on investment of maximal 5 years were considered for 6 different amounts of feedstock input: 0.5, 1, 2, 3, 4 and 5 tonnes per hour. Energy use, profit, investment and return on investment were analysed for each individual conversion route, these results have been compared.

From the results of this research the following conclusions can be drawn:

- A systematic analysis of processing agricultural materials to biobased products (conversion systems) was performed with RID.
- With RID a large overview of agricultural products and residues with additional chemical properties was created.
- RID has structured the design of a calculation tool in exploration phase which calculates the potential of farm located conversion systems that process fresh grass.
- The most important numbers that should be calculated by a calculation tool in exploration phase are: investments, production costs, energy use and return on investment.
- The calculation tool shows that scaling up, results in more potential conversion routes and an improved return on investment.
- Scaling up also affects investment and profit. Investment per tonne decreases and profit per tonne increases with increasing feedstock input. Energy use is not or minimally affected.
- With increasing input of feedstock, an increasing amount of longer conversion routes also have potential.
- Conversion routes with the most potential have the conversion method pre-treatment or pressing and fiberizing. The majority of these routes have pressing and fiberizing as conversion method. Other conversion methods do not create enough profit and/or have too high investments.
- Conversion routes with conversion methods that create (more) valuable (semi-finished) products are more likely to have potential due to a higher profit per tonne that can be realised.
- The current calculation tool still has a lot of limitations due to a large number of assumptions that were made but it can be used for exploration.

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1 Introduction

Accompanied with the production and harvest of agricultural products a wide variety of waste streams is created. These waste streams are partially left at the field or are temporarily stored as compost or manure on the farm to be spread on the field as fertilizer in the spring again. Examples are sugar beet leaves and tops that are left on the field or livestock manure stored on the farm. Though leaving these wastes on the field during the winter has no significant contribution to the fertilization of the field. The wastes degrade at a time no vegetation grows and therefore there is no use of the released minerals (Van der Weerden, Luo, Dexter, & Rutherford, 2014; Velthof, Kuikman, & Oenema, 2002). On top of that, leaving the wastes on the field or storing them on the farm results in avoidable emissions. The waste streams can now be seen as a liability or in some cases even a cost component for the farm (Cantrell, Ducey, Ro, & Hunt, 2008). Although these streams can be seen as waste, they have the potential for conversion into feed, materials or chemicals (Tuck, Pérez, Horváth, Sheldon, & Poliakoff, 2012). It is therefore better to call these waste streams agricultural residues.

According to Cantrell et al. (2008), these residues can generate annual revenues, moderate the impacts of commodity prices and diversify farm income. Not leaving the residues on the field avoids eventual emissions. These residues can be processed by conversion systems into potential semi-finished products or end-products that are more useful or even profitable. Examples are chemicals to sell as a valuable farm product and fertilizers that can be stored and spread at the appropriate moment (Alburquerque et al., 2012; Tuck et al., 2012). Conversion systems that are going to be developed can fulfil all aspects of the concept 'People, Profit, Planet' (3 P's). With conversion systems work is generated, profit can be made with valuable end products and emissions might be avoided.

(Pre-) processing of products and residues on farms is a small-scale activity. According to Bruins and Sanders (2012) simpler and less expensive process technologies are used. Besides, there is the possibility to increase rural employment. Small-scale processing in biorefineries can also be more effective if some design rules are taken into consideration. Bruins and Sanders (2012) also elaborate on advantages and disadvantages of small-scale biorefineries. Separation of products by pre-processing into fractions increases the overall value. Less transport of water, minerals, tare and organic matter of little value is then needed. Local biomass is re-used and therefore no waste streams are created at the centralized factory. Minerals can be used as fertilizers. Farmers benefit from the integration of part of the agricultural value chain into the farm. Local processing may also create incentives for farmers to increase productivity, reduce costs and recycle their agricultural residues. Pre-processing creates the option for prolonged storage. Farmers do not longer depend on the willingness of factories to accept the products. Factories can process the agricultural goods year-round. The reduction of fixed costs in the centralized factory that is realized can pay for the cost of pre-processing and investments for storage at the farm. Innovations and investments are easier because investors are more eager to invest in technologies on a small scale. This results in faster innovations of these biorefineries. The mentioned advantages fulfil all needs to make small-scale biorefineries sustainable according to the 3 P's. Disadvantages of small-scale biorefineries deal with the economy of scale. Large biorefineries have lower input costs and lower cost for buildings infrastructure and storage. Better processing yields and a reduction of investment costs are achieved.

Pre-processing or full processing of agricultural products and residues seem to be the result of tradition, intuitive thinking or is opportunity driven. In the literature, systematic analyses of the processing of agricultural materials to biobased products seems not to be present. In order to perform a good analysis, it is essential not to continue from the current situation but to restart with an open mind and to take all possibilities into consideration. The reflective interactive design (RID) method offers the opportunity to perform the analysis from scratch, this design approach is based on the 'Structured Design' method of Van den Kroonenberg which is described in Siers (2004).

Dröge & van Drimmelen, Schwandt Infographics, and Wageningen University (2017) made an interactive routemap which visualizes these routes with conversion methods, semi-finished products and end products for a variety of starting products. This infographic can be recognized as one of the steps in RID, but quantification of these routes is not included. Numbers of requirements for a conversion route like investments, production costs, revenues and energy use per process are not available. At the moment, the absence of these numbers creates a problem for farmers. It is almost impossible for a farmer to decide whether it is smart to convert biomass at the farm or not, the potential of conversion systems is unknown. Figuratively seen it is the same as giving the farmer a topographic map with different routes between 2 unknown locations in absence of a scale bar. The farmer does not exactly know which route is the shortest/smartest to take to get to the final destination from his start location.

The aim of this research is to apply RID to farm located conversion systems. The farmer's process of selection is centre stage. The farmer needs information on potential products and residues on the farm, he or she may want to change or increase a certain cultivation. Possible ways of conversion have to be determined and the potential of a complete conversion system has to be measured. The potential of conversion systems will be quantified by a calculation tool. The calculation tool is the missing 'scale bar' for the farmers, it gives a source of information/first impression of the possibilities and potential of a variety of conversion routes.

The aim of the research and the challenges are translated into the following research questions:

1. How should RID be configured for farm located conversion systems?
2. What are the most common agricultural products and residues present on the farm and/or field, what is the size of these streams, what are their chemical compositions and what product or residue should be chosen for this research?
3. What are the most important numbers that should be calculated by the model/calculation tool?
4. Which paths of conversion are possible for the agricultural products and residues and what are the features of the paths with the most potential?

This report consists of multiple parts to answer the research questions. The first part deals with the definition of the problem with the farmer at the centre stage. This is followed by a problem analysis where all possible conversion routes are visualized using the routemap of Dröge & van Drimmelen et al. (2017). Key actors and their needs are drawn up, whereupon their requirements for the design of a farm located conversion system are listed. Potential products and residues with accessory chemical compositions are already determined during part 1.

In the second part of this research, the most important numbers to be calculated by the model are specified based on the requirements found in the first part. References for these numbers are found by study of literature. Consequently, a selection of potential conversion routes is chosen. The conversion methods for the conversion routes are determined afterwards. Numbers and conversion routes are then translated into a calculation tool by modelling all processes in Matlab (R2016b). The features of all the routes are calculated and given as results. From all these routes a selection is made of the routes with the most potential. These routes and their specific features are the final results of this research.

2 Design process

2.1 Reflective interactive design (RID) Current application

RID was initially developed for the design of new animal husbandry systems. However, this method is widely employable and suitable for all design problems. Since the development of potential farm located conversion systems can be approached as a design problem, RID can be applied for its development. RID is based on the 'Structured Design' method of Van den Kroonenberg which is described in Siers (2004). The approach consists of 3 phases which can be clearly seen in Figure 1. The first phase consists of a thorough analysis of the problem, also the list of requirements is defined. In the second phase, an elaborate function analysis is performed. Also, possible conversion routes are generated. To assess these routes the calculated features are compared. Based on this comparison a final selection is made and consequently, the potential conversion routes can be proposed. The last phase considers the practical application and evaluation of the conversion routes that take into account all current set standards, rules, legislation etc.

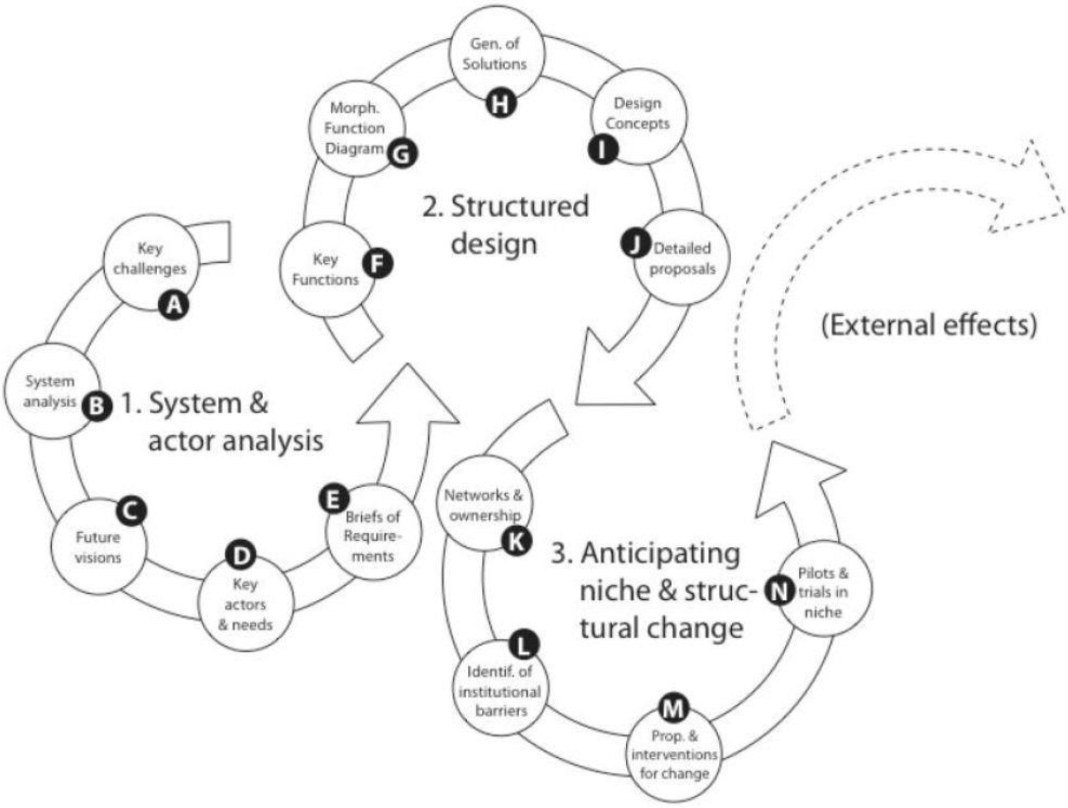

Figure 1 All three phases of Reflective Interactive Design with the corresponding steps (Van 't Ooster, Janssen, & Vroegindeweij, 2015).

2.2 Reflective interactive design (RID) for a Biobased application

A biobased problem for farm located conversion was approached, therefore the steps of RID were reconfigured to make the method fit this sort of problem. This research was limited to the first and second phase, step A up to and including step I were executed. Van 't Ooster et al. (2015) has been used as a guideline to execute the different steps in RID. Phase 1 was used to define the needs of the farmer, the focus was primarily on the farmer. The needs of the farmer were translated into a structured design approach supported by a calculation tool in phase 2 to make decisions. Principally the steps in phase 2 were translated into the calculation tool where RID was used to structure the development.

The design process is often repeated where every repetition is an extension of the previous one. This research is in the exploration phase and RID was executed for the first time. The steps were therefore not elaborately executed. The steps as defined in Figure 1 are clarified in the following sub-chapters.

2.2.1 Phase 1: System & actor analysis

First some boundaries were set for this research to limit the size. Food industry residues were not taken into account. Only products and residues present on the farm or field in Western Europe were considered. Arable farming, livestock farming and horticulture were selected as agricultural sectors from which products and residues were selected. There is a significant number of residues and products available, the available amount of time for this research limited the amount that could be taken into account. From all products and residues, one product would finally be chosen to use for this research.

To define the needs of the farmer, the research started with an elaborate description of the problem to get more insight into the background of the problem, the need for the problem and the scale of the problem. This description was already given in the introduction, see chapter 1. Based on the problem description, a mind-map of all associated elements was made with Microsoft Visio 2016 (Figure 2 chapter 3.1.1). A mindmap clearly visualized the current situation and how all elements were connected. Information was found by brainstorming and through the study of literature. Based on all the information that was found, key challenges were formulated. These were challenges that had to be answered by the design (process).

The current situation was analysed further to understand, improve or change it. During this analysis, the focus shifted to conversion systems because unavailability of information on these systems was identified as the main problem. Conversion systems and all its connections were then approached as a single system. The components or relations in this system that caused problems had to be clarified. The system components such as environment, main system, subsystems, aspect systems and system elements, were all distinguished. The system was approached by taking all the system elements as a starting point. Examples of elements were: livestock, crops, storage, energy and water. The relative positions and the interactions of the components were determined by following the element crops through the system. Special attention was paid to elements and relations that were unwanted or caused complications within the system. These unwanted elements and relations are called wicked links. All this information was used to create a 3-Circle-Chart that contained the system, sub-systems, environment, elements and the aspect-systems. The 3-Circle-Chart gave a more elaborate view of the current system. Interactions with added value, environmental impact and associated elements were made clear. The 3-Circle-Chart was built in Microsoft Visio 2016. The boundaries of the system, as already described above, were also implemented during the system analysis.

After analysing the current situation, the future vision of conversion systems was analysed. First, the identified wicked links and problems from the previous step were discussed to indicate the points of attention for future conversion systems. Future visions of conversion systems/routes were determined next, by visualizing all the possible routes from the routemap of Dröge & van Drimmelen et al. (2017) in Microsoft Excel 2016. The routes were worked out by laying out the whole route in chronological order with processes and intermediate products. No options were left out with the first observation of this online tool. Comparable routes were combined to see which feedstock products had the same processing steps. Not the routes but the feedstock was now taken as a starting point, Microsoft Excel 2016 was used to visualize the combined routes.

The farmer was chosen as the main stakeholder for this research. The farmer's needs were therefore centre stage in the first phase of RID. These needs would have a large impact on the decision for a conversion system. In the previous steps some needs already emerged, these were discussed together with other needs of the farmer. Some needs were even translated into concrete numbers that should be calculated by the calculation model. Finally, all needs were specified into a list of requirements for a potential conversion system. These requirements, where possible, needed to be fulfilled/calculated by the calculation model.

A list of products and residues with accessory chemical compositions were some requirements that needed some extra research, this was already executed during this phase.

The collection of agricultural products and residues in Western Europe is of significant size. To map all these products and residues a literature study was done. A variety of products or residues was selected from the following agricultural sectors: livestock farming, arable farming and horticulture. Only common products or residues from these sectors were selected. Streams of products or residues with no information about their size were not considered. The different biomass sources were placed in a table with corresponding size and references. The selection of products and residues was clustered in groups corresponding to the different agricultural sectors. Since green manure was used in all sectors, a separate green manure group was made.

The chemical compositions of the selected products and residues were also found by a study of literature. The following biomass precursors were chosen to describe the chemical composition: Starch, hemicellulose, cellulose, lignin, lipids and protein. The products and residues of which no information about these precursors was available, were not considered. Precursors have been put in a table for each individual product or residue, they have been given as a percentage of the dry matter content of the biomass source. From all these groups 1 biomass source with potential was chosen to use for the calculation model.

2.2.2 Phase 2: Structured design

During this phase, the needs of the farmers were used to find possible conversion routes, for this purpose a calculation model was developed. The model is a translation of the steps in phase 2. Actually, it automates all steps of phase 2. Based on the list of requirements from the previous phase the key functions for the calculation tool were determined.

Based on the chosen type of biomass in phase 1, a selection of conversion routes was made to eliminate the routes that did not convert this biomass. Conversion routes of input products comparable with the chosen biomass were also analysed to see whether some routes were not considered but were still possible. This new selection was visualized in a flow scheme in Microsoft Visio 2016. Some literature study was done on these routes and together with personal communication with experts, the routes that would certainly have no potential on the farm were also eliminated. The previous flow scheme was corrected for the eliminated routes.

Then the conversion methods for all conversion routes were determined. Only a single conversion method was chosen per process due to time limitations. The conversion methods were described shortly and placed in a table with the corresponding references.

Consequently, all key functions were used for the development of the calculation tool. As a basis for the calculation tool, a superstructure framework was used. This framework was developed by Tim Hoogstadt (Hoogstad, 2015). The framework reduces time-consuming manual input. The superstructure is formulated by functions, where every function stands for a different conversion method. The functions formulate the superstructure as a series of non-linear programming problems. One route is one non-linear programming problem. Optimisation of the superstructure is also possible but was not used for this research. For the superstructure framework to work the functions needed to be programmed individually and the necessary parameters needed to be defined.

The current calculation model is only in its exploration phase and therefore only calculates a selection of numbers for evaluation. The numbers that were calculated are: mass balances, energy consumption, production costs, water use, investments, revenues, profit and return on investment. These numbers above are the key functions derived from the list of requirements.

Table 2 gives the basic equations that were used to calculate the numbers of the individual conversion methods. Specific equations that vary from the basic equations can be found in the appendix in Table A-2.

Every conversion method was worked out into a function into Matlab (R2016b) and all involved parameters were determined. Some literature study was done to find the numbers for these parameters. The values and accessory sources for these parameters can be found in Table A-1 in the appendix.

Table 1 Annotations for the equations in Table 2.

Symbol	*Description*	*Unit*
F_{in}	Flow of input product	kg/h
F_{out}	Flow of output product	kg/h
W_{in}	Flow of water in	kg/h
W_{out}	Flow of water out	kg/h
Acc	Accumulation in the system	kg/h
p	Ratio between in- and output	$[-]$
q	Energy use per kg input product	kWh/kg
r	Water use per kg input product	$[-]$
s	Water output per kg input product	$[-]$
$CostA$	Purchase cost of unit operation A	€
$CostB$	Purchase cost of unit operation B	€
$SizeA$	Capacity of unit operation A	kg/h
$SizeB$	Capacity of unit operation B	kg/h
n	Scaling factor for the equipment (0.6 for this research)	$[-]$
P_c	Production cost per hour	$€/h$
I	Rate of interest	%
M	% of maintenance costs	%
C_I	Total investment costs	€
A	Depreciation time	$year$
C_e	Energy costs	€
C_c	Costs for consumables	€
C_l	Costs for labour	€
R	Revenues per hour	$€/h$
x	Revenues per kg end product	$€/kg$
P	Profit per hour	$€/h$
ROI	Return on investment	$year$

Table 2 The basic equations that were used to calculate the requirements for all conversion methods.

Requirement	*Equation*	
Output product n	$F_{out} = F_{in} * p$	(1)
Energy use	$E = F_{in} * q$ or $E = F_{out} * q$	(2)
Water use	$W_{in} = F_{in} * r$	(3)
Water out	$W_{out} = F_{in} * s$	(4)
Accumulation	$Acc = F_{in} + W_{in} - F_{out} - W_{out}$	(5)
Investment	$CostB = CostA * \left(\frac{SizeB}{SizeA}\right)^n = C_I$	(6)
Production costs	$P_c = (0.5I + M) * C_I + \frac{C_I}{A} + C_e + C_c + C_l$	(7)
Revenues	$R = F_{out} * x$	(8)
Profit	$P = R - P_c$	(9)
Return on investment	$ROI = \frac{C_I}{P * 24 * 300}$	(10)

The finished tool returned all conversion routes with the corresponding numbers mentioned before. A selection was made to score out the conversion routes with no potential. Profit was the first requirement that was used to select the different conversion routes. Conversion routes that lost a profit were not considered anymore. Next return on investment was evaluated, this value was not to be higher than 5 years. Otherwise, the conversion route was not considered anymore. The conversion routes were evaluated for 6 different amounts of feedstock input: 0.5, 1, 2, 3, 4 and 5 tonnes per hour. These results were evaluated, the focus was on the features of the routes with (the most) potential.

3 Application of RID for farm located processing

3.1 Phase 1: System & actor analysis

3.1.1 Step A: Farmers challenges

In the introduction, it has already been described that agricultural residues can be seen as a liability or in some cases even a cost component for the farm (Cantrell et al., 2008). Systems for processing agricultural residues and products are mostly anaerobic digesters to produce heat and electricity. 72% of these biogas plants in the EU operate locally on farms (EBA (European Biogas Association), 2014). Other systems for processing are not available or not (yet) implemented. Some companies are developing small-scale biorefineries to create added value from biomass. Grassa for example is a working principle of a biorefinery that is momentarily tested in the Netherlands. This biorefinery fractionates fresh grass into protein, fibres, whey and a concentrate of phosphates (Grassa, 2016). Apart from these examples the total amount of available systems is limited. Routes for processing are known but the numbers that describe the potential of these routes are absent. It is therefore unknown what route has the most potential on the farm.

A mind map of the current situation was created and can be seen in Figure 2. Numbers that should give information about the conversion methods, the size of the system, chemical composition, prices and the size of streams are not directly available. The potential of different conversion routes can therefore not be determined.

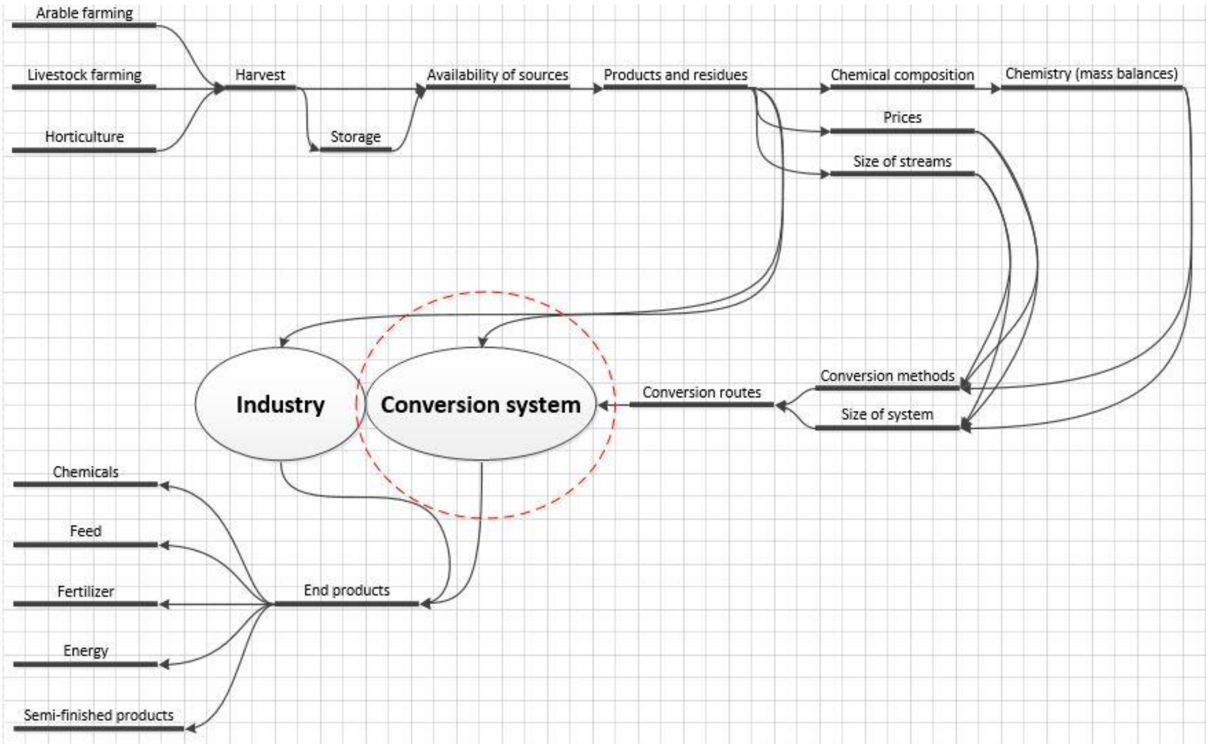

Figure 2 A mindmap of the current situation. Products and residues are produced during harvest by arable farming, livestock farming or horticulture. These sources of biomass are stored or directly available, they are processed by industry or a conversion system on the farm. In this research, the focus is on processing the products and residues via a conversion system. Chemical composition, prices and the size of the streams of biomass influence the choice of the conversion methods and the size of the system. Conversion methods and the size of the system influence the conversion route that is chosen, this will finally lead to a conversion system that produces a variety of end products. The red dashed circle indicates the focus of step B.

The design of a farm located conversion system should answer key challenges. The key challenges are listed below:

- What are possible input products?
- What is the chemical composition of these products?
- What are possible conversion routes?
- What will be the size of the conversion system (integration on the farm)?
- What features define the potential of a route best?
- What is the potential of the different routes?

These key challenges are quite in line with the research questions that were mentioned in the introduction.

3.1.2 Step B: System analysis

The red dashed circle in Figure 2 indicates the focus of this step. The system analysis of a conversion system has been visualized in a '3-Circle-Chart' (Figure 3). Figure 2 can be seen as a flow scheme, whereas Figure 3 has more focus on interactions with elements in the environment. This system analysis indicated the missing sources of information to calculate the numbers that determine the potential of conversion routes.

The elements of the system analysis are depicted with the rectangles. The green circle represents the main system which can be seen as the conversion system were the focus is on. The blue circle is the environment of the main system, all the white circles are sub-systems and the yellow circles are aspects systems. The connected lines represent the relations between all the systems and elements. The total universe (super-system) of which the main system and its environment are a part, is not considered for the '3-Circle-Chart' and therefore not drawn. The effects of the super-system on the environment and main system are not important for this research.

The environment only contains elements, aspect-systems and sub-systems that influence elements of the main system or are influenced by elements of the main system. The boundaries of the system have already been mentioned in the introduction and have also been used for the system analysis. To elaborate on the system analysis, we will follow the agricultural products and agricultural residues. The same approach has also been used to do the system analysis and create the figure. It gave a clear view of the all the sub-systems, aspect systems and elements that were directly or indirectly influenced by these starting elements.

Livestock and crops produce agricultural products and residues which are both stored or directly processed by a conversion system. These produced products and residues already have added value, storage of the products and residues generates additional added value. Products and residues influence the system size and conversion method by differences in availability, size of the stream and chemical composition. The system size and conversion method are also influenced by the height of the investment and the market price of possible end products. Information about the system size and conversion methods results in a conversion route. Consequently, some end products can be created by this conversion route. These end products generate added value on the farm. The end product energy is both produced and used by a conversion system. The use of energy causes emission because fuel is combusted to generate energy. These emissions have a negative influence on the environment. Water is also used and produced by conversion methods. The use of large quantities of water by a conversion method also has an environmental impact, more water that is used results in more water that is polluted. Both water use and energy use influence the conversion method when looking at sustainability and energy efficiency.

Attention has been paid to wicked links and problems that were identified during the system analysis. Wicked links are elements and relations that are unwanted or cause complications within the system. Emissions have a negative impact on the environment which creates a wicked link. Using large quantities of water for a conversion method also impacts the environment, this creates a second wicked link. The most important and biggest wicked links are the unavailable sources of information. Investments, market prices, water use, energy use, amount, availability and chemical composition of the agricultural products and residues are unavailable for the farmer.

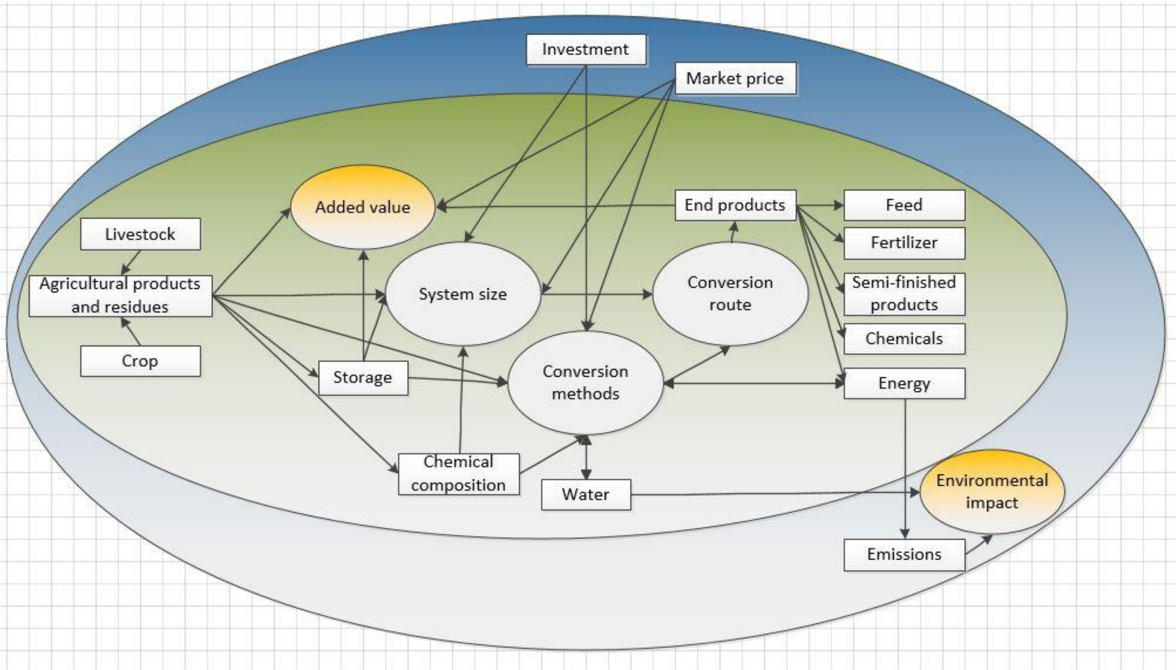

Figure 3 The system analysis visualized in a '3-Circle-Chart. The circles represent the systems: main system (green), environment (blue) and aspect system (yellow). The elements are depicted by the white rectangles. The arrows represent the relations.

3.1.3 Step C: Future visions

The future vision of the considered system functions without the presence of wicked links. There is lack of information about system size and conversion methods in the current system.

The unknown sources of information were determined in step B. The potential of conversion routes can be calculated when these sources are found and documented. Therefore these sources need to be brought together in a calculation tool. With insight on the potential, conversion routes with low energy use and water use can be chosen to decrease the environmental impact. Simultaneously conversion routes can be chosen that create the most added value (benefit) by focussing on the type of end product that is produced. In the end, all wicked links can be tackled by the calculation tool.

During this step, all possible routes from the routemap of Dröge & van Drimmelen et al. (2017) were visualized in Microsoft Excel 2016 (Available in a separate file *Biorefinery routes.xlsx)*. Comparable routes were combined to get a first insight in which input products had the same processing steps (Available in a separate file *Conversion routes per product.xlsx)*. This was done to see whether comparable products could be processed in the same way and whether there were possibilities for the farmer to process more than one product with the same conversion system. Grasses and wet biomass showed similar processing methods and routes. This meant a large variety of biomass could be processed similarly. Although, it became clear that the number of conversion routes was of significant size. The need to scale down the number of conversion routes that were going to be considered was evident. The choice was made to consider a single input product to decrease the scope of the research.

3.1.4 Step D & E: Farmer's needs and list of requirements

The farmer was chosen as the main stakeholder for this research. The needs were therefore very decisive for the list of requirements and the further progress of the design. From the previous steps some needs already emerged, together with other needs of the farmer a list was created. This list with additional requirements is found in Table 3.

The needs will be described in more detail below. The requirements for products and residues on the farm were already worked out in these steps, the remaining requirements were worked out in the following steps.

Table 3 Needs and additional requirements of the farmer

Need	*Requirement*
Information on available sources of biomass	List of common products and residues on the farm
Information on chemical composition of biomass	Defined precursors determine the composition of the common products and residues
Conversion systems for a single input product	Selection of potential of systems for 1 type of feedstock
Information on conversion methods	Per conversion method, only 1 option is chosen to use for the calculations
Information on water use	Water use per conversion method
Information on energy use	Energy use per conversion method
Information on investments	Investments per conversion method, they should be calculated by the model using empirical relations
Information on market prices	Market prices for created products
Information on revenues	Total revenues of a conversion system should be calculated by the model
Information on production costs	Production costs per conversion method
Information on profitability	Profit should be calculated by the model per conversion system
Information on return on investment	Return on investment should be calculated by the model

During problem and system analysis the sources of information that were missing to determine the potential were identified. Information on investments, market prices, water use, energy use, amount, availability and chemical composition of the agricultural products and residues were unavailable. These sources of information were all defined as needs. Additionally, production costs, revenues, profit and the return on investment are of interest to the farmer to do a selection based on economic potential. To narrow down the number of conversion routes the decision was made to choose only one type of biomass. Information on availability and chemical composition were used to select 1 single input product.

The products and residues that were selected and of which quantities were available in literature have been placed in Table 4. The quantities per product or residue differ a lot from each other.

Table 4 All selected products and residues from the different agricultural sectors with their quantities and corresponding references.

Product/ residue	Quantity	References
		Livestock farming
Cow manure	75.2 kg/day/cow	(Nennich et al., 2005)
Chicken litter	43-80 kg/day/1000 kg live animals	(Moffitt, 1999)
Pig manure	27.2-106.0 kg/day/1000 kg live animals	(Moffitt, 1999)
Maize	13.3-19 t DM/ha	(van Schooten, Philipsen, & Groten, 2016)
Grass	8.1-12.9 t DM/ha	(Remmelink, van Dooren, Curth-van Middelkoop, Ouweltjes, & Wemmenhove, 2016)
Hemp	9.6-11.6 t DM/ha	(Svennerstedt & Sevenson, 2006)
Sorghum bicolor	16.91 t DM/ha	(Mahmood & Honermeier, 2012)
		Arable farming
Wheat straw	1.3 t/ 1 t grain	(National Research Council, 1958)
Barley straw	1.2 t/ 1 t grain	(National Research Council, 1958)
Maize straw	1 t/ 1 t grain	(National Research Council, 1958)
Rapeseed straw	3 t/ 1 t seeds	(Kazmi, 2011)
Sugar beet leaves and tops	4.1 t DM/ha	(Diamantidis & Koukios, 2000)
Chicory leaves and tops	3.46 t DM/ha	(van der Voort, Klooster, van der Wekken, Kemp, & Dekker, 2006)
Potato leaves	2.1 t DM/ha	(Diamantidis & Koukios, 2000)
Onions (leaves/stems)	1 t DM/ha	(Haverkort, Zwart, Struik, Dekker, & Bosch, 1994)
Carrots (leaves/stems)	3.1 t DM/ha	(Haverkort et al., 1994)
Celeriac (leaves/tops)	3.3 t DM/ha	(Haverkort et al., 1994)
Green peas (leaves/stems/pods)	6.3 t DM/ha	(Haverkort et al., 1994)
Cabbage (peels)	3.5 t DM/ha	(Haverkort et al., 1994)
		Horticulture
Cucumber (leaf&stalk)	0.45 t / 1 t total yield	(Jölli & Giljum, 2005)
Tomatoes (leaf&stalk)	130g DM/plant	(Heuvelink, 1995)
		Green manures (temperate legumes)
Black lentil	2.3-2.7 t DM/ha	(Brandt, 1999)
Blue lupine	2.1 t DM/ha	(Gallaher, 1991)
Yellow trefoil	0.6-20.4 t DM/ha	(Stopes, Millington, & Woodward, 1996)
Alfalfa	3.7-5.7 t DM/ha	(Griffin, Liebman, & Jemison, 2000)
Barrel medic	2.4-4.5 t DM/ha	(Guldan, Martin, Cueto-Wong, & Steiner, 1996)
Yellow sweet clover	3.1-5.4 t DM/ha	(Blackshaw, Moyer, Doram, & Boswell, 2001)
Field pea or Austrian winter pea	4.8 t DM/ha	(Karpenstein-Machan & Stuelpnagel, 2000)
Berseem clover	9.2 t DM/ha	(Ross, King, Izaurralde, & O'Donovan, 2001)
Kura clover	6.2-10.7 t DM/ha	(Zemenchik, Albrecht, Boerboom, & Lauer, 2000)

Alsike clover	6.1 t DM/ha	(Ross et al., 2001)
Crimson clover	4-10.5 t DM/ha	(Karpenstein-Machan & Stuelpnagel, 2000)
Crimson clover and rye	6-12 t DM/ha	(Karpenstein-Machan & Stuelpnagel, 2000)
Balansa clover	7.2 t DM/ha	(Ross et al., 2001)
Red clover	5.2 t DM/ha	(Ross et al., 2001)
White clover	4 t DM/ha	(Ross et al., 2001)
Persian clover	7.2 t DM/ha	(Ross et al., 2001)
Hairy vetch	5.6-8.9 t DM/ha	(Singogo, Lamont, & Marr, 1996)
		Green manures (cabbage family)
Oilseed radish	2.5-3.5 t DM/ha	(Dapaah & Vyn, 1998)
Colza	2.1-6.4 t DM/ha	(N'dayegamiye & Tran, 2001)
Mustard	2.3-3.8 t DM/ha	(N'dayegamiye & Tran, 2001)
		Green manures (grasses)
Ryegrass	13.83 t DM/ha	(Van Eekeren, Bos, De Wit, Keidel, & Bloem, 2010)
Oat	3.3-4.3 t DM/ha	(Dyck & Liebman, 1995)
Rye	9-13.5 t DM/ha	(Karpenstein-Machan & Stuelpnagel, 2000)
Wheat	4.9-9.8 t DM/ha	(Singogo et al., 1996)
Sorghum (sudanense)	13.5 t DM/ha	(van der Mheen, 2011)
		Green manures (rest)
Buckwheat	2.1-3.7 t DM/ha	(N'dayegamiye & Tran, 2001)
Phacelia	1.5 t DM/ha	(Talgre, Lauringson, Makke, & Lauk, 2011)
Tagetes(leaf/ flower/ multiple species)	6.77 t DM/ha	(Marotti, Piccaglia, Biavati, & Marotti, 2004)
Sticky nightshade	14.34 t DM/ha	(Timmermans et al., 2007)
Corn spurry	2.6 t DM/ha	(Timmer, Korthals, & Molendijk, 2004)

Chemical compositions were not found for all selected products and residues in Table 4. The ones where chemical compositions were found, were placed in Table 5.

Table 5 Chemical composition of different agricultural products and residues with corresponding references.

Product/ residue	*Starch % of DM*	*Hemi-cellulose % of DM*	*Cellulose % of DM*	*Lignin % of DM*	*Lipids % of DM*	*Protein % of DM*	*References*
							Livestock farming
Cow manure	-	19.6	21.0	12.2	0.30	29.7	(Amon et al., 2007)
Chicken litter	-	25	63	5	-	-	(Garg & Bahl, 2008)
Pig manure	-	19.9	15.1	0.88	4.9	17.1	(Xiu, Shahbazi, Shirley, & Cheng, 2010)
Maize (silage)	-	19.5[a]	51.7[a]	16.6[a]	1.4[b]	7.9[b]	a (Oleskowicz-Popiel, Lisiecki, Holm-Nielsen, Thomsen, & Thomsen, 2008) b (Møller et al., 2005)

Grass (silage)	-	23-28[a]	24-36[b]	4.8-10[b]	-	10-18[c]	a (Vuuren, Bergsma, Frol-Kramer, & Beers, 1989) b (Harrison, Blauwiekel, & Stokes, 1994) c (Dewhurst, Fisher, Tweed, & Wilkins, 2003)
Fresh grass	0	24.5	24.1	2.1	3.8	18.3	(Eurofins Agro, 2017)
Sorghum bicolor		25.3	21.9	3.1	-	7.5	(Mahmood & Honermeier, 2012)
							Arable farming
Wheat straw	-	36	39	10	-	-	(Marsden, Gray, & Mandels, 1985)
Barley straw	-	27	44	7	-	-	(Marsden et al., 1985)
Maize straw	-	30	36.7	27.1	-	-	(Kirkpatrick, 2008)
Rapeseed straw	0	21.2	34.8	11.9	-	3.6	(Godin et al., 2013)
Sugar beet tops	-	26-32	22-24	1-2	-	7-8	(Michel, Thibault, Barry, & de Baynast, 1988)
Sugar beet leaves	0	8.9	7.1	2.5	-	17.9	(Godin et al., 2013)
Chicory tops	0	2.0	3.8	0.6	-	7.3	(Godin et al., 2013)
Chicory leaves	0	5.0	10.2	2.5	-	16.8	(Godin et al., 2013)
Potato leaves	2.5	6.6	11.5	3.8	-	18.2	(Godin et al., 2013)
Onions (leaves/stems)	0	3.5	9.1	1.6	-	10.3	(Godin et al., 2013)
Carrots (leaves/stems)	0	21.3	31.6	18.5	-	-	(Kopania, Wietecha, & Ciechańska, 2012)
Green peas (leaves)	5.8	8.5	22.1	6.9	-	11.2	(Trevino, Centeno, & Caballero, 1987)
Green peas (stems)	3.5	13.0	31.5	12.9	-	8.1	(Trevino et al., 1987)
Cabbage (peels)	0	5.3	9.4	1.3	-	23.1	(Godin et al., 2013)
							Horticulture
Cucumber (leaf&stalk)	-	11.4	21.2	2.6	-	-	(Jagadabhi, Kaparaju, & Rintala, 2011) ,(Heuvelink & Marcelis, 1989) Used for DM correction
Tomatoes (leaf&stalk)	1.1	6.3	12.8	2.5	-	29	(Godin et al., 2013)
							Green manures (temperate legumes)

Alfalfa		21.1	4.9	7.1	1.8	20.1	(Whiting, Mutsvangwa, Walton, Cant, & McBride, 2004)
Berseem clover		26.6	9.3	7.0	2.6	1.7	(Kälber, Meier, Kreuzer, & Leiber, 2011)
Hairy vetch		38	14.8	11.4		10.9	(Bruno-Soares, Abreu, Guedes, & Dias-da-Silva, 2000)
							Green manures (grasses)
Ryegrass		20.2	19.5	1.8	2.8	12.5	(Hammond et al., 2011)
Sorghum (sudanense)		30.9	23.2	5.5	-	8.0	(Mahmood & Honermeier, 2012)
							Green manures (rest)
Buckwheat		30.0	11.9	8.3	2.0	1.4	(Kälber et al., 2011)
Phacelia		26.6	12	8.4	2.4	1.5	(Kälber et al., 2011)
Tagetes (leaf/stalk)	0	25	14.6	6.6	-	8.3	(Godin et al., 2013)

From this wide variety of products and residues, fresh grass was finally chosen as the product to be considered for this research. Consequently, the need for a selection of conversion routes (systems) was determined based on the choice to process only fresh grass. Examples of conversion routes are torrefaction, biorefinery and anaerobic digestion. Finally, the need for a selection of conversion methods, which were going to be used for the conversion methods, was added to the needs.

3.2 Phase 2: Structured design

3.2.1 Step F & G: Key functions and morphologic function diagram

These steps represent the preparation for and programming of the model. First, the remaining requirements from the previous step were worked out to collect and select all information needed for modelling.

The calculation tool was developed for a limited number of paths for conversion. As a starting point, Dröge & van Drimmelen et al. (2017) was used to define the routes that were programmed. Comparable routes with fresh grass were analysed and added to the selection of potential routes. All these routes with starting product, intermediate products and conversion methods were drawn in Microsoft Visio 2016. Starting products, intermediate products and conversion methods with all possible connections were clearly visible in this drawing. These routes and products were evaluated with an expert on process technology (Van Boxtel, 2017e) and an expert on chemistry (Scott, 2017a) to eliminate some routes and/or products that would definitely not have any potential for a farm located conversion system. The figure of the final selection of conversion routes and corresponding methods is found in Figure 4.

This model will calculate water use, energy use, investments, production costs, net revenues, profit, return on investment for all the possible conversion routes. These numbers were defined as the key functions of the calculation tool. Information on numbers for these calculations was found in literature, these numbers with corresponding references can be found in the appendix.

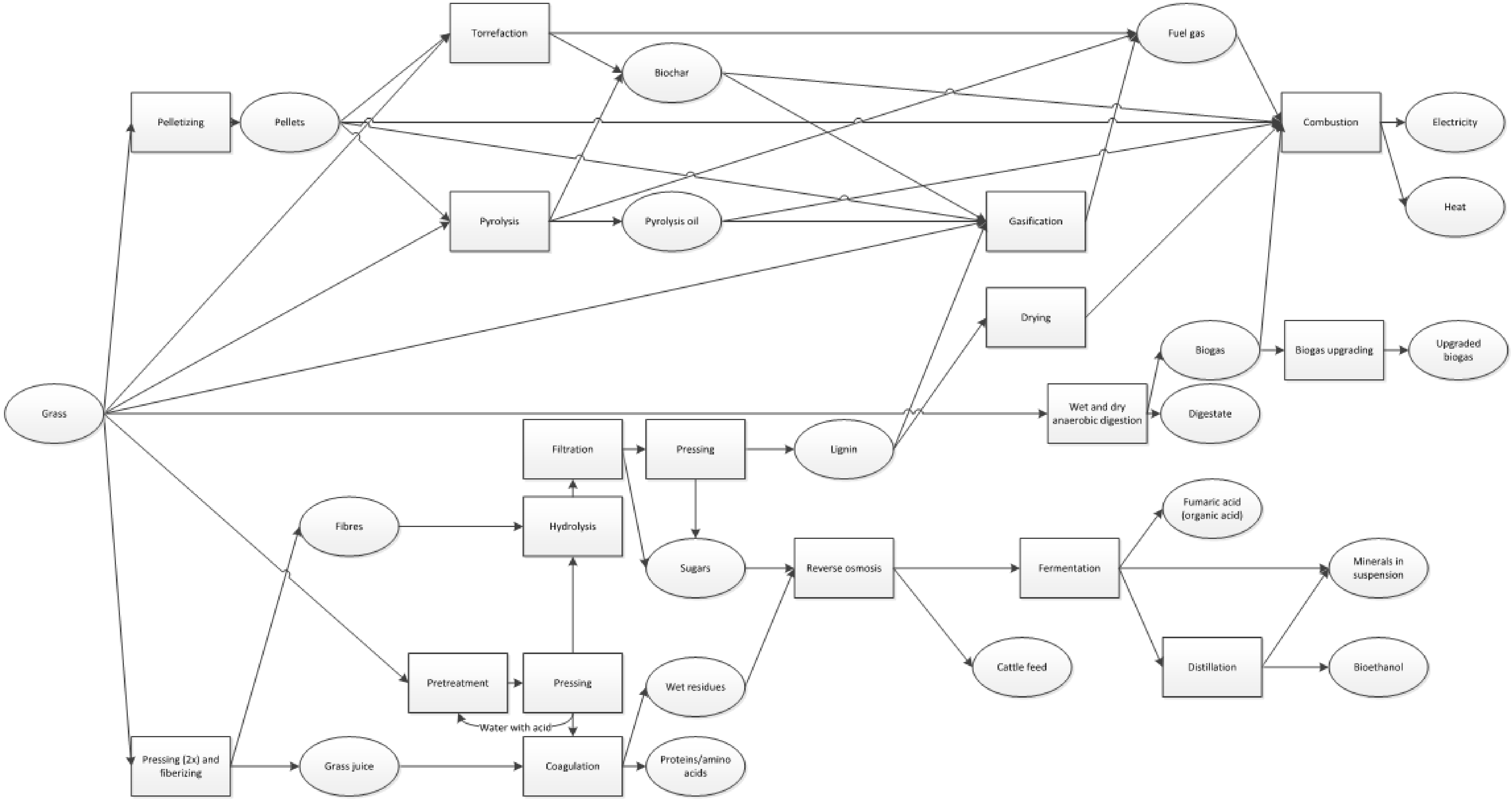

Figure 4 All conversion routes that were programmed, ovals indicate the products and the squares indicate the conversion method. The lines indicate the direction of the products and the connection of the products with the conversion methods. This figure also clearly visualises how the superstructure framework is made, how it works and how it is all connected.

A description of the conversion methods that were selected for the model can be found in Table 6.

Table 6 All conversion methods with a short description and corresponding references.

Conversion method	*Description*	*References*
Pelletizing	For the process of pelletizing, the feedstock is first milled to the right particle size in a hammer mill. The feedstock is then conditioned to the right conditions and pelleted. After pelleting the pellets are cooled down. Finally, dust, particles and fragments are separated.	(Samson, Stamler, Ho Lem, & Ho Lem, 2008)
Torrefaction	With torrefaction the biomass is thermally upgraded. The process is normally carried out in an inert environment (typically nitrogen) and under atmospheric conditions. The temperature in the reactor is between 200°C-300°C. Biochar is the main output product.	(Batidzirai, Mignot, Schakel, Junginger, & Faaij, 2013)
Pyrolysis	Pyrolysis is a treatment were biomass is thermally decomposed in absence of oxygen. Temperatures in the reactor range between 400°C-800°C. Pyrolysis oil is the main product that is produced.	(Uslu, Faaij, & Bergman, 2008)
Gasification	The feedstock is gasified under atmospheric conditions in a fluidized bed gasifier. The reactor temperature ranges between 700°C-950°C. Oxygen is used as the oxidizing agent. Syngas is the output product.	(Arena, Di Gregorio, De Troia, & Saponaro, 2015)
Combustion	The combustion technique depends on the biomass that is used as fuel. Solid or liquid biomass[a] is combusted in a stirling engine, syngas[b] is combusted in an organic rankine cycle and biogas[c] in a biogas engine.	a (Obernberger & Thek, 2008) b (Arena et al., 2015) c (Smyth, Smyth, & Murphy, 2010)
Pressing and fiberizing	Water is added to silage feedstock whereupon the biomass is fed into a fiberizer that opens up the plant cells. The material is pressed twice. Press juice and a dried fibre product are the output products.	(O'Keeffe, Schulte, Sanders, & Struik, 2011)
Coagulation	Press juice from the pressing and fiberizing process is coagulated with steam. The proteins curdle and are separated by skimming. Dried protein product and whey are the final output products.	(O'Keeffe et al., 2011)
Pre-treatment	Lignocellulosic biomass (straw) is pre-treated to improve cellulose accessibility to cellulolytic enzymes. Straw is milled twice and maleic acid solution is mixed with the straw. Pre-treatment is performed at 170°C for 30 minutes.	(Kootstra, Beeftink, Scott, & Sanders, 2009a)
Pressing	A screw press separates fluids (with dissolved products) from the wet solid input product.	(Flotats Ripoll et al., 2012)
Hydrolysis	Pre-treated biomass is hydrolyzed by enzymes. The hydrolysis is performed under atmospheric conditions at 50°C for 24 hours.	(Kootstra, Beeftink, Scott, & Sanders, 2009b) (Scott, 2017b)
Filtration	The resulting slurry from hydrolysis is separated by filtration. The biomass (lignin) is separated from the liquid with sugars. Filtration is done with a pressure plate filter.	(Matches, 2014)
Reverse osmosis	The solution with sugars coming from the filtration step is concentrated by reverse osmosis. By exerting a certain fluid	(Galema, 2014)

	pressure on the solution only water is forced through a membrane.	
Fermentation	Sugars (xylose and glucose) are fermented by a culture of bacteria. Depending on the type of bacteria a different end product is created. The temperature of the solution is kept at 30°C during the whole process.	(Fu, Peiris, Markham, & Bavor, 2009) (Liu et al., 2017)
Distillation	The alcohol produced during fermentation is separated from the fermentation broth by distillation. Based on the difference in boiling temperature the alcohol is evaporated.	(Intelligen Inc., 2017)
Wet and dry anaerobic digestion	There are two types of anaerobic digestion (AD), dry and wet AD. The difference is that the space between the solids in the reactor is filled with gas for dry AD and with water for wet AD. The principle of AD is the conversion of biomass into biogas by bacteria under anaerobic conditions.	(Smyth, Murphy, & O'Brien, 2009) (Smyth et al., 2010) (Singh, Nizami, Korres, & Murphy, 2011)
Biogas upgrading	Biogas upgrading is a process where the methane content of biogas is increased by removing carbon dioxide from the biogas. A selective membrane captures the carbon dioxide resulting in an outflow of upgraded biogas.	(Deng & Hägg, 2010)

3.2.2 Step H & I: Generation of solutions and design concepts

All information was programmed and calculations were made. Equations for these calculations were already mentioned in

Table 2 in chapter 2.2.2. Numbers used for these equations can be found in Table A-1 in the appendix. The complete results are available in a separate file *Results complete.xlsx*. Only routes that made a profit and had a return on investment of maximal 5 years were considered for 6 different amounts of feedstock input: 0.5, 1, 2, 3, 4 and 5 tonnes per hour. Energy use, profit, investment and return on investment were analysed for each individual conversion route, these results have been compared. The names of the conversion routes were configured by putting the different conversion methods, the conversion route is composed of, in chronological order (Table 7).

Table 7 Conversion routes with corresponding numbers for all results.

Conversion route	*Conversion route no.*
UOstart Pressing_fiberizing Coagulation Reverse_osmosis Fermentation_ethanol Distillation_70	1
UOstart Pressing_fiberizing Coagulation Reverse_osmosis Fermentation_ethanol Distillation_30	2
UOstart Pressing_fiberizing Coagulation Reverse_osmosis Fermentation_ethanol	3
UOstart Pressing_fiberizing Coagulation Reverse_osmosis Fermentation_fumaric_acid	4
UOstart Pressing_fiberizing Coagulation Reverse_osmosis	5
UOstart Pressing_fiberizing Coagulation	6
UOstart Pressing_fiberizing Hydrolysis Pressure_filtration Reverse_osmosis Fermentation_ethanol Distillation_30	7
UOstart Pressing_fiberizing	8
UOstart Pretreatment Pressing Hydrolysis Pressure_filtration Reverse_osmosis Fermentation_ethanol Distillation_30	9
UOstart Pretreatment Pressing	10
UOstart Pretreatment	11

Specific values for energy use, profit, investments and return on investment, for the different feedstock inputs, can be found in the appendix (Table A-3 to Table A-8). Only column charts are shown as results.

Conversion routes consist of multiple conversion methods. Conversion routes with the most conversion methods will be referred to as long conversion routes. The same holds for the routes consisting of the least methods, these will be referred to as short conversion routes.

Figure 5 Column charts for energy use, profit, investment and return on investment for all conversion routes using an input of 0.5 tonnes/hour.

With a feedstock input of 0.5 tonnes/hour, there are 5 potential conversion routes. Routes 2,7 and 9 are the longest routes and show de highest energy use per tonne. They also have the highest investment and profit per tonne. These long routes also have higher returns on investment together with route 11. The shortest routes, 8 and 11, have the lowest energy use per tonne. Route 8 has a relatively high profit per tonne compared with route 11, this shows in the return on investment. Route 8 also has a lower investment per tonne than route 11.

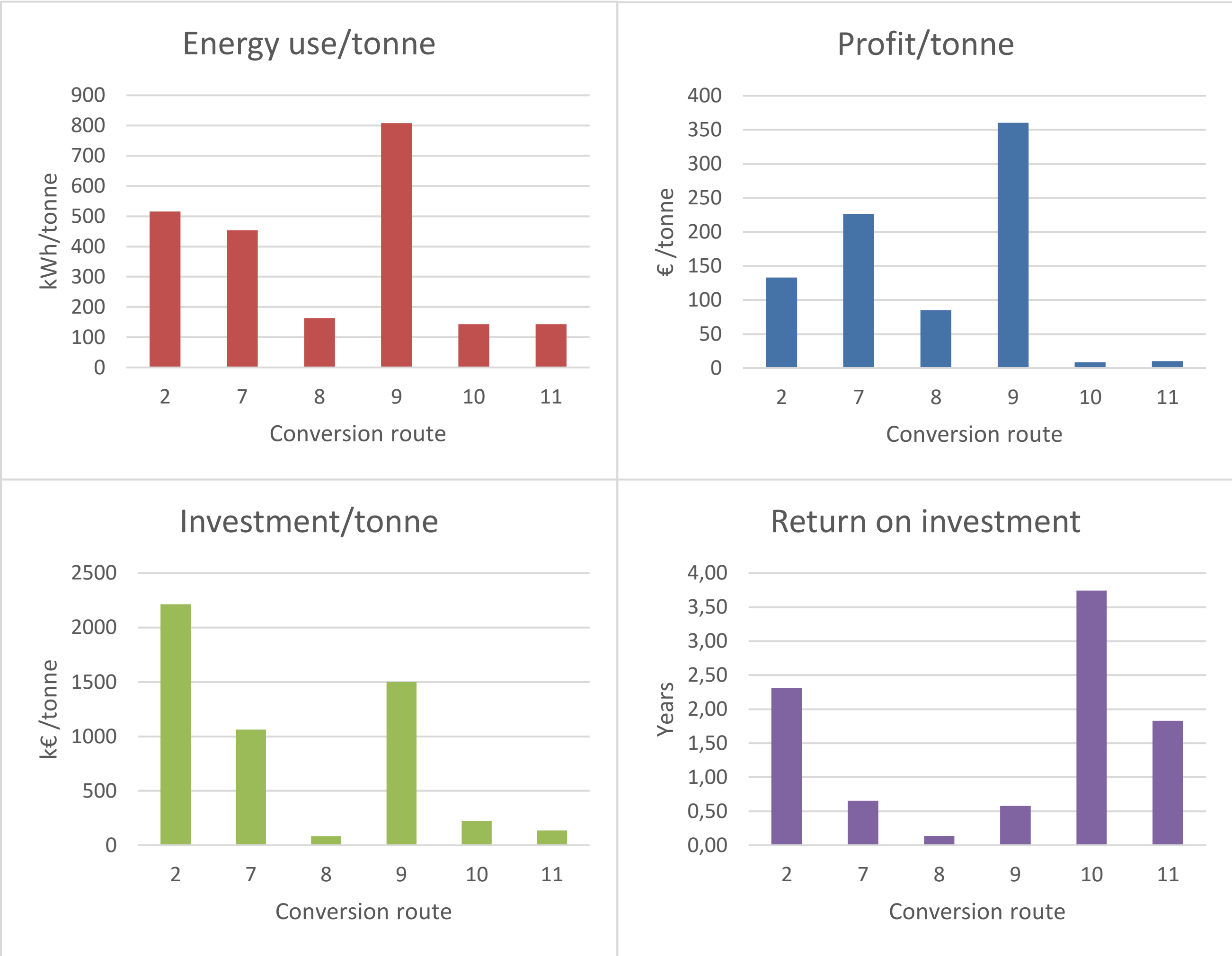

Figure 6 Column charts for energy use, profit, investment and return on investment for all conversion routes using an input of 1 tonne/hour.

1 tonne per hour of feedstock resulted in 6 potential conversion routes. 3 relative long conversion routes compared with 3 relative short conversion routes. Routes 2,7 and 9 are the relative long routes, all these routes have the highest numbers for energy use, profit and investment per tonne. The short routes have the lowest numbers for energy use, profit and investment per tonne. The return on investment shows a different pattern for the long and short routes. Routes 10 and 11 have a relatively low profit per tonne compared to route 8. They also have a higher investment per tonne for than route 8. This results in a larger return on investment.

Figure 7 Column charts for energy use, profit, investment and return on investment for all conversion routes using an input of 2 tonnes/hour.

5 routes short routes (5,6,8,10 and 11) and 5 routes long routes (2,3,4, 7 and 9) result from an input of 2 tonnes per hour. From the short routes, routes 8, 10 and 11 show a lower energy use per tonne than all other routes. Route 5 and 6 show comparable energy uses per tonne with the longer routes. The same holds for investments per tonne. Profit per tonne shows relatively comparable results for routes 3, 4, 5, 6 and 8. The other routes are much higher or lower. The highest profits per tonne are all accounted for by the longer routes, this shows in the return on investment.

Figure 8 Column charts for energy use, profit, investment and return on investment for all conversion routes using an input of 3 tonnes/hour.

Only 1 potential route is added to the list of potential routes with an input of 3 tonnes per hour. This is route 1 and this is one of the long routes. Route 1 is very comparable with route 2, the energy use per tonne is slightly higher but the investments per tonne are equal. The profit per tonne is much lower for route 1 compared with route 2. This results in a larger return on investment for route 1.

Figure 9 Column charts for energy use, profit, investment and return on investment for all conversion routes using an input of 4 tonnes/hour.

Figure 10 Column charts for energy use, profit, investment and return on investment for all conversion routes using an input of 5 tonnes/hour.

The potential routes for 4 and 5 tonnes per hour are the same as the routes for 3 tonnes per hour. The energy use per tonne is about the same or entirely the for 3, 4 and 5 tonnes per hour. The profit per tonne increases slightly with increasing input. Investments per tonne decrease with increasing input, the same holds for return on investment. Looking at the results of 3, 4 and 5 tonnes per hour, an increasing feedstock input (scaling up), results in higher profits due to lower production costs. Investments decrease due to the size of operation. The energy use is equal or decreases and the return on investment is improved.

Looking at all the potential conversion routes together, almost all the 11 potential conversion routes contain the conversion method pressing and fiberizing as the first method. The remaining potential conversion routes contain the conversion method pretreatment as the first method.

4 Discussion

4.1 Design process and application

The calculation tool has been designed to give more information about the possible conversion routes at this moment in time. The design process is iterative, the first results are coarse but will become refined as the process progresses. Due to time limitations, assumptions have been made for this research. These assumptions and their effects will we discussed below.

In this research, a biobased problem for farm located conversion was approached and RID was used to structure the process. The steps of RID were reconfigured to make the method fit this sort of problem. As this research is in the exploration phase, the steps were also not executed elaborately. The first results are coarse but give a good idea on the order of magnitude.

A lot of literature was studied for this research, this has resulted in a large overview of agricultural products with corresponding size and chemical properties. This overview can provide information for other researches or can be used for improving the current analysis of processing agricultural materials into biobased materials.

Only the most common agricultural products and residues were chosen. Besides the products and residues that lacked information about quantity and chemical properties were also not selected. From this selection, one product was chosen for the calculation tool. This limited the amount of information available from the tool for the farmers. Although the overview of products and residues is also a large available source of information that can be used by the farmers.

Dröge & van Drimmelen et al. (2017) was used as a guideline to find all potential routes for different sorts of feedstock. Some routes might not have been considered by this online tool, this can be a limitation for the current model. Conversion methods were also largely based on information from Dröge & van Drimmelen et al. (2017). Methods other than the examples in the online tool were found by search of literature. Due to time limitations, only one conversion method was chosen where multiple are possible, this might also be a limit for the model.

All parameters that were used for the calculation tool were fixed to a given value, these values can be found in the appendix in Table A-1. Some parameters are dependent on other parameters which means they should have been variable instead of fixed. The accuracy of the model can have been affected by this. Though calculations for the investments have largely been determined by empirical relations where possible. Some conversion methods only have a basic empirical relation that was not found in literature. These empirical relations should be reconsidered as this has effect on numbers that are returned by the calculation tool. The exponent that was used in these empirical relations (equation 6 in
Table 2) was based on personal communication (Van Boxtel, 2017c). Formulas for water and energy use are linear relations that should also be reconsidered as the these often decrease with increasing size of the machinery due to higher efficiencies. There are also variables that were not considered but are important parameters. Labour is a variable that is currently not considered but has a large influence on the production cost of a conversion route.

Most parameters are that were used are fixed, it would be better to give the parameters a range of values to make the model more flexible. The fixed parameters for revenues of all end products for example, have a significant effect on the profitability of conversion routes. The results are very sensitive to a change in the revenues. Due to the absence of a range for the parameters a sensitivity analysis is not possible. The basic program that was used as a basis for the calculation tool, has the option to do a sensitivity analysis but then the written program should be extended. Right now, information on the sensitivity of the different conversion routes is missing. Adding a range to the parameters and creating the possibility to do a sensitivity analysis would improve the accuracy of the results given by the calculation tool.

The numbers that are currently returned by the calculation tool give a good indication on the order of magnitude. Reconsidering equations and parameters will give more refined results, the accuracy of the numbers will improve.

At the moment, the calculation tool only considers one type of feedstock product that is processed year-round. Often feedstock products are not available year-round and their might even be no possibility for prolonged storage of the feedstock. This raises the question what combination of products should be processed to achieve year-round production. The conversion methods should also be reconsidered as these should be able to process the different sorts of biomass. The current tool is not yet programmed to take these things into account.

The chemical properties that were found by study of literature have only been used to choose the feedstock that was going to programmed in the calculation tool. It would be a huge improvement for the calculation tool if these chemical properties would be inserted as changeable parameters into the model. Based on these properties the production of for example proteins and sugars as final products could be calculated per type of feedstock. Multiple feedstock products can be compared by looking at the amounts and quality of the final products, these are then also partly based on chemical properties. In the current model, also lots of assumption have been done for production rates. But in a future model, these assumptions can be changed into determined parameters.

The model that was developed, aimed at farm located conversion systems. The size of the conversion systems is therefore important. To get insight into the effect of size, the input of feedstock was varied. This was done for a limited range so the effect of size is not completely clear.

Though a trend was visible when the conversion routes were scaled up by increasing the feedstock input. This was best observed when comparing 3, 4 and 5 tonnes per hour as feedstock input. With these inputs, the potential conversion routes stayed the same which made a good comparison possible. Energy use stayed the same or decreased slightly due to the fact a linear function was used to do the calculations. Improvements in energy efficiency because of scaling up should be taken into account when the calculation tool is improved. Investment is calculated by empirical relations as described before, the relations are dependent on the size of the operation. With increasing size, the investment per tonne decreases. Profit is based on revenues and production cost. Revenues are calculated linearly, production costs depend on the investment so they are not calculated linearly. When the feedstock input increases, the profit per tonne also increases because the production costs per tonne decrease due to decreasing investment and the revenues stay the same. Eventually, the return on investment improves because the profit per tonne increases and the investment per tonne decreases. Scaling up in the lower ranges of feedstock input (0.5, 1 and 2 tonne/h) also showed a trend. With increasing input, the number of longer routes increased. This might be caused by the fact the investments of long routes are larger but decrease with increasing size till the point they are profitable and have potential. Lower investments due to a larger economy of scale was also described in Bruins and Sanders (2012).

The results showed that most potential conversion routes contain the conversion method pressing and fiberizing as the first method in the route. The other routes contain pretreatment as the first method. With pressing and fiberizing more valuable (semi-finished) products are created than pretreatment. Value is added to these products or other products are created along the route, therefore more revenue is generated. A higher profit per tonne is realised which means routes with this conversion method have more potential.

Only a few criteria are used to score the different conversion routes in the current model. Besides, there is no gradation between these criteria. There is a possibility that the current selection is not the best selection because of the lack of criteria and the absence of gradation between the criteria.

The final conversion routes that were returned as results, were chosen based on profitability and return on investment. The numbers for these criteria have a large influence on the results and conclusions of this research. Other numbers for these criteria will almost certainly give other results.

Heat recovery and recycling have not been considered, improvement of efficiency with these methods has an effect on the potential of routes. Other processes that deal with energy, for example heat losses, are also not considered. This influences the energy use that is calculated by the tool.

For this research only single conversion routes were calculated, combinations of conversion routes were not considered. It would be possible to manually combine multiple routes but it has not been programmed for the calculation tool. Not being able to combine different conversion routes is a limitation of the calculation tool.

4.2 Recommendations

Most of the recommendations for this research result from the discussion. As designing is an iterative process a large part of the recommendations are physical improvements for the calculation tool and the design process. The recommendations will be listed below:

- To design a complete calculation tool all possible agricultural products and residues should be considered and programmed in the calculation tool.
- All possible conversion methods that can be applied in a conversion route should be considered and programmed in the current tool to get a complete view of the possibilities.
- The current model is very basic and needs improvements on multiple levels. Parameters are missing or incomplete, they should be reconsidered. Parameters should be made variable to make dependence on other parameters possible. Make use of empirical formula's if possible.
- Use a range of values for parameters, this makes a sensitivity analysis also possible.
- The size of conversion routes should be elaborated on in future calculation tools.
- Throughout the design process, more criteria should be used and gradation between these criteria should be present in future models, sensitivity analysis could provide input for these criteria.
- It should be possible to combine single conversion routes to a combined route. The full potential of multiple conversion routes would be better visible.

5 Conclusions

From the results of this research the following conclusions can be drawn:

- A systematic analysis of processing agricultural materials to biobased products (conversion systems) was performed with RID.
- With RID a large overview of agricultural products and residues with additional chemical properties was created.
- RID has structured the design of a calculation tool in exploration phase which calculates the potential of farm located conversion systems that process fresh grass.
- The most important numbers that should be calculated by a calculation tool in exploration phase are: investments, production costs, energy use and return on investment.
- The calculation tool shows that scaling up, results in more potential conversion routes and an improved return on investment.
- Scaling up also affects investment and profit. Investment per tonne decreases and profit per tonne increases with increasing feedstock input. Energy use is not or minimally affected.
- With increasing input of feedstock, an increasing amount of longer conversion routes also have potential.
- Conversion routes with the most potential have the conversion method pre-treatment or pressing and fiberizing. The majority of these routes have pressing and fiberizing as conversion method. Other conversion methods do not create enough profit and/or have too high investments.
- Conversion routes with conversion methods that create (more) valuable (semi-finished) products are more likely to have potential due to a higher profit per tonne that can be realised.
- The current calculation tool still has a lot of limitations due to a large number of assumptions that were made but it can be used for exploration.

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7 Appendix

Some remarks can be placed with the content of Table A-1. Production costs with value 0 have a separate equation for the calculation of these costs in the subprogram for the conversion method. Revenues of semi-finished products like sugars in water were found by multiplying the final product with 0.8^n, exponent n depending on the number of processing steps (conversion methods) preceding the final product in its pure form. For investments a Lang factor of 2.5 was used, simpler processes became a factor 1.5 or 1 (Ter Stege, 2017). Empirical equations were created for distillation, pressure filtration, hydrolysis and fermentation by using values found on Matches (2014), these equations can be found in Table A-2. For the heat exchanger, no sources are mentioned because it was not used in the model.

Table A-1 Values of all the parameters that were used in the model. Sources for these values are in the last column of the table.

Parameter	*Value*	*Unit*	*Source*
			Basic parameters
In_prod	5000	kg/h	-
Elec_cost	0.081	€/kWh	(Eurostat, 2017a)
Gas_cost	0.028	€/kWh	(Eurostat, 2017b)
DM_content	0.176	-	(Eurofins Agro, 2017)
Ex_rate	0.932	-	(XE, 2017)
			Pelletizing
Pel_in_out_ratio	1.000		(Campbell, 2007)
Pel_energy_use	0.110	kWh/kg end product	(Campbell, 2007)
Pel_prod_cost	0.048	€/kg end product	(Samson et al., 2008)
Pel_invest	349425	€	(Campbell, 2007)
Pel_rev	0.203	€/kg end product	(Propellets Austria, 2017)
			Torrefaction
Tor_in_out_ratio_1	0.657	-	(Batidzirai et al., 2013)
Tor_in_out_ratio_2	0.343	-	(Batidzirai et al., 2013)
Tor_energy_use	0.224	kWh/kg end products	(Batidzirai et al., 2013)
Tor_invest	1000000	€	(Batidzirai et al., 2013)
Tor_prod_cost_factor	0	€/kg end product	(Van Boxtel, 2017a)
Tor_rev_1	0.500	€/kg end product biochar	(Pyreg, 2017)
Tor_rev_2	0.133	€/kg end product torrefaction gasses	Adapted from (Trippe et al., 2013)
			Pyrolysis
Pyr_in_out_ratio_1	0.727	-	(Uslu et al., 2008)
Pyr_in_out_ratio_2	0.136	-	(Uslu et al., 2008)
Pyr_in_out_ratio_3	0.127	-	(Uslu et al., 2008)
Pyr_in_out_ratio_4	0.009	-	(Uslu et al., 2008)
Pyr_energy_use	0.075	kWh/kg input product	(Uslu et al., 2008)
Pyr_prod_cost	0	€/kg end product	(Van Boxtel, 2017a)
Pyr_rev_1	0.025	€/kWh end product bio oil	(btg-btl, 2017)
Pyr_rev_2	0.133	€/kg end product fuel gas	Adapted from (Trippe et al., 2013)
Pyr_rev_3	0.500	€/kg end product biochar	(Pyreg, 2017)

			Gasification
Gas_in_out_ratio	2.493	-	(Arena et al., 2015)
Air_in_ratio	1.760	-	(Arena et al., 2015)
Dust_out_ratio	0.267	-	(Arena et al., 2015)
Gas_energy_use	0.142	kWh/kg input product	(Arena et al., 2015)
Gas_prod_cost	0	€/kg input product	(Van Boxtel, 2017a)
Gas_invest	1556000	€	(Arena et al., 2015)
Gas_rev	0.028	€/kg end product fuel gas/syngas	(Eurostat, 2017b)
			Combustion
LHV_fgas_tor	5.700	MJ/kg	(Batidzirai et al., 2013)
LHV_fgas_pyr	15.000	MJ/kg	(Uslu et al., 2008)
LHV_biomass	16.500	MJ/kg	(Arena et al., 2015)
LHV_pel	17.700	MJ/kg	(Zeng, Weller, Pollex, & Lenz, 2016)
LHV_bchar_tor	21.500	MJ/kg	(Batidzirai et al., 2013)
LHV_bchar_pyr	32.000	MJ/kg	(Uslu et al., 2008)
LHV_poil	16.100	MJ/kg	(Van de Beld, Holle, & Florijn, 2013)
LHV_lignin	21.500	MJ/kg	(Svennerstedt & Sevenson, 2006) (Hansen, Jørgensen, Laursen, Schjørring, & Felby, 2013)
LHV_bgas_AD	20.779	MJ/m3	(Smyth et al., 2009)
Comb_rev_1	0	€/kWh heat	-
Comb_rev_2	0.125	€/kWh electricity	Adapted from (Smyth et al., 2009)
			Organic Rankine Cycle
ORC_th_eff	0.623	-	(Arena et al., 2015)
ORC_el_eff	0.177	-	(Arena et al., 2015)
ORC_invest	890000	€	(Arena et al., 2015)
ORC_prod_cost	0	€/kWh	-
			Gas engine
Gas_eng_th_eff	0.400	-	(Smyth et al., 2010)
Gas_eng_el_eff	0.350	-	(Smyth et al., 2010)
Gas_eng_invest	150000	€	(Smyth et al., 2010)
Gas_eng_prod_cost	0.010	€/kWh electricity	(Smyth et al., 2010)
			Stirling engine
STE_th_eff	0.787	-	(Obernberger & Thek, 2008)
STE_el_eff	0.110	-	(Obernberger & Thek, 2008)
STE_invest	777000	€	(Obernberger & Thek, 2008)
STE_prod_cost_1	0.158	€/kWh electricity	(Obernberger & Thek, 2008)
STE_prod_cost_2	0.023	€/kWh heat	(Obernberger & Thek, 2008)

			Pressing and fiberizing
Press_in_out_ratio_1	0.111	-	(O'Keeffe et al., 2011)
Press_in_out_ratio_2	0.885	-	(O'Keeffe et al., 2011)
Press_sugar_content	0.021	-	(Eurofins Agro, 2017)
Press_DM_content	0.420	-	(O'Keeffe et al., 2011)
Press_water_in_ratio	0.149	-	(O'Keeffe et al., 2011)
Press_water_out_ratio	0.153	-	(O'Keeffe et al., 2011)
Press_energy_use	0.163	kWh/kg input product	(O'Keeffe et al., 2011)
Press_prod_cost	0.008	€/kg input product	(O'Keeffe, Schulte, Sanders, & Struik, 2012)
Press_invest	75000	€	(O'Keeffe et al., 2012)
Press_rev_1	0.800	€/kg fibre	(O'Keeffe et al., 2012)
Press_rev_2	0.077	€/kg free sugars in suspension	(Scott, 2017c)
Press_rev_3	0.320	€/kg protein in pressing suspension	(Euro Koe IDEE, 2017)
			Coagulation
Coag_in_out_ratio_1	0.014	-	(O'Keeffe et al., 2011)
Coag_in_out_ratio_2	0.952	-	(O'Keeffe et al., 2011)
Coag_water_out_ratio	0.034	-	(O'Keeffe et al., 2011)
Coag_energy_use	0.251	kWh/kg input product	(O'Keeffe et al., 2011)
Coag_prod_cost	0.021	€/kg input product	(O'Keeffe et al., 2012)
Coag_rev_1	0.478	€/kg crude protein	(Euro Koe IDEE, 2017)
Coag_rev_2	0.096	€/kg rest juice free sugars	(Scott, 2017c)
			Pre-treatment
Pret_DM_content_1	0.176	-	(Eurofins Agro, 2017)
Pret_DM_content_2	0.100	-	(Kootstra et al., 2009a)
Pret_in_out_ratio	1.760	-	-
Pret_water_in_ratio	0.760	-	-
Pret_energy_use_1	0.143	kWh/kg input product	Own calculations
Pret_energy_use_2	0.039	kWh/kg input product	Own calculations (O'Keeffe et al., 2011)
Pret_prod_cost	0.007	€/kg input product	(Kootstra et al., 2009b)
Pret_rev_1	0.057	€/kg wet solids lignin	Adapted from (Bruijnincx, Weckhuysen , Gruter , Westenbroek, & Engelen-Smeets, 2016)
Pret_rev_2	0.066	€/kg glucose in suspension	(Kootstra et al., 2009b)
Pret_rev_3	0.033	€/kg xylose in suspension	(Kootstra et al., 2009b)
Pret_rev_4	0.061	€/kg free sugars in suspension	(Scott, 2017c)
Pret_rev_5	0.256	€/kg protein in pressing suspension	(Euro Koe IDEE, 2017)
Pret_retention_time	0.833	h	(Kootstra et al., 2009b)
			Pressing 2
Press_2_DM_content	0.400	-	Adapted from (O'Keeffe et al., 2011)
Press_2_DM_energy_use	0.0003	kWh/kg input product	(Flotats Ripoll et al., 2012)
Press_2_prod_cost	0.001	€/kg input product	(Flotats Ripoll et al., 2012)
Press_2_invest	75000	€	(Flotats Ripoll et al., 2012)

Press_2_rev_1	0.072	€/kg wet solids lignin	Adapted from (Bruijnincx et al., 2016)
Press_2_rev_2	0.082	€/kg glucose in suspension	(Kootstra et al., 2009b)
Press_2_rev_3	0.041	€/kg xylose in suspension	(Kootstra et al., 2009b)
Press_2_rev_4	0.077	€/kg free sugars in suspension	(Scott, 2017c)
Press_2_rev_5	0.320	€/kg protein in pressing suspension	(Euro Koe IDEE, 2017)
			Hydrolysis
Hyd_DM_content	0.050	-	(Kootstra et al., 2009a)
Hyd_in_out_ratio_glucose	0.340	-	(Kootstra et al., 2009b)
Hyd_in_out_ratio_xylose	0.167	-	(Kootstra et al., 2009b)
Hyd_energy_use	0.270	kWh/kg input product	Own calculations
Hyd_prod_cost	0.022	€/kg input product	(Kootstra et al., 2009b)
Hyd_rev_1	0.102	€/kg glucose	(Kootstra et al., 2009b)
Hyd_rev_2	0.051	€/kg xylose	(Kootstra et al., 2009b)
Hyd_rev_3	0.089	€/kg wet solids lignin	Adapted from (Bruijnincx et al., 2016)
Hyd_retention_time	24	h	(Scott, 2017b)
			Reverse osmosis (Galema, 2014)
RO_prod_cost	0	€/kg input product	(Van Boxtel, 2017a)
RO_invest	750	€/m2	(Van Boxtel, 2017b)
RO_rev_1	0.160	€/kg glucose	(Kootstra et al., 2009b)
RO_rev_2	0.080	€/kg xylose	(Kootstra et al., 2009b)
			Fermentation
Ferm_in_out_ratio_1	1.000	-	(Fu et al., 2009)
Ferm_in_out_ratio_2	0.500	-	(Fu et al., 2009)
Ferm_energy_use	0.090	kWh/kg input product	Own calculations
Ferm_prod_cost	0.007	€/kg input product	(Van Boxtel, 2017a)
Ferm_rev	0.120	€/kg fermentation liquid	(Scott, 2017c)
Ferm_retention_time	19	h	(Fu et al., 2009)
			Distillation
Dist_in_out_ratio_1	0.950	-	(Intelligen Inc., 2017)
Dist_in_out_ratio_2	0.010	-	(Intelligen Inc., 2017)
Dist_energy_use	0.254	kWh/kg input product	(Intelligen Inc., 2017)
Dist_prod_cost	0.021	€/kg input product	(Van Boxtel, 2017a)
Dist_rev1	0.150	€/kg ethanol (70%)	(Scott, 2017c)
Dist_rev2	0	€/kg rest water with minerals	-
Dist_rev3	20.160	€/kg fumaric acid with minerals	(Sanders, 2017)
			Wet Anaerobic Digestion
WAD_in_out_ratio_1	0.108	-	(Smyth et al., 2009)
WAD_in_out_ratio_2	0.109	-	(Smyth et al., 2009)
WAD_in_out_ratio_3	2.091	-	(Smyth et al., 2009)
WAD_water_in_ratio	1.200	-	(Smyth et al., 2009)
WAD_energy_use	1.037	kWh/m3 biogas	(Smyth et al., 2009)
WAD_prod_cost	0.123	€/m3 biogas	(Smyth et al., 2010)
WAD_invest	745000	€	(Smyth et al., 2010)

WAD_rev_1	0.081	€/m3 biogas	(Deng & Hägg, 2010)
WAD_rev_2	0	€/kg digestate	-
			Dry Anaerobic Digestion
DAD_in_out_ratio_1	0.105	-	(Singh et al., 2011)
DAD_in_out_ratio_2	0.109	-	(Singh et al., 2011)
DAD_in_out_ratio_3	0.891	-	(Singh et al., 2011)
DAD_energy_use	0.369	kWh/m3 biogas	(Singh et al., 2011)
DAD_prod_cost	0.127	€/m3 biogas	(Smyth et al., 2010)
DAD_invest	745000	€	(Smyth et al., 2010)
DAD_rev_1	0.081	€/m3 biogas	(Deng & Hägg, 2010)
DAD_rev_2	0	€/kg digestate	-
			Biogas upgrading
Bgasup_in_out_ratio	0.761	-	(Deng & Hägg, 2010)
Bgasup_energy_use	0.307	kWh/m3	(Deng & Hägg, 2010)
Bgasup_prod_cost	0.075	€/m3	(Deng & Hägg, 2010)
Bgasup_invest	2543814	€	(Deng & Hägg, 2010)
Bgasup_rev	0.284	€/m3	(Deng & Hägg, 2010)
			Filtration
Filt_DM_content	0.400	-	-
Filt_energy_use	0	kWh/kg suspension of hydrolysed grass fibre	-
Filt_rev_1	0.112	€/kg retentate (wet solids) lignin	Adapted from (Bruijnincx et al., 2016)
Filt_rev_2	0.128	€/kg permeate (water with fermentable sugars) glucose fraction	(Kootstra et al., 2009b)
Filt_rev_3	0.064	€/kg permeate (water with fermentable sugars) xylose fraction	(Kootstra et al., 2009b)
			Heat exchanger
Heat_ex	0.800	-	-
Heat_ex_energy_use	0	kWh/kg	-
Heat_ex_invest	0	€/m2	-
			Fermentation 2
Ferm2_in_out_ratio_1	1.000	-	(Liu et al., 2017)
Ferm2_in_out_ratio_2	0.503	-	(Liu et al., 2017)
Ferm2_energy_use	0.090	kWh/kg input product	Own calculations
Ferm2_prod_cost	0.007	€/kg input product	(Van Boxtel, 2017a)
Ferm2_rev	1.200	€/kg fermentation liquid	Adapted from (Sanders, 2017)
Ferm2_retention_time	84	h	(Liu et al., 2017)
			Distillation 2
Dist2_in_out_ratio_1	0.950	-	(Intelligen Inc., 2017)
Dist2_in_out_ratio_2	0.057	-	(Intelligen Inc., 2017)
Dist2_energy_use	0.231	kWh/kg input product	(Intelligen Inc., 2017)
Dist2_prod_cost	0.019	€/kg input product	(Van Boxtel, 2017a)
Dist2_rev1	3.206	€/kg ethanol (30% gin)	(Gall&Gall, 2017) (Belastingdienst, 2017)

Dist2_rev2	0	€/kg rest water	-
			Drying
Dry_DM_content	0.900	-	
Dry_energy_use	1.115	kWh/kg evaporated water	(Van Boxtel, 2017d)
Dry_prod_cost	0.091	€/kg evaporated water product	(Van Boxtel, 2017a)
Dry_rev_1	0.140	€/kg dry lignin	(Bruijnincx et al., 2016)
Dry_rev_2	0	€/kg dry grass	-

In Table A-2 the variables in de equation for production costs of combustion stand for the following: LHV (lower heating value), f (thermal or electrical efficiency of the combustion device) and z (production cost per kWh electrical or thermal energy generated).

Table A-2 All equations that diverge from the basic equations that were used in the model are listed below.

Conversion method	*Parameter*	*Equation*	*Source*
Coagulation	Investments	$C_I = 5.0311 * 10^6 * (F_{in} * 0.22 * 10^{-3})^\wedge 0.5906$	(O'Keeffe et al., 2012)
Combustion	Production costs	$P_c = F_{in} * LHV * f * z$	-
Drying	Investments	$C_I = 2.5 * 15792 * F_{out}^{0.382}$	(Matches, 2014)
Fermentation	Investments	$C_I = 2.5 * CostA * Volume^n$	(Matches, 2014)
Hydrolysis	Investments	$C_I = 2.5 * CostA * Volume^n$	(Matches, 2014)
Pressing and fiberizing	Investments	$C_I = F_{in} * 24 * \frac{300}{1000} * 2.75$	Disk mill
Pressure filtration	Energy in	$E = \frac{\frac{1}{0.8} * 5 * 10^5 * F_{out} * 10^{-3}}{3.6 * 10^6}$	(Matches, 2014)
Pretreatment	Investments	$C_I = 2.5 * 9876.6 * \left(\frac{volume}{0.9}\right)^{0.7312}$	(Matches, 2014)
Pyrolysis	Investments	$C_I = 40804 * F_{in}^{0.6194}$	(Bridgwater, Toft, & Brammer, 2002)
Reverse Osmosis	Investments	$C_I = 2.5 * 300 * \frac{F_{out}}{15}$	(Van Boxtel, 2017b)

Table A-3 Energy use, profit, investment and return on investment per conversion route for an input of 0.5 tonnes/hour.

Conversion route no.	*Energy use (kWh)/tonne*	*Profit (€/tonne)*	*Investment (k€/tonne)*	*Return on investment (years)*
2	515	116	3053	3.65
7	453	217	1517	0.97
8	163	85	104	0.17
9	808	349	2035	0.81
11	143	10	164	2.33

Table A-4 Energy use, profit, investment and return on investment per conversion route for an input of 1 tonne/hour.

Conversion route no.	*Energy use (kWh)/tonne*	*Profit (€/tonne)*	*Investment (k€/tonne)*	*Return on investment (years)*
2	515	133	2214	2.32
7	453	226	1064	0.65
8	163	85	84	0.14
9	808	360	1501	0.58
10	144	8	226	3.74
11	143	10	136	1.83

Table A-5 Energy use, profit, investment and return on investment per conversion route for an input of 2 tonnes/hour.

Conversion route no.	*Energy use (kWh)/tonne*	*Profit (€/tonne)*	*Investment (k€/tonne)*	*Return on investment (years)*
2	515	145	1622	1.56
3	422	51	1615	4.41
4	422	59	1732	4.05
5	386	56	1503	3.69
6	386	57	1481	3.59
7	454	232	805	0.48
8	163	85	68	0.11
9	808	368	1127	0.43
10	144	9	181	2.70
11	143	11	113	1.45

Table A-6 Energy use, profit, investment and return on investment per conversion route for an input of 3 tonnes/hour.

Conversion route no.	*Energy use (kWh)/tonne*	*Profit (€/tonne)*	*Investment (k€/tonne)*	*Return on investment (years)*
1	525	48	1353	3.88
2	516	150	1353	1.25
3	422	56	1349	3.34
4	422	65	1472	3.17
5	386	61	1273	2.90
6	386	62	1251	2.81
7	454	234	669	0.40
8	163	85	61	0.10
9	809	371	975	0.37
10	144	10	159	2.27
11	143	11	101	1.27

Table A-7 Energy use, profit, investment and return on investment per conversion route for an input of 4 tonnes/hour.

Conversion route no.	*Energy use (kWh)/tonne*	*Profit (€/tonne)*	*Investment (k€/tonne)*	*Return on investment (years)*
1	525	51	1204	3.25
2	516	153	1204	1.09
3	422	59	1200	2.82
4	422	68	1294	2.64
5	386	64	1132	2.46
6	386	65	1110	2.39
7	454	236	604	0.36
8	163	86	57	0.09
9	809	373	882	0.33
10	144	10	146	2.01
11	143	11	94	1.16

Table A-8 Energy use, profit, investment and return on investment per conversion route for an input of 5 tonnes/hour.

Conversion route no.	*Energy use (kWh)/tonne*	*Profit (€/tonne)*	*Investment (k€/tonne)*	*Return on investment (years)*
1	525	53	1099	2.85
2	516	155	1099	0.99
3	422	61	1096	2.49
4	422	70	1183	2.34
5	386	66	1033	2.18
6	386	67	1011	2.11
7	454	237	559	0.33
8	163	86	53	0.09
9	810	374	801	0.30
10	144	10	136	1.84
11	143	11	88	1.08