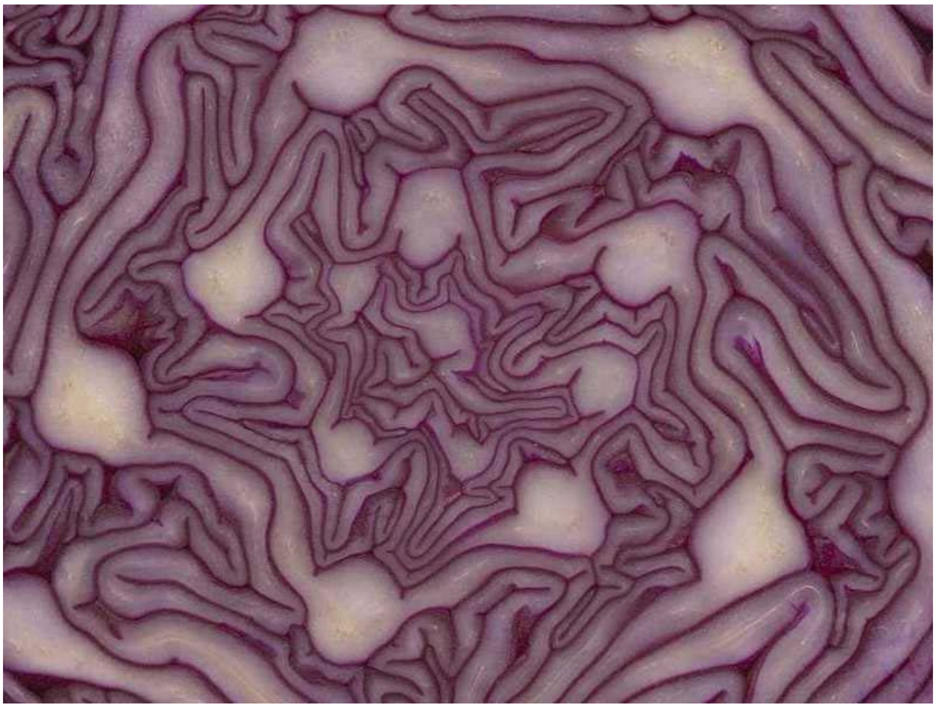

Environmental LCA of utilizing red cabbage trimmings as novel products

Simulation of environmental impact, costs and microbiological activity related to processing red cabbage trimmings

Master of Science Thesis in the Master Degree Programme, Automation & Mechatronics

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Göteborg, Sweden, 2005

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Cover:
Red cabbage; A cross-section picture of red cabbage.

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Abstract

The environmental potential of producing novel products out of RCT (red cabbage trimmings) has been compared with using it as fodder to husbandry. Life cycle assessment (LCA) has been used to make the comparison. It is believed that in the future the volume of by-products from the food chain used as cattle feed will be minimized. The product Red cabbage trimmings was chosen to focus on because of the valuable compounds in the plant, and because of the waste generation in form of RCT that RC (red cabbage) refining means.

The novel products that were produced were dietary fiber, phytochemical juice, pectin and MHR (modified hairy regions). Running costs of the process and microbiological activity in the end products were also evaluated in order to assess the realisation of processing RCT into novel products.

A system called the RCT system was defined. In this system RCT could be processed into novel products, treated as fodder or composted. These alternatives were later reduced to the production and fodder system, since the compost system proved to be hard to define. The RCT production process system was modeled in higher detail level than the other alternatives (a simulation model in Simulink was made) and was divided in simulation alternatives, based on product mix. The product mixes that were evaluated were:

1. Production of phytochemical juice and dietary fiber.
2. Production of phytochemical juice and pectin.
3. Production of phytochemcial juice, dietary fiber and pectin.

In order to compare the two RCT system alternatives two scenarios were designed (the compost excluded). These scenarios were called the process scenario (RCT is processed) and the feed scenario (RCT is treated as fodder). These scenarios were combined with the three alternatives of producing novel products, which resulted in 2x3 different combinations of using RCT. System expansion was used when designing the scenarios. No existing alternative production system that was producing MHR was found, which made any product mix including MHR irrelevant.

When the process was modeled according to the original specification the process scenario proved to be the worst one seen from an environmental point of view. A number of improvments were then suggested, and if they were implemented the production process scenario proved to be as environmentally potential as the other scenario. To summarize, this work should be looked upon as a framework used for developing and evaluating the scenarios. Especially the RCT process model is a feasible tool for working with and improving the RCT process.

REPRO

This master thesis work was carried out within the REPRO project. REPRO, Reducing Food Processing Waste, is a European commission funded project which was first initiated in February 2005. It aims to reduce wastes, and transform plant-derived by-products into high and medium added value food, feed and pharmaceutical products (Waldron, 2007).

Acknowledgements

This report has been accomplished at SIK (The Swedish Institute for Food and Biotechnology).

I would like to thank my supervisor Johanna and Karin who have provided me with detailed process information. I would also like to thank all of the staff and thesis workers at the department of process and environment and SIK in general. Together we have had bad and good times, luckily more of the latter. In particular I will remember the Lucia tåg, the annual SIK party, cozy dinners at restaurants and a spectacular show at Scandinavium, Gothenburg where mr. Al Gore received the city of Gothenburg environmental award 2007.

Finally, thank you Anne-Marie for being my examiner and for graduating me!

Table of Contents

1 Introduction

1.1 Background

This master thesis work was carried out at SIK, the Swedish institute for food and biotechnology in the autumn of 2007, and was a 20 weeks student project all-in-all. By the time this master thesis started, there was a lot of background information built up, which was used as the foundation of this master thesis.

Some information used in this thesis comes from project internal REPRO reports, which are unpublished. Many of these reports are referenced to as unpublished REPRO reports, but in those cases it has been possible the internal project number is included to increase transparency.

Since REPRO is about reusing by-products from the food chain, a few potential case-studies were decided as potential. The first case-study to be further investigated was about utilizing brewers' spent grain. The idea was to use the spent grain as a main ingredient in snacks. A lab-scale process was modeled and simulated, and the output depending on different parameter settings were evaluated. The second case-study was to be modeled in a similar way, and the work is described in this report.

1.1.1 The food industry

Global food production is a heavily debated subject and since there are predictions of a world population increase to 9.1 billion inhabitants by 2050 and with an annual growth of 34 million people by mid-century, it is likely to remain one of the most important issues for the next fifty years (Mattsson, 1999; UN, 2005).

Almost all food products originate from agriculture in some way. Therefore, it can be argued that they are renewable resources since all crop uses solar energy to grow. There seem to have been a shift in perception concerning these renewable resources. Previously, there was an emphasis on the future shortage of non-renewable resources in the environmental debate. Now there is more focus on the way the renewable resources previously mentioned are utilized and the way that utilization of non-renewable resources, such as fossil fuel, affects the environment. This is partly because the population growth diminishes the arable area per person (Mattsson, 1999). In 1992, developing countries as a whole had an average of less than one-fifth of a hectare arable land per person. If current trends in population growth and land use continue, in 2050 the amount of arable land will be just over one-tenth of a hectare per person (Harrison, 1997) in (Population reports, 1997). Growth means less arable land and increased total purchasing power. This will lead to more consumption of food and more demand on both non- and renewable resources.

To increase the efficiency of resource and food product use, it is important to regard both how food is traded and how it is utilized on a technical level. Today, there is no fair and market-oriented trading system. WTO (World Trade Organization) which is the only international body dealing with rules of trade between nations and failed in 2006 to improve world-wide market conditions. The main reason for this was that foremost the United States and the European Union could not agree on the reduction of domestic agricultural subsidies. Lower subsidies will lead to different prices on both agriculture products and value added food products, which in turn will lead to new markets to the food industry, but also new competitors (Global forum, 2007). This will in turn lead to a more efficient use of food products. On the technical level it is more a matter of realizing the full potential of the food-chain and the products in it. The more that is grown, the larger impact it will have on the environment. By using what is grown in a more efficient way, environmental impact can be reduced.

1.1.2 Red cabbage

The reason for choosing red cabbage trimmings (RCT), or *Brassica oleracea var. rubra* trimmings as a potential case-study within the REPRO project was because of the involved scientists' knowledge about the benefits of processing red cabbage. Red cabbage is both beneficial in the sense that it contains anthocyanins, glucosinates and dietary antioxidants, and that the processing of red cabbage (RC) generates a lot of waste in form of trimmings. In the Netherlands the annual production of 18.000 tonnes *Brassica* vegetables comprise 15% of total fruit and vegetables product volume, and generate a large amount of RCT (REPRO, 2008). Around 80% of the RCT is disposed of as cattle feed. Due to changes in legislation it is expected that within the next five to ten years the volume of by-products from the food chain used as cattle feed will be minimized.

1.2 Aim and objectives

The aim of this work is to evaluate potential environmental benefits of utilizing the red cabbage trimmings as high value food compounds or ingredients, compared to treating it as waste or fodder. These ways of utilizing RCT will henceforth be referred to as scenarios.

Independent of how the RCT (red cabbage trimmings) is treated, the main reason will still be to reduce waste generated from RC (red cabbage) production. Thus it will not be a matter of the amounts of products that RCT is refined into, but a matter of how much RCT that is treated.

In order to make the process easier to grasp, costs and microbiological activity will be simulated as well as environmental impact in the same model. Economic profit from a process is one of the reasons a process exists. Therefore the costs of running the process is modelled and if it is possible compared with the values of the end products produced. Bacteria levels in the end products also need to be modelled, since contaminated products that are harmful have no value. Finally the model will be used as an optimization tool for improving the process. Because of that, the model has to be easy to use and to understand. Changes should be easy to apply, without extensive knowledge of the model or programming skills.

Specific objectives related to the aim are:

- The fictive industry producing new products from the red cabbage trimmings will be modelled. The model representing the production of novel products will include environmental impact assessment, as well as microbiological and economical analysis. A GUI (graphical user interface) will be developed in order to enhance the model's feasibility.
- Two more models used for the environmental assessment of the fodder and the waste processes will be built.

- Scenarios of the different situations (RCT treated as raw material in a process, animal feed or compost matter) combining the above mentioned models will be designed.
- The environmental impact of using a specific amount of red cabbage trimmings according to the different scenarios will be compared in order to see which one that is the most environmentally beneficial.

2 Life cycle assessment

LCA (Life Cycle Assessment) is a tool used to estimate the environmental impact of a product throughout its life cycle. When carrying out an LCA one studies a whole product system and its interaction with the natural system (Figure 1). The reason for applying LCA methodology is to avoid sub optimization, which may occur when analyzing smaller parts separately. This chapter covers the basics and the ISO standard of LCA.

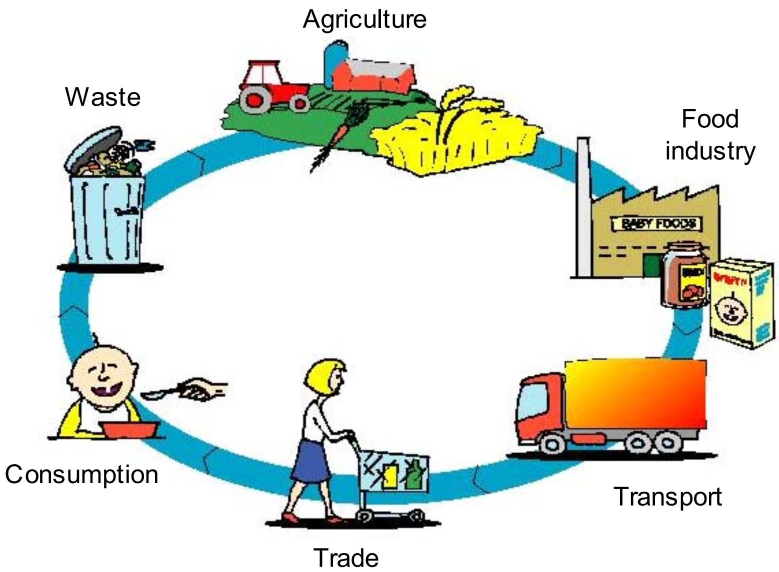

Figure 1 A product life cycle (SIK).

2.1 Different types of LCA

Depending on the scope of the LCA, there are two general types of LCA studies (Tillman and Baumann, 2004):

- The Accounting LCA is used to estimate a product's environmental impact, but also to compare different products.
- The Change- oriented LCA is used for evaluating the best option among different possible scenarios.

2.2 Methodology

There is an ISO standard that describes LCA methodology, and the main phases in a LCA procedure can be summarized as following (ISO14040, 2006):

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Life cycle interpretation

It is stated that LCA is an iterative process, and the relations of the work phases are presented in Figure 2.

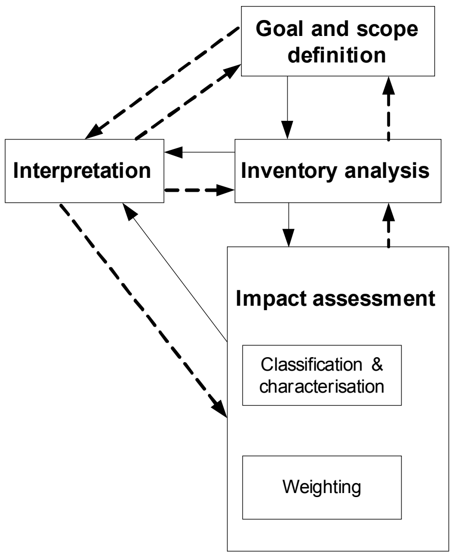

Figure 2 The iterative working process of LCA (Tillman and Baumann, 2004).

2.2.1 Goal and scope definition

In the goal and scope definition it is stated why the LCA is carried out and what questions it should answer, as well as to whom the results are to be communicated. The project plan is made and specifications of the modeling to be performed are defined. The main phases are described below.

2.2.1.1 Functional unit

In LCA environmental impact relates to a function of the product, process or production under study (Tillman and Baumann, 2004). Thus, the function of a product has to be expressed in quantitative terms (Table 1). All calculations in a LCA are related to the functional unit.

Table 1 Examples of functional units (Tillman and Baumann, 2004).

Product system	Functional unit
Beverage packaging	Liters of packaged drink
Cover material (tiles, paint, etc)	Square meters of covered area and year (m^2 x year)
Passenger transportation	Person and km (person x km)

2.2.1.2 System boundary

In the goal and scope definition, it should be made clear what activities that will be included. A first flow chart of the system is made, which will later be improved and more detailed. Some LCAs are extensive and covers the whole life cycle from extraction of raw materials to deposit and recycling of the product. They are called cradle-to-grave LCAs. The cradle is where it all starts with mining and extracting, and the grave is when the product is considered to leave the system. The gate is often defined as when the product leaves the factory or the store and is sold to a consumer.

When it is decided what parts of the system that is to be included, then other delimitations need to be decided on. For instance, it has to be decided what emissions to include in the assessment. Emissions can be released to air, water and ground and originates from different parts of the life cycle. An LCA can also be delimited to geographical location and to time.

When defining the system boundary, the system under study can be subdivided into a foreground and a background system (Figure 3). The foreground system should include the main process operations and everything else in focus. The background system should include all systems that are linked to the foreground system in an important way. Examples can be resources to the main process, such as material flows into the process or electricity. System subdivision can be useful, especially when performing a prospective or change-oriented LCA (Tillman, 1999).

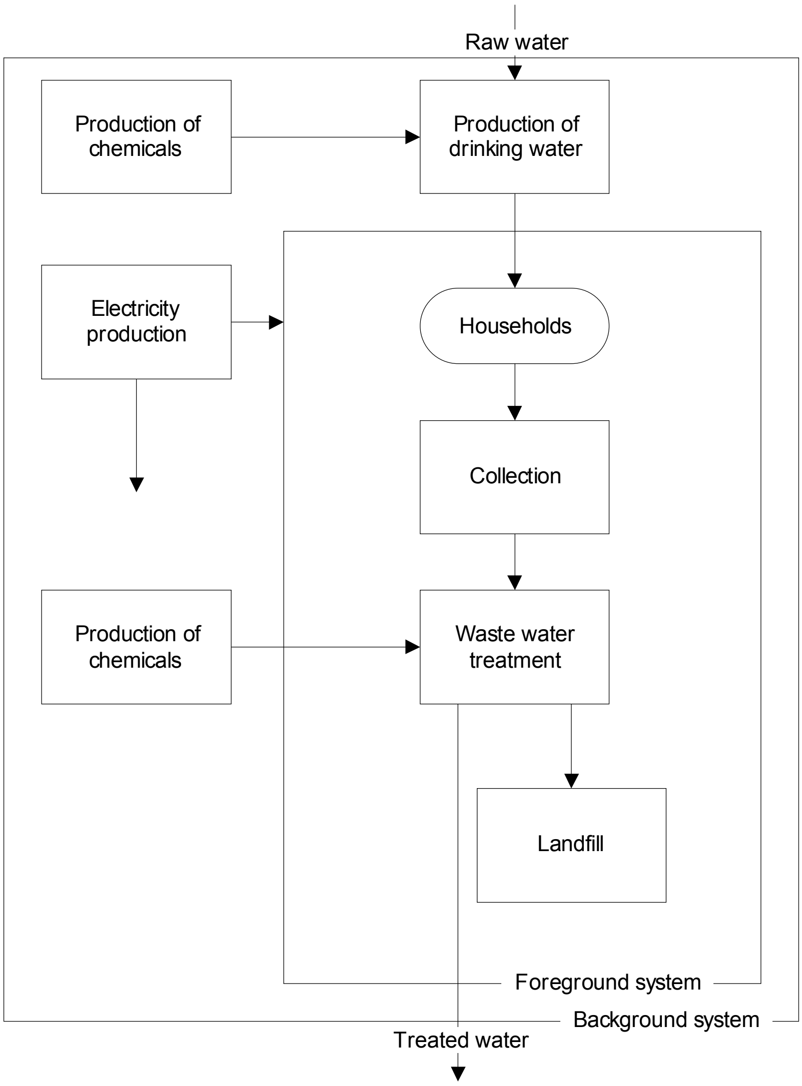

Figure 3 Flowchart for treatment of waste water from households (Tillman, 1999).

When working according to LCA standard, defining system boundaries and performing an inventory analysis can be complicated, since different product life cycles are connected to each other. A particular example is when more than one product is being produced in the same product system. The problem is then how to divide the environmental burden between the products, and it can be solved by allocation or by carrying out a system expansion. System expansion means evaluating the environmental load of another existing product system with similar functionality. As an example, the package system in Figure 4 is considered. After a product has been consumed, the package material is incinerated. The incineration has two functions: It reduces waste by incinerating package material, and it generates heat. By doing a system expansion, one estimates just how much environmental load that would have been caused by a producing the same amount of heat using an alternative fuel, and subtracts this from the system. Another way of dealing with the problem is simply to partition the environmental impact of the system between the products by for example using economical or physical allocation. Economical allocation means that the relation between the economical values of the products is used to partition the impact. An example of physical allocation is when heat values of the products are used to partition impact.

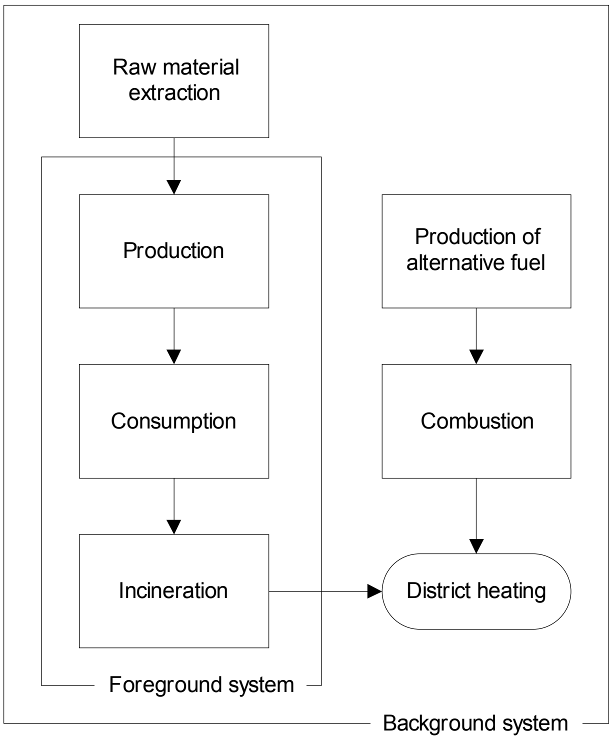

Figure 4 A simple example of system expansion. The foreground system reduces waste and heat is generated. The heat is then distributed to households which means that less heat is needed from the municipal heating plant (Tillman and Baumann, 2004).

2.2.1.3 Environmental impacts

All systems will have an impact on environment, such as various emissions, land use and resource use. These impacts will trigger cause-effect chain reactions that are neither accounted for nor consistent all over the world. By describing environmental impact on a low level, i.e. primary effects of the impact, one can express the impact as potential impact rather than having to declare all actual effects caused. The ISO standard divides environmental impact in the following impact categories: resource use, human health, and ecological consequences (ISO14040, 1997) in (Tillman and Baumann, 2004). These must be interpreted in more operational impact categories:

- GWP – Global warming potential.
- POCP – Photo-oxidant creation potential (Potential of forming smog)
- Acidification
- Eutrophication
- Resource depletion
- Etc.

The magnitudes of the impacts calculated depend on the impact method used. There are several impact methods, which evaluate and measure environmental impact in different ways. Acidification for instance, can be measured in SO_2-equivalents or H^+-equivalents and eutrophication can be measured in both P- and N-related equivalents. However, all impact methods use the global warming potential definition that is defined by IPCC (the UN intergovernmental Panel on Climate Change). IPCC defines the GWP of a substance as the ratio between the increased infrared absorption it causes and the increased infrared absorption caused by 1 kg of CO_2:

$$GWP_{T,i} = \frac{\int a_i \cdot c_i(t)dt}{\int a_{CO_2} \cdot c_{CO_2}(t)dt},$$

Where a_i is the radiative forcing per unit concentration increase of greenhouse gas i (W/m^2), $c_i(t)$ is the concentration of greenhouse gas i at time T after release (kg/m^3) and t is the time over which the integration is performed (year). GWPs have been calculated for different time horizons, e.g. GWP-10 and GWP-100 (10 and 100 years, respectively).

2.2.1.4 Level of detail and requirements of data

When performing a LCA, access to relevant data is one of the most important requirements. Data on emissions, resource use and energy consumption is needed for all activities within the system boundary.

Data should be relevant in that sense that it represents what it is supposed to represent. Data also needs to be traceable and consistently collected. There is also a matter of industry average data or site-specific data, and to decide what is considered most appropriate for the LCA in mind. Another type of data is marginal data. When talking about electricity consumption, marginal data describes the situation when consumption exceeds supply, and electricity needs to be produced in auxiliary systems or imported. Average data then represents the electricity that is consumed when supply is larger than demand.

2.2.2 Inventory analysis

Inventory Analysis, or LCI, means to collect data that is relevant to all activities within the system boundary. It is now that the flow chart previously defined is made more detailed. Data Activities may prove to be more complex than first thought, and in order to get desired results activities may have to be mapped into several smaller activities. The model is based on mass and energy balances, and everything else is dependent on this mass flow. Required data for the mass and energy balances are collected, as well as input data to the process. Data on energy consumption, emissions etc. can then be obtained from the model. Finally, the LCI result is used for the impact assessment (Figure 5).

2.2.3 Impact assessment

Life Cycle Impact Assessment (LCIA) aims to better communicate the actual environmental impact of the quantified environmental loads obtained in the inventory analysis. In order to do that, all emissions and resource uses need to be aggregated and translated into the environmental impact categories decided upon in the goal and scope section. When LCI data is divided between the impact categories it is called classification, i.e. the inventory parameters are sorted according to the type of impact they have on environment. Characterization is the calculation of the relative contribution of the emissions and resource consumptions to each impact category. This is described in Figure 5.

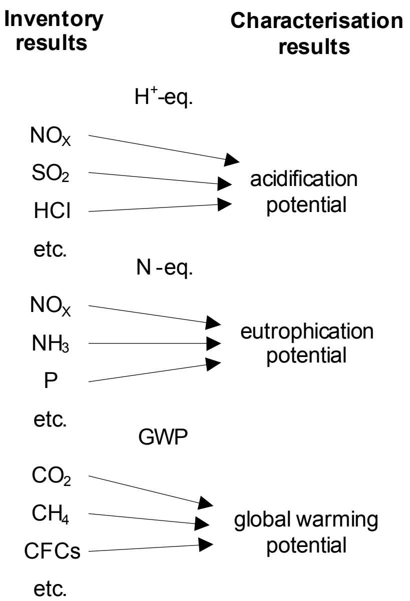

Figure 5 Classification and characterization. When emissions are grouped into impact categories it is called classification. When it is decided how much each compound contributes to its corresponding impact category it is called characterization (Tillman and Baumann, 2004).

2.2.4 Life cycle interpretation

The last phase of the LCA is life cycle interpretation or improvement assessment. The results from the LCIA and the LCI are discussed and the results should according to the ISO standard be:

"The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations." (ISO14040, 2006)

It further states that "The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal."

Data quality analysis is used to see how the result is depending on data. Data of low quality can be replaced by extreme values in order to see how the result changes.

2.2.4.1 Data quality analysis

There are techniques to be used when analyzing uncertainty and sensitivity of the LCIA results (ISO14042, 2000) in (Tillman and Baumann, 2004):

- Dominance analysis; identification of the most polluting activities in the life cycle.
- Sensitivity analysis; should be carried out whenever several allocation procedures seem possible, and identifies different crucial sets of data for which slight changes in value change the outcome of the result. The reasons for carrying out a sensitivity analysis can vary and depending on what data that are replaced the analysis may answer:
  - What significance the methodological choices have.
  - Which inventory data that affects results the most.
  - Which impact assessment data that affects results the most.
- Uncertainty analysis; analysis of the degree of the uncertainty in the results. This measure is taken when input data are estimates, intervals or probabilities.

3 LCA and process modeling

Chapter three covers the description of the three scenarios where the RCT system is included. In the RCT system, RCT can be processed into novel products or treated as animal feed or compost. The novel products that can be produced are pectin, MHR (modified hairy regions, which is a pectic oligosaccharide), phytochemical juice and dietary fiber. Chapter three also includes system expansions of the RCT system alternatives, i.e. what product system the system in question replaces.

3.1 The scenarios

There were three scenarios considered in the RCT system: The RCT can be processed, treated as animal feed or composted. In each scenario, an equal amount of RCT is treated. If it is processed, novel products are produced, if it is treated as fodder the RCT is transported to a cattle farm and if it is composted it is treated at a compost facility. These cases are first described separately, and then compared in the three main scenarios that are to be evaluated in this master thesis:

1. The RCT is used in an industrial process to produce novel products; Barley production is needed for feed
2. The RCT is to be treated as cattle feed; The novel products are produced elsewhere
3. The RCT is composted; Pectin, MHR, dietary fiber and phytochemical rich juice is produced elsewhere AND barley production is needed for feed

When the RCT is used as feed or composted, the novel products have to be produced somewhere else and vice versa. In other words, when RCT is used to produce something, something else is replaced and not manufactured (Figure 6). This interaction with other production systems has been analyzed with system expansion.

The MHR production and the compost scenario were later excluded from the scenarios, but were still documented in this report. It is possible that they will be further analyzed in the REPRO project.

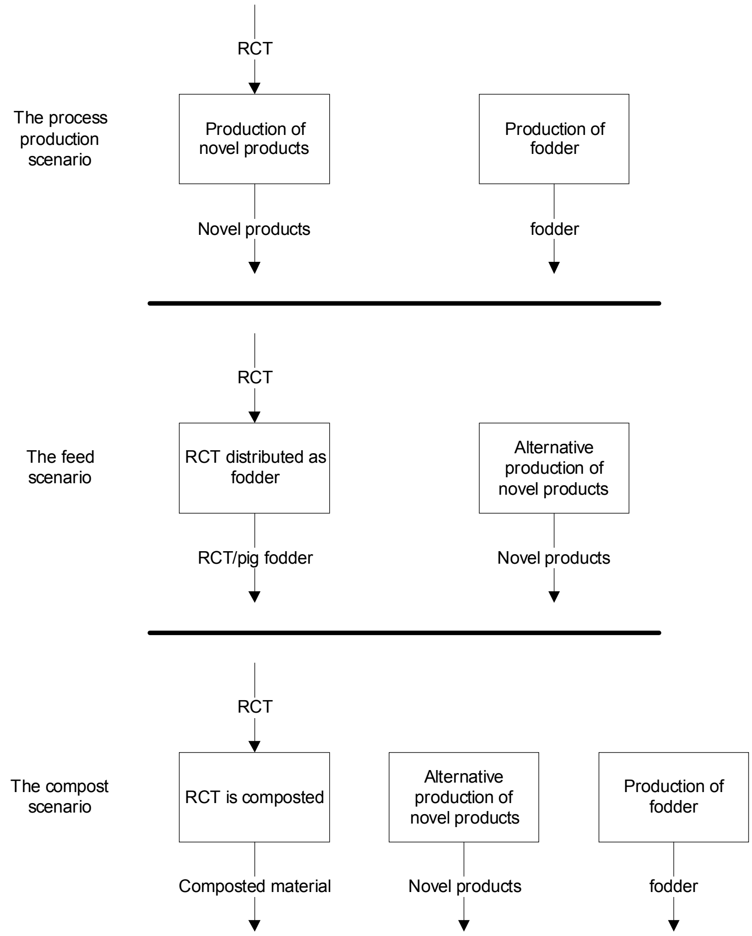

Figure 6 The three scenarios. In order to make the scenarios comparable, one has to take the replaced product systems into concern. The RCT system can produce novel products, animal feed or compost matter (The box to the left in each scenario).

3.2 LCA and process modeling of the RCT system

The process, feed and compost systems that together are called the RCT system have similar goal and scope, except for some differences. The RCT system when RCT is processed into novel products is considered to be the reference alternative, and because of that, the RCT system is first described with the process alternative in mind.

3.2.1 Goal and scope of the RCT system

The goal is to evaluate the different ways of treating RCT, and to make the considered system alternatives possible to use in the scenarios.

Since the RCT process system is considered to be the reference system, the process scenario is regarded to be the reference scenario. Focus is on the reference scenario, since this is regarded as potential and a possible replacement for the other system alternatives. Therefore it will be made the most detailed, and analyzed by testing different product mixes, i.e. production of different relative amounts between the novel products.

3.2.1.1 Functional unit

Since the functionality of the system is to treat RCT, the functional unit is represented in kg RCT. The main flow, referred to as the reference flow is defined as the RCT inflow to the model, in order to keep track of how much RCT that is treated. The functional unit is 1000 kg RCT.

3.2.1.2 System boundary of the RCT system

Since RC is not grown in order to get RCT, and since it is RC that generates the revenues, the RCT was considered to have no environmental impact. Thus, agricultural environmental load was not taken into account. This can also be justified by noting that there may be no future market for using RCT as fodder, because of the changes in legislation mentioned in section 1.1.

The RCT system is presented with the process system in Figure 7. All stages from transportation to utilization of the RC in a number of ways are covered, but the distribution and use of the novel products, animal fodder or compost matter are excluded. The life cycle of possible products produced from RC are not considered. The energy consumed in this LCA is mostly electric, and the "cradle" of the energy is where fuels such as uranium or coal are mined. The cradle of all chemicals and other materials needed for the scenarios are similarly the initial extraction of raw materials. Some minor materials, such as machinery use and process equipment wear are neglected since their contributions to total results are estimated as small. Chemicals that according to lab results only are used in small amounts are also neglected, e.g. chemicals that are used to calibrate to exact pH levels (REPRO, 2008). The system only considers a process that has already been put into operation. Thus, no initial issues such as constructions, warm up times etc. are taken into consideration. Neither are issues regarding personnel, such as transportations or consumption of goods included.

Concerning the time frame, there were a number of aspects that had to be taken into consideration. This study was to be used as a basis for decision-making. Thus the time perspective would be the time when the process may be put into operation. That would happen when the scenarios and data quality would have been improved beyond the scope of this thesis. Then plans for building the process plant would be made, construction would be initiated and then the process could be put into operation. Other aspect regarding time frame can also be important to consider. All products used in the system have short biological degradation time and are non-toxic, i.e. no waste will be persistent. Moreover, some products that persist over time like wood can be considered to accumulate and store CO_2. This is not the case with food, since it is consumed in a short time after production. This implies a short time perspective. On the other hand, one can also speculate about the impact of the system in a longer time perspective. The resource situation may change, and the process may be built out so that demands on resources and electricity increases etc.

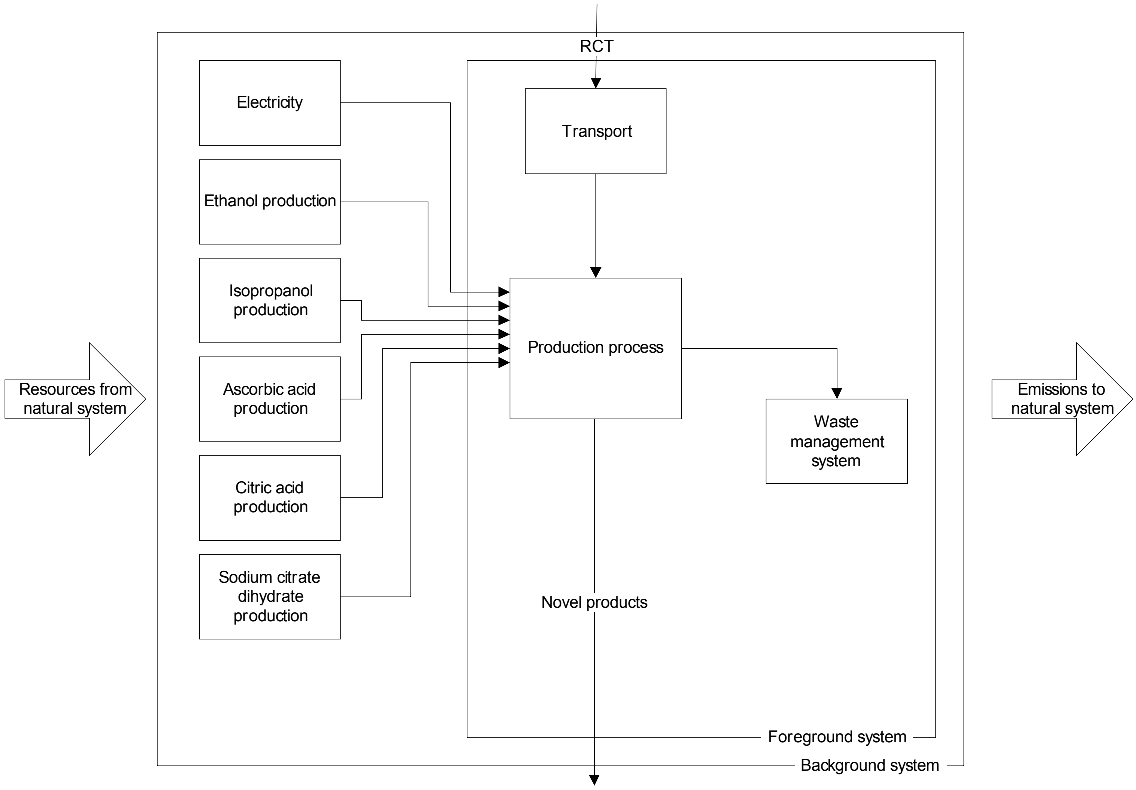

Figure 7 The RCT system with the process case. The process is in the foreground system and various auxiliary product systems are included in the background system.

The general data for the activities or the process units (represented as blocks in flowcharts) in the system comprises:

- Raw materials
- Emissions to air and water
- Energy use

The production process was assumed to be located in the central Netherlands. The outer geographical boundary was defined as Europe. Except for that, there were no geographical restrictions.

3.2.1.3 Data quality requirements

The purpose of this study was to investigate the most environmental friendly way of treating RCT as either raw material to a process, fodder or compost matter. The pilot scale study provided information about mass flows and relevant mass balances, but did not cover energy data. Since there was no energy data from a similar process available, general process operations data were used that were found in literature. These data had to be valid not only for pilot scale production, but also for large-scale production. Therefore linear energy functions dependent on mass flow were used. The pilot scale data was assumed to be representative on a large scale. Concerning the feed scenario, European average data would best suit the purpose, since RCT would replace fodder at the European fodder market. In the compost scenario, Netherlands average compost data was the most representative data, since the generic organic waste from households as well as from industry was assumed to be treated within the country borders. The alternative production of novel products and the production of chemicals used in the process should be represented with European average data, since these products were assumed to be traded at the European market. These requirements and the fact that as recent data as possible is desired dictated the choice of data in this study. When it would not be possible to meet these requirements, site-specific data or estimates would be used.

Apart from RCT, there are other resources that are used in all of the scenarios. Electricity is consumed, and Netherland average electricity is used. The foremost reason for choosing average data was that the time frame was considered to be longer than the start-up phase of the process, and that energy consumption in the future would be constant. Thus, energy supply was considered to stabilize which would lead to the use of average data.

The data used was found mostly in literature, but also in databases such as Ecoinvent (2008). On before hand gathered information in the REPRO project such as project reports were available, as well as information obtained through personal contact in REPRO.

3.2.1.4 Allocation

What allocation technique that is used when putting together data is another important matter. The ISO standard states that system expansion is preferred (ISO14044, 2006). However, when data on alternative production of novel products and chemicals have been collected from literature, the allocation technique that was used in the corresponding study of each product has been used.

Within the scenarios, system expansion will be used, in order to estimate the amount of product one does not have to produce when RCT is used to produce the product instead. Regarding the auxiliary products that are used in the production process, allocation principles are chosen depending on the situation of each auxiliary product.

3.2.1.5 Method of impact assessment

The method chosen for the life cycle impact assessment (LCIA) is EDIP/UMIP, which has also been used for previous work in the REPRO (Wenzel and Alting, 1997). The method is developed for use in product development processes and distinguishes itself in that it covers assessment of toxic substances. For environmental impacts, the EDIP method uses Danish political targets, and for resource use the weighting is based on the relation between consumption and regeneration of reserves. Weighting factors are from EDIP/UMIP 97 and the weights for CH_4 and N_2O in the GWP category are changed to 23 and 296 respectively, which is according to the newest IPCC directive (Ecoinvent, 2007).

3.2.1.6 Environmental impacts

Regarding environmental impact, one has to consider what impacts that are most valid for food industry and agriculture. Emissions related to food production are known to contain high concentrations of methane, ammonia, nitrate etc. These emissions cause global warming, acidification and eutrophication. N_2O, which is formed during the denitrification and nitrification processes (processes that reduce nitrous compounds into gaseous nitrogen), is another green house gas that may contribute to global warming.

The most common green house gas is CO_2, and it is always formed when there is combustion (Mattsson, 1999). Regarding energy demand or total energy, it is cost related and also related to environmental impact in that sense that part of the energy is always based on fossil resources. Even when using renewable energy, fossil fuel is used to produce solar, water and wind plants. Energy is also more likely to be measured than emissions. Hence, primary energy always should be included as a category when a system consumes energy. Use of agricultural land is not of interest to investigate, since RC uses land and not RCT.
The following environmental impacts are chosen in order to compare the different scenarios:

- Global warming potential, GWP-100 (g CO_2-eq./kg treated RCT).
- Acidification potential, (g SO_2-eq./kg treated RCT).
- Eutrophication potential, (g NO3-eq./kg treated RCT).
- Total (primary) energy, (MJ/kg treated RCT).

3.2.2 Inventory analysis of the RCT process system

Here the process scenario, that is also the reference scenario, is described in its context. It is divided into a foreground and a background system (Figure 7). The foreground system contains the scenarios and the parts of the LCA that is in focus. The background system contains the interconnected systems, such as the chemicals and the electricity systems. When performing the accounting or retrospective LCA, there is no use dividing the system, since all parts of the LCA are equally focused on. However, when performing a change-oriented LCA as will later be done, the foreground system is the set of processes that will be altered because of decisions based on the LCA study. For both transport, electricity and natural gas (gas is not used in the reference scenario) the ecoinvent database has been used (Ecoinvent, 2003) (Table 2). Transport is assumed to be a local transport with a truck that loads 28 tonnes with a load factor of 50%.

Table 2 Ecoinvent data on Transports, electricity and natural gas.

	GWP [CO_2-eq.]	Acidification [SO_2-eq.]	Eutrophication [NO_3-eq.]	Primary energy [MJ-eq.]	Unit
Transport	0.0016	0.0025	0.324	0.0038	Eq./tonne km
Electricity	194.46	0.31	0.37	3.17	Eq./MJ_{Fuel}
Natural gas	67.9	0.0567	0.0591	1.19	Eq./MJ_{Fuel}

3.2.2.1 The process simulation model

To make the model, some general guidelines were used:
First it must be decided what type of model that is required to represent the real system. Is it enough with a simple static flow model, or are more complex dynamic flow model simulations required? Is warm-up or start-up analysis required, or more advanced modeling such as feed-back loops or discrete event states? Finally, the model needs to be verified and validated. Verification means it is evaluated whether the model meets the specifications, and validation means that it is evaluated if the model represents reality.

Since the model would be used when working with optimization of the process, it had to be detailed. It also had to include economical and microbiological calculations to assess the realization of the production. It was decided that a static flow simulation model would give the desired results. The model also had to contain one feed-back loop. This feed-back loop was modeled as yet another branch, identical to the actual path to which the flow was back fed. The results of the feed-back branch were then summed together with the original branch. Concerning the start-up, it was decided only to consider a stabilized system that already had been put into operation. If the production would go on long enough, the initial environmental impact per processed amount RCT would be very small. Ethanol would be used and circulated in the process and the initial impact from producing ethanol would also be very small depending on the circulation rate. The model was then built with process units as the building bricks and with flows connecting them. The general idea was to keep track of the flow by dividing it into smaller categories:

- Dry matter material, which by definition is all that do not evaporate.
- Wet matter material, which is divided into two more categories:
    - Water
    - Alcohol

In some of the process units the matter was separated into a solid and a liquid phase. These two phases were represented by dividing the above mentioned categories in two sets: One for the solid phase, and one for the liquid phase. Another matter that had to be simulated was how much left there would be of certain valuable compounds in the end products. Since the lab scale data provided for modeling this process contained data gaps, another four separate flows representing the valuable compounds were designed, independent of the main mass flow. The concentrations of these components could be set by the user from step to step. Concerning microbiological activity, the model functions of growth and reduction of bacteria were independent of the amount of substance in which they were forming colonies. Thus the number of bacteria was also made independent of the main flows, and would grow only as a function of temperature etc. and not as functions of mass.

The process units were modeled according to lab data from experimental refining of the RCT. Concerning process energy consumption, various linear energy models for heaters, centrifuges etc. were used.

Because of the complexity of the model, and because of the need for testing different parameter settings for the process, the model was built and simulated in a simulation software program called Matlab Simulink.

The model was first verified by comparing simulation results with lab results, and then validated (REPRO, 2008). Validation means that a model is compared with what it represents in reality, which could not be done since the model did only represent a fictive production.

Process description

The flow in the model diverges after the extraction step into four different flows, all of them resulting in different products (Figure 8). Three of these flows are dependent and can be regulated in order to alter the amounts of produced products. Because of the feed-back loop, MHR can be produced by using waste from the pectin flow. The fourth flow is independent of the others, and depends only on the reference flow. The input alcohol solution concentration in the model was allowed to be set by the user, which would result in different amounts of alcohol solution. This in turn, would affect the total weight, which is why it was decided to base all mass calculations on the dry matter weight. This weight would only be dependent on the reference flow. The alcohol was recirculated into the system after it had been used. The other added chemicals were not circulated and left the system with the end products. There was no information about the amounts of these chemicals in the end products, or if they reacted with other substances. All chemicals used were approved for food processing, and could therefore be considered non-toxic and in the health aspect neglected. That is why the chemicals flows except for the alcohol were not modeled. More information about the process can be found in Appendix A.

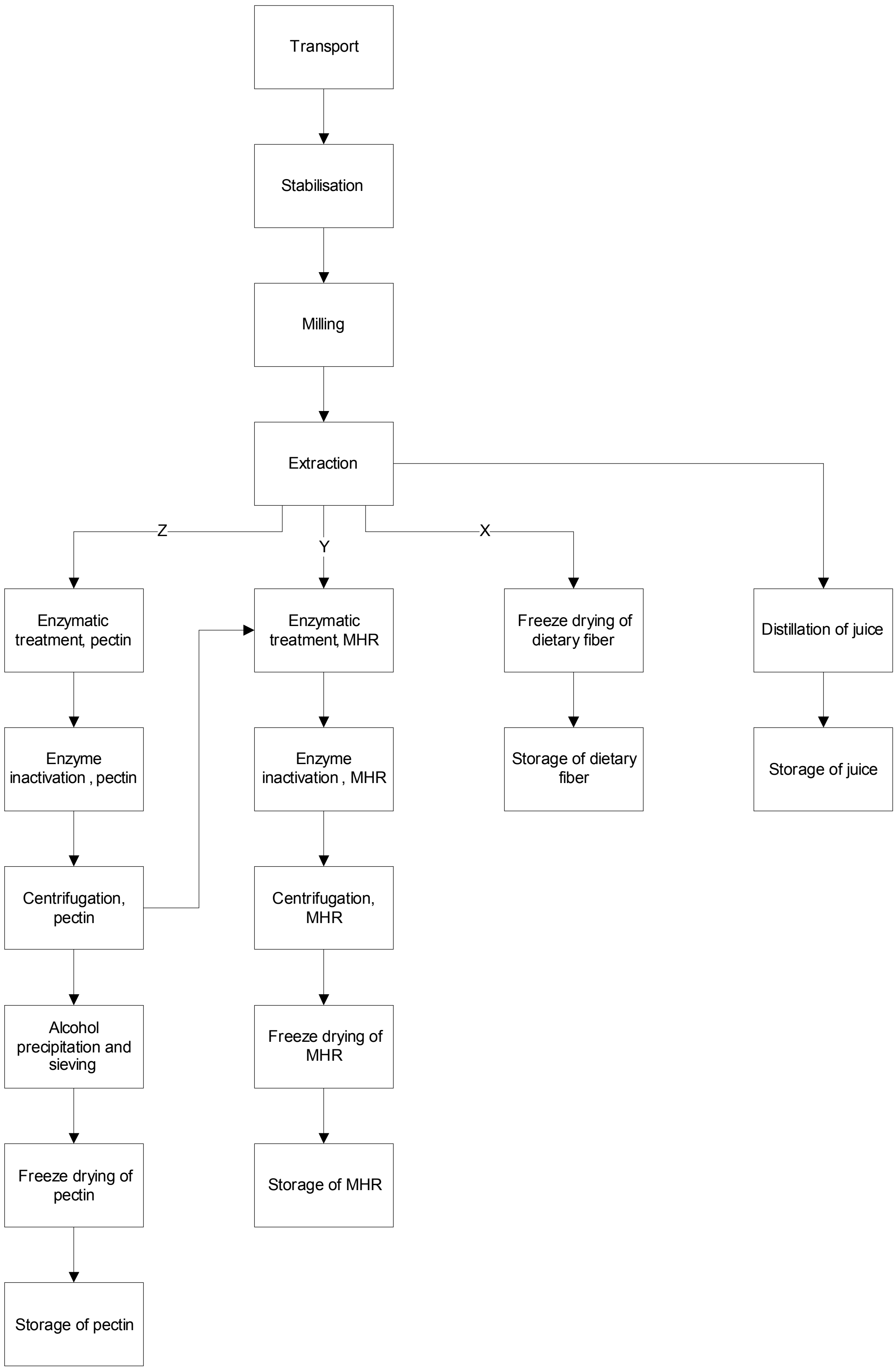

Figure 8 The process model. It has several features, and among them the options of setting different product mixes (X,Y,Z) and enabling feedback loop from pectin flow to MHR flow

The novel products
As can be seen in Figure 8, four products are produced in the process:

- Phytochemical juice: This juice contains large amounts of glucosinates and anthocyanins, of which the latter can be used as colorants. Phytochemicals is a term used for chemical compounds that have no nutrition value, but still are of value to an organism's other functions (Phytochemicals, 2008).
- Dietary fibers: Dietary fibers exist in plants and are indigestible, thus have no nutrition value. The fibers are important in that sense that they absorb water and facilitate defecation.
- Pectin: Pectin is present in all plants. It binds water and is known for its thickening and gelling abilities. This feature makes it an essential additive to many food production processes.
- MHR; No complete information has been found about the benefits and uses of MHR or modified hairy regions. However, MHR is a pectic oligosaccharide, and it has been argued that pectins decrease blood cholesterol and prevent colon cancer (Schroot, 2008).

The process model simulations
The model output data will differ depending on how the parameters are set. There are several interesting simulation settings from which environmental impact can be analyzed, but focus of this thesis will be on how the environmental impact varies depending on what products that are produced. The MHR flow was not interesting in this case since there were no alternative product system to compare with. Hence, these simulations were performed with the feed-back loop disabled. The simulation alternatives are presented below:

- The product mix is 100% pectin (of Z).
- The product mix is 100% dietary fiber (of X).
- The product mix is 50/50 of each branch flow (X and Z) (Figure 8).

3.2.2.2 Production of resources

A number of chemicals are used in the process:

- Ethanol
- Isopropanol
- Ascorbic acid
- Citric acid
- Tri- sodium citrate
- Enzymes
- Water

The production systems of the chemicals are described below and how environmental impact eventually has been put together. In those cases environmental impact data on the chemicals have been calculated by using literature data and differ from the original reports, the calculations are presented in Appendix B.

Ethanol production
Ethanol is produced by fermenting sugar with yeast in the absence of oxygen (Figure 9). The sugar comes from plants, like grain, wood, beets, corn etc. Except for ethanol,

another product is produced. It is the residue of the fermentation mass, and is often used as animal feed.

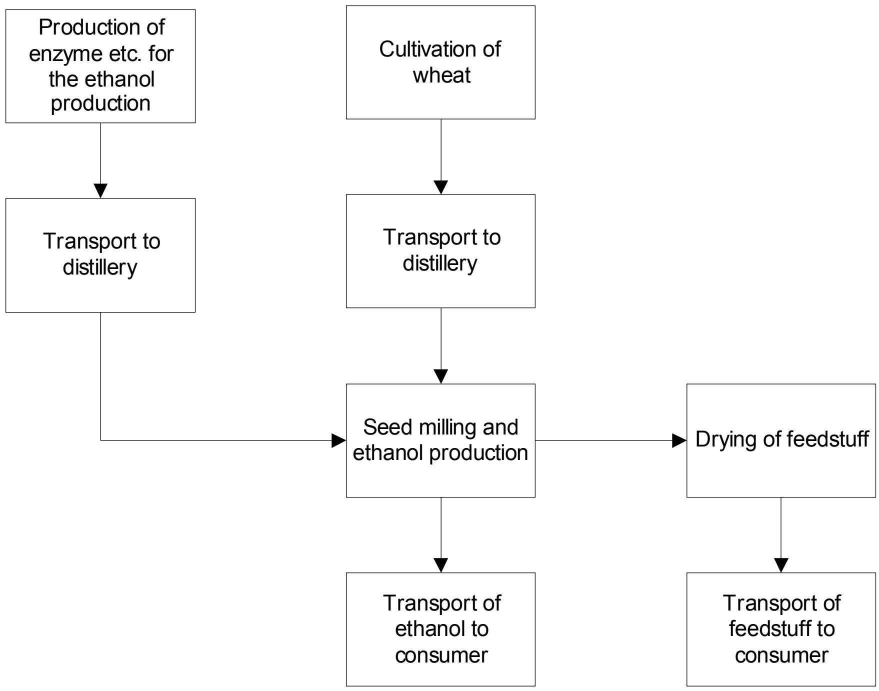

Figure 9 The production of ethanol. Cultivated wheat is fermented, distilled and transported to the consumer (Bernesson, 2004).

The ethanol was assumed to be produced in Sweden, and then transported to the Netherlands. It was not investigated if it was likely to import ethanol from Sweden, but since only data representing Swedish conditions was found it was used. Moreover, it was considered likely that Swedish ethanol was a worst-case choice, compared to choosing Dutch ethanol. This was because of longer transports of the ethanol and worse weather conditions regarding wheat cultivation in Sweden.

The (Bernesson, 2004) report

Data representing the ethanol production system is based on results from Bernesson (2004). Since that study includes the preparation and consumption of ethanol, only a part of the result will be used.

All emissions data has been recalculated from g/ha to g/kg wheat, and from g/kg wheat to g/kg ethanol.

The ethanol production was considered to be situated in Sweden and to be produced from wheat. Thus Swedish average electricity data was used. The production was assumed to take place in a large-scale plant and serve an area of 50,000 ha. The model of the production includes cultivation of wheat, transport of wheat to ethanol plant, ethanol production, transport and production of chemicals used in the ethanol production process, treatment of waste water from ethanol production, drying of distiller's waste and transport of ethanol and distiller's waste to consumption (Figure 9). The life cycle of equipment used for the ethanol production is also included in this LCA.

Bernesson's study is delimited to emissions to air, which is one reason why the original cultivation of wheat data was replaced by recent and more accurate data on cultivation of winter wheat in Mälardalen (Flysjö, 2008) (Table 3). These data included emissions to water and soil. Further, only CO_2 of fossil origin is included. The other emissions accounted for are CO, HC (hydrocarbons except for methane), CH_4, NO_X (nitrous oxides), SO_X (sulphur oxides), NH_3, N_2O, and HCl. Energy data is available as primary energy and the energy contents of all fuels are expressed in lower heating values.

Table 3 Environmental impact of cultivation of wheat when producing 1 kg ethanol

units	g CO_2-eq.	g SO_2-eq.	g NO_3-eq.	MJ
Cultivation of autumn wheat	1410.27	7.58	94.76	9.06

The environmental impact of 1 kg ethanol is presented in Table 4. Physical allocation in MJ of heat value was used when partitioning the impact between the ethanol and the distiller's dried grains.

Table 4 Environmental impact data on 1 kg ethanol (Bernesson, 2004).

units	g CO_2-eq.	g SO_2-eq.	g NO_3-eq.	MJ
ethanol data	1003.5	6.16	60.20	16.80

The (Paulsson, 2007) report

Another report studied for obtaining ethanol data was Paulsson (2007). This report is an energy analysis but data from it had been used to calculate environmental impact (Flysjö, 2008).

These results were calculated from energy related data to mass related data, as in the previous study.

The ethanol production system was studied in combination with a combined heat and power plant that provided the ethanol process with steam. The analysis included energy consumption for cultivation of grain, production of chemicals, the production chain for wood chips, the steam production and the ethanol production. This system also included biogas as a by-product from the ethanol production.

Since this report only included energy, some assumptions were made. The consumption of wheat was reported to be 2680 kg wheat per m^3 ethanol. For wheat production, the data on cultivation of winter wheat in Mälardalen was once again used. Concerning the steam production, the actual amount of wood fuel required to produce the steam was not included. Only the energy for producing and distributing the wood fuel was considered, which was why the actual energy content and emissions from combustion of wood chips also was added to the analysis. Data on wood chips are from Ecoinvent (2003).

Economic allocation in SEK per kg product was used when partitioning the environmental impact between the ethanol and the distiller's spent grain. Since this system also produces natural gas, a system expansion of production of natural gas was been performed before the allocation. Since the data in Paulsson (2007) only represents energy use in categories of diesel, oil, coal etc., some complementary data from Ecoinvent (2003) was used. The environmental impact of 1 kg ethanol is presented in Table 5.

Table 5 The environmental impact data on 1 kg ethanol (Paulsson, 2007) (Flysjö, 2008).

Units	g CO_2-eq.	g SO_2-eq.	g NO_3-eq.	MJ
Ethanol data	1185.8	6.21	73.3	27.96

Comparison

As can be seen the sets of data are similar except for the total or primary energy. The most energy consuming process when calculating the total energy in Table 4 and Table 5 is the use of biomass. The biomass is incinerated in a heat plant, and energy is transported as steam to the ethanol plant (Paulsson, 2007). The steam requirements for producing ethanol in the systems are similar. In Paulsson (2007), the recalculated value to biomass energy per kg of ethanol is 13.55 MJ/kg ethanol and in Bernesson (2004), the corresponding value is 12.10 MJ/kg. These values are calculated without any allocation and only secondary energy is included. When consulting Bernesson about this matter (Bernesson, 2007), an error was found but this error could not alone explain the deviation. A smaller deviation can be explained by the fact that Palusson includes dehydration of the ethanol solution, and that Bernesson does not. Another deviation may be because of the allocation method. The main reason for the deviation was identified when considering primary energy. According to Bernesson (2004) the production, distribution and energy content of wood chips used for steam production is 1.04 MJ/MJ_{fuel} (Uppenberg, 2001). This gives a primary energy of 12.58 $MJ_{primary\ energy\ wood\ chips}$/kg ethanol. When comparing the value with Flysjö (2008), in which data from Ecoinvent (2003) of 1.46 MJ/MJ_{fuel} is used, the corresponding value is 27.96 $MJ_{primary\ energy\ wood\ chips}$/kg ethanol and this is an allocated value. Since it will not be investigated further which source that is most accurate, Uppenberg (2001) in Bernesson (2004) will be used.

Isopropanol production

Data concerning production of isopropanol has been found in a study by Spielmann, Kägi et al. (2004) and is presented in Table 6. Isopropanol, 2-propanol or isopropyl alcohol is formed when propylene is hydrolyzed (Equation 1). Hydration can be indirect or direct, and both reactions are practiced industrially. Indirect hydrolysis is based on a two-step reaction of propylene and sulphuric acid and do not require a high purity propylene feedstock. Direct hydration on the other hand is made possible by using a reaction catalyst. There are different catalysts used in commercial operation with different needs of replenishment and possibilities of recycling. In order to render direct hydration possible, higher pressure is needed. Products and by-products for both processes are similar, as are the refining systems (Logsdon and Loke, 2008).

Table 6 Environmental impact data on production of 1 kg isopropanol. Transport distance of 400 km to process is included (Althaus, Hischier et al., 2004).

units	g CO_2-eq.	g SO_2-eq.	g NO_3-eq.	MJ
Isopropanol data	1792.57	11.54	8.25	62.81

$$CH_3CH{=}CH_2 + H2O \rightarrow (CH_3)_2CHOH$$

Equation 1 The reaction of propylene into isopropanol.

The functional unit represents 1 kg of anhydrous liquid isopropanol.

Data on isopropanol production is obtained from Althaus, Hischier et al. (2004). The process was assumed to be located in central Europe. The isopropanol production system analysis included raw materials and chemicals used for production, transport of materials to manufacturing plant and estimated emissions to air and water from production. Concerning the two production processes, a 50:50 split was assumed because of lack of information. There are however uncertainties of the process data and an approximation of the production energy and estimations for the emissions to water and air have been used. The data is therefore recommended to be used only in systems where the impact of isopropanol is not considered to be high.

The two main raw materials used are propene and sulphuric acid. The sulphuric acid is only used in the indirect hydration and is recycled within the process. Stoechiometry and some general assumptions of losses and recycling rates give that 0.737 kg propene and 0.18 kg sulphuric acid is required to produce 1 kg of isopropanol. Water is calculated in a similar way, and it is estimated that 3.2 kg water is required.

The emissions to air and water were estimated using mass balance. It was further assumed that waste water was treated in an internal waste water treatment plant. As no data on the internal waste water treatment was found the waste water plant was approximated with data from another chemical factory (Gendorf, 2000).

No air emission data was found. Based on the input 1.47 g of propene and 1.15 g of sulphuric acid per kg produced isopropanol are emitted to air. The rest of the un-reacted propene, 35.38 g per kg product, was assumed to leave the process with the waste water. After treatment the water was assumed to contain 3.54 g propene. The carbon in the removed propene was accounted for as CO_2 emissions to air. Concerning the sulphuric acid, it was assumed that the remaining part leaves with the water, an amount of 347.71 g per kg produced isopropanol. All of the sulphuric acid was assumed to leave the system untreated.

Concerning the process energy demand, electricity is needed to run the process auxiliaries and the waste water treatment. Fossil fuel is needed to generate the required heat for the main process. (Papa, 2000) quoted in (Althaus, Hischier et al., 2004) that the indirect hydration consumes ca 3.5 kg steam and 0.04-0.05 kWh electricity per kg of isopropanol produced. For the direct hydration no such information was available. Data was instead approximated with data from a large chemical plant (Gendorf, 2000) in (Althaus, Hischier et al., 2004). This plant produced propylene oxide and the process required 3.2 MJ per kg product. The total energy demand contained a split of 50% natural gas, 38% electricity and 12% steam from external energy sources. For the steam production the energy was assumed to come from natural gas.

All transport data is from Frischknecht, Althaus et al. (2003), quoted in (Althaus, Hischier et al., 2004).

Ascorbic acid production

Ascorbic acid, or vitamin C is produced through various modifications of the Reichstein and Grüssner’s second L-ascorbic acid synthesis (Kuellmer, 1999). The synthesis is complex and includes a number of process operations (Figure 10).

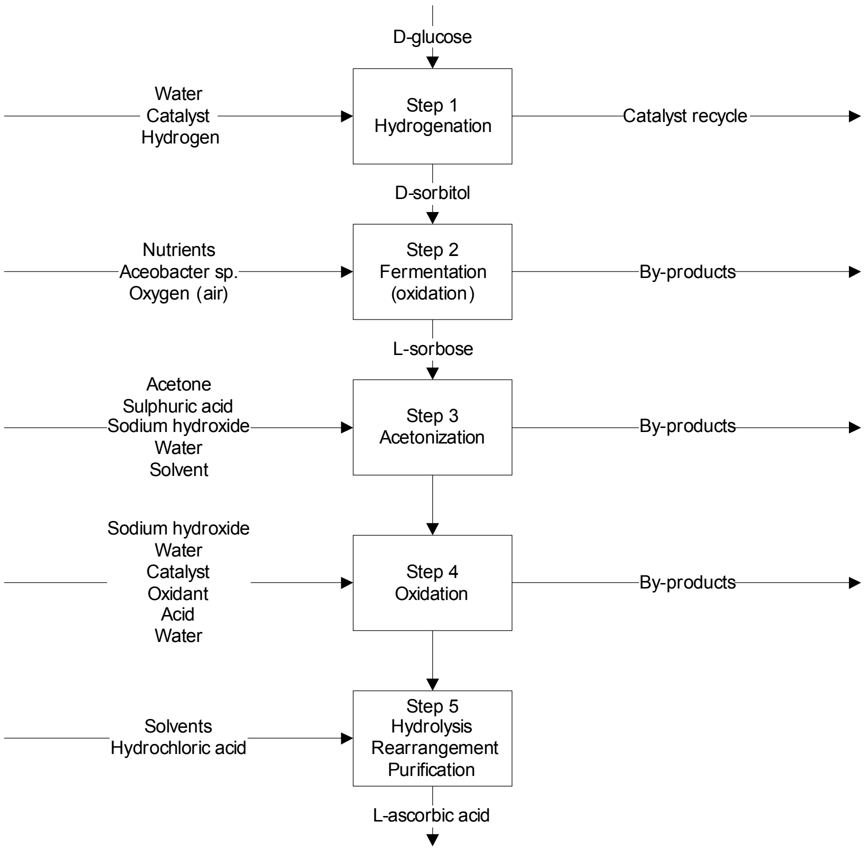

Figure 10 Production of ascorbic acid. Synthesis is complex, but the main characteristics of the process can be described with sugar being fermented by using an Aceobacter bacteria and thorough various modifications of fermentation output ascorbic acid is created (Kuellmer, 1999).

The ascorbic acid yield from L-sorbose can be ca 75% (Kuellmer, 1999). Step 1 is carried out at elevated temperature and pressure, and hydrogen is added. D-sorbitol and D-mannitol is formed, and the yield of D-glucose to D-sorbitol is more than 97%. In step 2 the D-sorbitol is fermented with Aceobacter suboxydans in the presence of large amounts of air. The L-sorbose is isolated by crystallization, filtration and drying. If the process is kept sterile, the yield is estimated to 90%. In the third step L-sorbose is reacted with acetone and excess sulphuric acid. In step 4 the chemical is oxidised and in step 5 purification takes place.

No relevant information about the production of ascorbic acid was found. Instead an average environmental load of similar chemicals was calculated. The data on the chemicals were found in Ecoinvent (2003). The production processes for the chemicals have been compared with the process of producing ascorbic acid, in order to improve the estimated value of the chemical. Eventually three out of twenty were chosen:

- Formaldehyde
- Methanol
- Acetic acid

The average environmental impact of the chemicals is presented in Table 7 (A transport of 400 km is included).

Table 7 Chemical average data on chemicals including a 400 km transport.

units	g CO_2-eq.	g SO_2-eq.	g NO_3-eq.	MJ
Chemical average data	963.14	5.87	59.75	16.11

Another way to solve this problem would be to simply use the environmental data of ethanol for ascorbic acid. Both chemicals use crop as raw material in one way or another, and both chemicals have comparable operations in their corresponding processes. Ethanol is distilled and ascorbic acid is crystallized, filtrated and dried. Of course, both of these estimations are rough, and should not be used where ascorbic acid dominates. For environmental impact of ascorbic acid, chemical average data will be used as an approximation.

Citric acid production

Citric acid [77-92-9], or2-hydroxy-1,2,3-propanetricarboxylic acid is produced commercially by fermentation of sugar. Raw materials for making citric acid include Molasses (mainly beet), sucrose, dextrose (mainly from corn, wheat or tapioca) and unrefined sweet potato. After the fermentation, where the micro organism *Aspergillus niger* is most commonly used, the citric acid broth is generally separated from the biomass using filtration or centrifugation (Figure 11). The citric acid is then purified either by a lime-sulphuric acid method or a liquid extraction process. Lime-sulphuric extraction is more traditional and used in many older plants. Citric acid is recovered by calcium salt precipitation and acidification by using sulphuric acid, and although the chemistry is straightforward, the process itself is complex. The liquid extraction is even more complex, but the technique is basically about using water and hydrocarbons as purifiers.

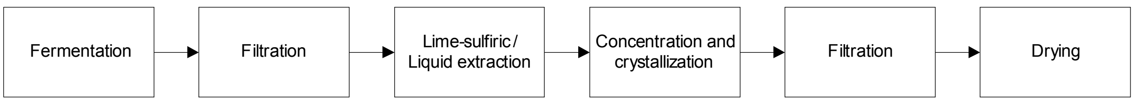

Figure 11 Production of citric acid. Citric acid is formed by fermentation of sugar. The citric acid is then purified (Lopez-Garcia, 1999).

The biomass from the fermentation can be used as animal feed. The lime-sulphuric extraction produces calcium sulphate, which is usually disposed of into a landfill.
The liquid extraction process generates few by-products.

Since there was no information to be found concerning emissions and energy use of production of citric acid, and since the production process is similar to that of ascorbic acid citric acid data was approximated with the chemical data.

Sodium citrate dihydrate

Sodium citrate dihydrate, or trisodium citrate is a salt formed from citric acid. It is generally produced by neutralization of a water solution of citric acid with sodium hydroxide. The neutralization reaction is highly exothermic and gives off 1109 J per g of citric acid.

Due to lack of information and the rough estimation of the other dry chemicals' environmental impact, trisodium citrate was considered to have the same environmental impact as citric acid.

Enzymes
There are three enzymes used to process the RCT in the process:

1. Pectinase (product name: Rapsidase) is a general term for enzymes that break down pectin, a polysaccharide substrate that is found in the cell wall of plants (Wikipedia, 2007).
2. Cellulase (product name: Cellulyve) refers to a class of enzymes that break down cellulose. Cellulose is the most common organic polymer and is found in plants. When present in food, it is referred to as dietary fiber (Wikipedia, 2007).
3. Protease (product name: Neutrace) is any enzyme that breaks down proteins (Wikipedia, 2007).

There were no available reports of the production processes of the used enzymes. Instead an average of the LCIA results from Nielsen (2006) was used.

There are four main processes involved in all enzyme production mentioned in Nielsen (2006) (Figure 12):

1. Fermentation: Micro-organisms are grown.
2. Recovery: Extra cellular enzymes are separated from the biomass
3. Formulation: Preservation and standardisation of enzyme products and addition of formulation chemicals
4. Biomass treatment: Inactivation of micro-organisms and preparation of the biomass for use as soil improver in agriculture.

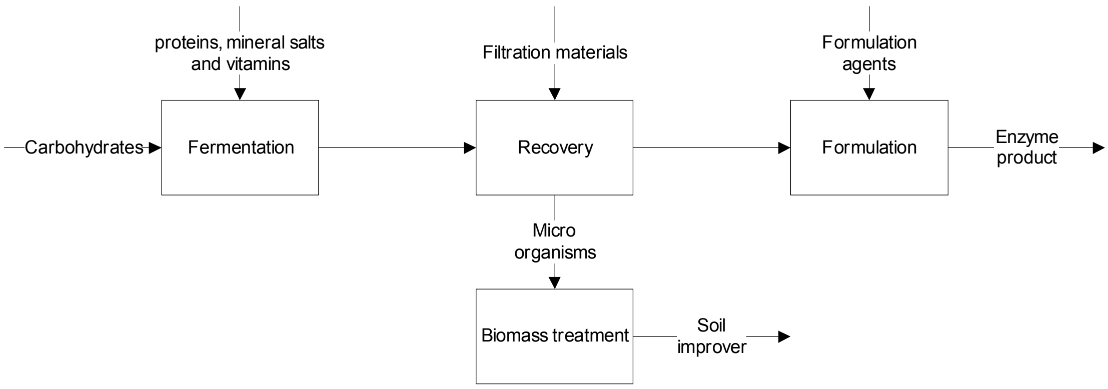

Figure 12 Production of enzymes. Carbohydrates are fermented and micro organisms grow and produce enzymes. The residue from the fermentation is used as a soil improver (Nielsen, 2006).

Environmental impact can vary widely depending on which enzyme that is produced. Different enzymes have slightly different production processes, because of different level of optimization etc.

The functional unit in the report is 1 kg enzyme. The enzyme products can be both liquid and solid.

Emissions from natural gas combustion are included, as well as emissions from the complementary combustion of oil. There is no information about emissions specifically to water, but the waste water is first treated in the company's own treatment system and then treated in the municipal waste water facility. After that it is piped into the sea.

Electricity is used in most of the operations, and heat is used in the formulation and biomass treatment units. Except for the process units in Figure 12, there is also a waste water treatment. Electricity is from Danish national grid, and natural gas power plants have been identified as the marginal sources of electricity. Production of enzymes is not located at one specific site, and means of producing steam differs from site to site. Supply of heat and power are determined by the electricity demand in the society in one place, and sometimes oil is used as a complement.

A wide range of chemicals and other substances are used when producing enzymes. Exact quantities and the names of some of the substances used in small amounts were confidential, and thus not presented.

The system expansion is used to estimate how much alternative fertilizers that is not produced when distributing the soil improver to agriculture.

The transport of the soil improver is included. Concerning ingredients, the ones with the longest distances and/or those that are used in the largest quantities are included.

The average values of the LCIA results of the different enzymes in the report are used (Table 8). The LCIA is however calculated with eco-indicator v2.1 which makes only the GWP and the primary energy category valid. This is because both EDIP and eco-indicator uses IPCCs GWP method, and because energy is not weighted and thus measured the in the same way. Eutrophication and acidification values will still be used, and if it will have great impact on the result further investigations will be done. Since the GWP varied between 1 and 10 kg CO2-eq. per kg enzyme, a value of 10 will later be used in the scenario analysis. The other values were set according to the ratio between the average values.

According to Nielsen (2007), the environmental impact of all enzyme processes vary within the same interval of those mentioned in the report.

The differences between the different enzymes LCIA results can be explained by:

1. Differences in concentrations of enzyme in the final products
2. Differences in energy consumption per produced unit
3. Differences in quantities and types of ingredients, particularly major ingredients such as carbohydrates and formulation chemicals.

Table 8 Environmental impact average data on production of 1 kg enzyme

GWP [kg CO_2-eq]	Acidification [g SO_2-eq]	Eutrophication [g NO_3-eq]	Primary energy [MJ]
4.94	15.8	6.95	61.2

Water

The water impact data used included transport of water to user, and were valid for European water production (Table 9) (Ecoinvent, 2003).

Table 9 Environmental impact data on production of 1 kg water.

GWP [kg CO_2-eq]	Acidification [g SO_2-eq]	Eutrophication [g NO_3-eq]	Primary energy [MJ]
0.301553	0.00143183	0.00096622	0.0062224

3.2.2.3 The waste treatment system

Regarding the treatment of the process waste, there was first the problem of choosing type of waste treatment. The waste is measured in dry weight and wet weight divided in water and alcohol weight. The dry weight is not divided further in amounts anthocyanins, citric acid etc. which made it difficult to decide a proper waste treatment. If waste nutrition content would be low, it may not be worthwhile transporting it and feeding husbandry. If the waste would instead be composted it would possibly be too wet to compost, but this was depending on other compost matter. If other input material to the compost facility was too dry it would be beneficial to use RCT process waste. Then there would also be the system expansion issue, and what would happen with other waste if the RCT process waste was composted. This is further discussed in section 3.2.3.2. Because of the problems with defining a waste treatment system, the waste from the process is neglected.

3.2.2.4 System expansion of the RCT system

According to the scenarios in section 3.1, when novel products are not produced from RCT they need to be produced elsewhere. In order to find an equivalent production system, the system has been expanded (Figure 13).

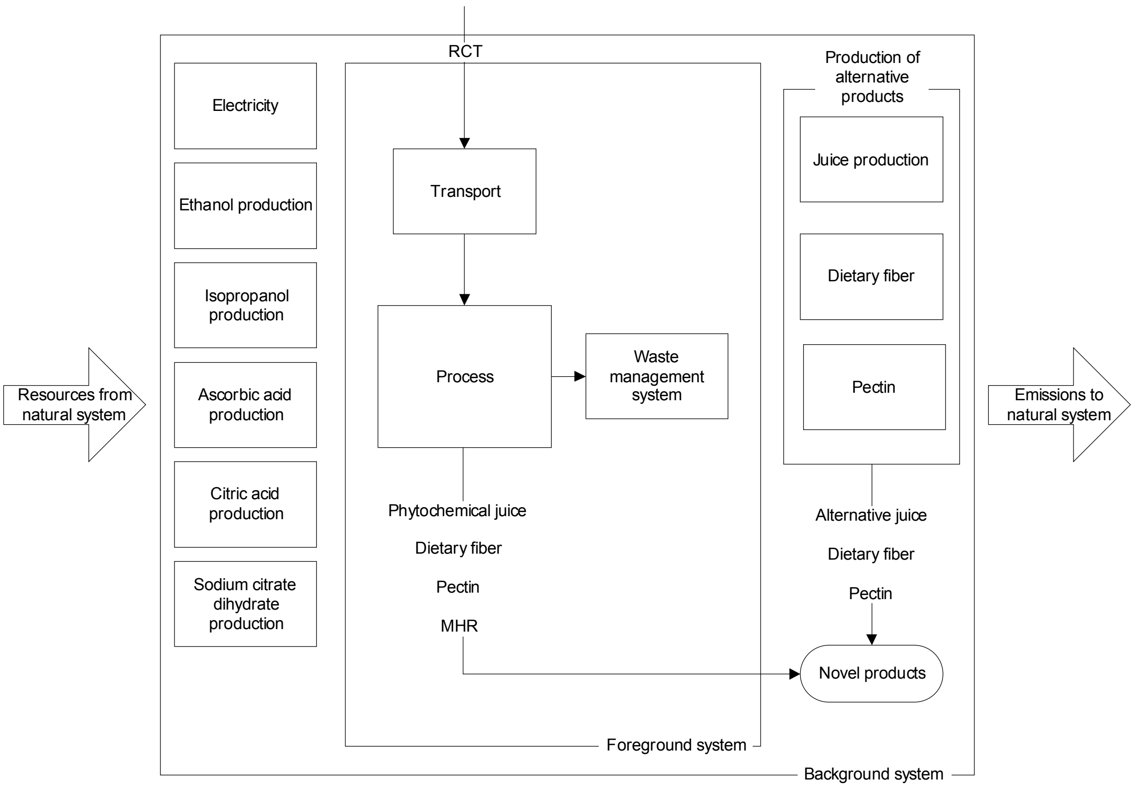

Figure 13 The RCT system with the process case and system expansion of novel products.

Alternative production of juice
According to REPRO (2008), there are two likely competitors of equal function to this product:

- Mixed vegetable or fruit juices
- More basic or intermediate products like carrot or tomato juice.

No information from producers of these product types was available due to confidentiality reasons. Therefore a previous study on carrot purée was used (Mattsson, 1999) in REPRO (2008). Cultivation, washing, peeling, cutting, freezing, unfreezing and grinding processes are included in the study (Table 10).

The phytochemical juice has a concentration of 77 g dry matter per kg juice. The carrots have been assumed to have a dry matter concentration of 10%. The function is then estimated accordingly:

1 kg phytochemical rich juice ↔ 77 g dry matter carrot purée ↔ 770 g carrot purée

Table 10 Environmental impact data on the production of 1 kg carrot purée (REPRO, 2008).

	Total	Cultivation of carrots	Tap water, Switzerland	SIK Diesel tractor with net energy	Electricity, medium voltage, at grid, The Netherlands	SIK Natural gas with net energy	Electricity, medium voltage, at grid, The Netherlands	Emissions
GWP g CO_2	1100,47	36,45	7,17	1,22	293,56	757,28	4,79	0,00
Acidification g SO_2	1,34	0,20	0,03	0,01	0,47	0,63	0,01	0,00
Eutrophication g NO_3	3,31	1,93	0,03	0,02	0,55	0,66	0,01	0,12
Energy MJ eq	19,11	0,61	0,26	0,02	4,79	13,36	0,08	0,00

Alternative production of dietary fiber
According to REPRO (2008), beet-pulp is one of the main fiber ingredients in cattle feed in south-western Sweden. Dried beet-pulp is together with molasses by-products from sugar production. Economical allocation has been used when environmental impact was partitioned between the products:

- Sugar; 80% of the impact
- Beet-pulp; 15% of the impact
- Molasses; 5% of the impact

Regarding the process at the factory, only the drying of the beet-pulp is included. The dry matter content of beet-pulp after drying is assumed to be 90%. The equivalent functional unit of one 1 kg dietary fiber is estimated as follows:

1 kg dietary fiber ↔ 0.96 kg dry matter beet pulp ↔ 1.07 kg beet-pulp

The environmental impact data on beet fiber is presented in Table 11.

Table 11 Environmental impact data on 1 kg beet fiber

GWP [kg CO_2-eq]	Acidification [g SO_2-eq]	Eutrophication [g NO_3-eq]	Primary energy [MJ]
712.14	4.7	10.37	8.49

Alternative production of pectin
No information was available from the contacted companies because of confidentiality reasons (REPRO, 2008). Therefore, limited conventional pectin production data has been used:

- Energy use (oil, natural gas and electricity): 50-55,000 kWh/ton pectin
- Water use: 0.1 m3/kg pectin
- Alcohol use: 150 g isopropanol/kg pectin

Concerning energy data only one reference was found on the energy mix. Therefore the energy distribution was assumed to be 73% oil, 6% natural gas and 21% electricity.

The raw material for producing pectin is also trimmings, e.g. apple peels etc.

The commercially produced pectin was assumed to replace the exact same amount of pectin from RCT. Environmental data is presented in Table 12.

Table 12 Environmental impact data on the production of 1 kg pectin. Heavy oil is assumed to be used. Data is from Ecoinvent (2003).

	Unit	Total	Tap water, at user, Switzerland	Isopropanol, at plant, Europe	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating, Europe	Natural gas, burned in industrial furnace >100kW, Europe	Electricity, medium voltage, at grid, The Netherlands
GWP	g CO_2	21 180,20	1,63E+01	258,93	12 429,23	769,77	7 705,99
Acidification	g SO_2	98,18	6,01E-02	1,66	83,44	0,64	12,37
Eutrophication	g NO_3	44,08	5,90E-02	1,13	27,71	0,67	14,51
Energy	MJ-eq	335,35	5,81E-01	9,29	186,13	13,58	125,78

Alternative production of MHR
Since the use of MHR was not known, it was not clear which product it should replace (REPRO, 2008). Therefore, this product was not included in the analysis.

3.2.3 Inventory analysis of the feed and compost systems

These systems were only to be used to analyze environmental impact of the scenarios. Hence, a pure LCA approach was used when working with them, without costs and microbiological activity. Therefore system expansion expansions were used in order to see how the alternative processes would look like.

Concerning level of detail these systems will not be as detailed as the process model, but merely detailed enough to make a comparison.

Background systems that have been used are from eco-invent (Table 13).

Table 13 Background system information on the feed and compost scenarios (REPRO, 2008). Data are from Ecoinvent, in which RER means Europe and CH means Switzerland.

Element	Ecoinvent Process	Geographical area	Functional Unit	Literature Reference
Electricity	Electricity, medium voltage, at grid /NL	The Netherlands	1 kWh	(Dones R, 2004)
Oil	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER	Europe	1 MJ	(Dones R, 2004)
Natural Gas	Natural gas, burned in industrial furnace >100kW /RER	Europe	1 MJ	(Dones R, 2004)
Water	Tap water, at use /CH	Switzerland	1 kg	(Althaus, Hischier et al., 2004)
Isopropanol	Isopropanol at plant /RER	Europe	1 kg	(Althaus, Hischier et al., 2004)

3.2.3.1 The RCT feed system

Because of its content of nitrogen and proteins, RCT was considered most likely to replace silage. The ensilage was supposed to be completely dry and concerning RCT the dry matter content was measured to 8.8% of the total weight. Thus it was assumed that the production of one tonne RCT replaces the production of 88 kg ensilage. An average of three different types of ensilage was used: Bunker silo, round-bales and tower silo. Waste from each of the ensilage types was assumed to be 13%, 16% and 9% respectively, and was included in the impact data Table 14.

Cultivation, mowing, harvesting and silo storage processes under Swedish conditions are included in the system (Figure 14). Transports are considered to be short and are therefore neglected.

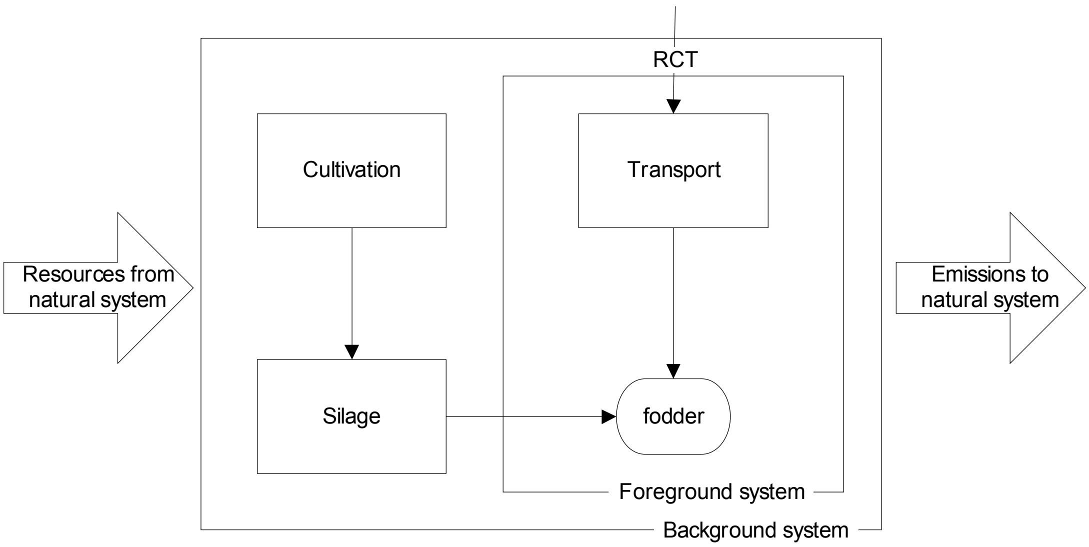

Figure 14 The RCT system with the fodder case and system expansion of the fodder production. The transport is neglected.

Table 14 Environmental impact average data on ensilage production

	Unit	Bunker silo	Round-bales	Tower silo	Average
GWP	g CO_2	289,94	297,39	272,86	286,73
Acidification	g SO_2	2,70	2,75	2,53	2,66
Eutrophication	g NO_3	35,19	36,46	33,57	35,08
Energy	MJ-Eq	1,83	1,83	1,77	1,81

3.2.3.2 The RCT compost system

When working with the compost system there was a problem of defining what alternative waste that was composted. If it was waste like the RCT then all scenarios would include an equal amount of environmental impact from composting and in that case the compost could be removed. On the other hand, if the alternative waste could be considered to have an environmental impact the compost impact from the alternative compost treatment system would be larger. Therefore the compost scenario was removed, and the compost system was removed from the other scenarios.

Another reflection is the function that the compost provides in the feed and process scenarios. The compost takes care of waste from other systems, which is why it can be argued that a system expansion should be carried out. Depending on what system that is chosen for the expansion, e.g. incineration, anaerobic digestion etc., the impact can be negative or positive.

A data set called compost at plant was used for this system (Ecoinvent, 2003). Annually 10,000 tonnes of waste is used to produce 5,400 tonnes of composted matter. Therefore, 1 kg RCT results in 0.54 kg composted matter. The expanded compost system is presented in Figure 15 and environmental data is presented in Table 15.

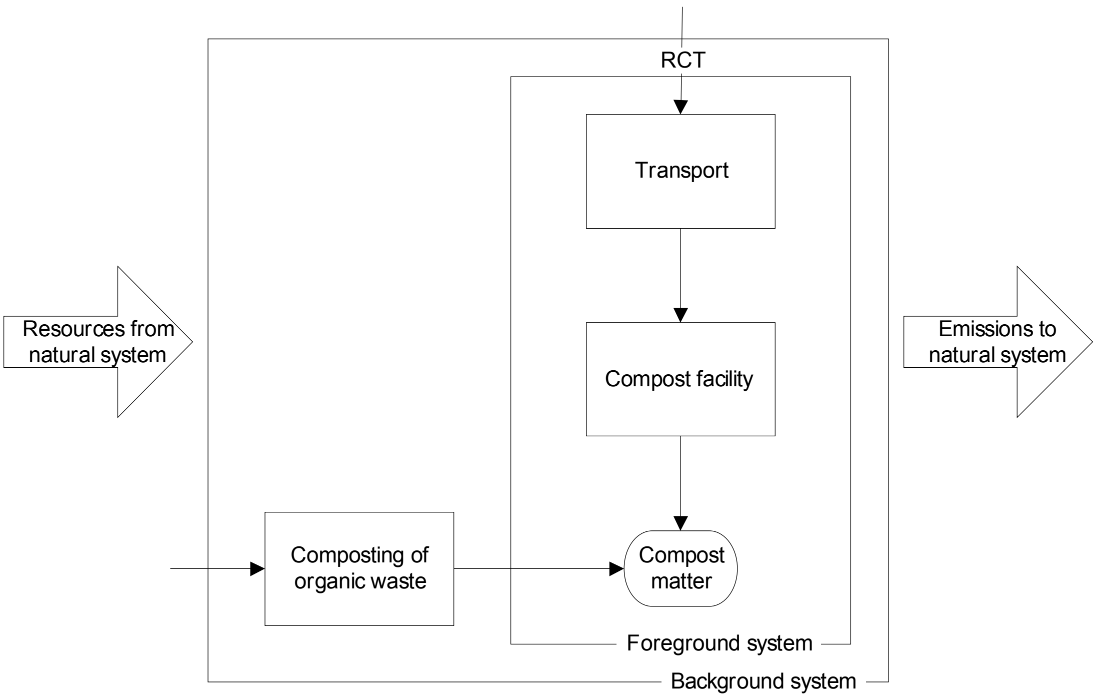

Figure 15 The expanded compost system

Table 15 Environmental impact data on compost.

GWP [kg CO_2-eq]	Acidification [g SO_2-eq]	Eutrophication [g NO_3-eq]	Primary energy [MJ]
341,37	3,25	4,41	0,58

4 Results of the impact assessment

First the results of the RCT production system are presented. The three production simulations or alternatives are shown in section 4.1. Then a dominance analysis of the different processes in the production system is presented. Finally the scenario results are presented. The treated amount of RCT is 1000 kg. The impact was considered to belong to a process, resources, transport or waste category. The waste and transport categories were too small to be relevant to show.

4.1 The RCT production system simulations

Among the three process simulations, simulation 1 resulted in the largest impact (Figure 16 to Figure 19).

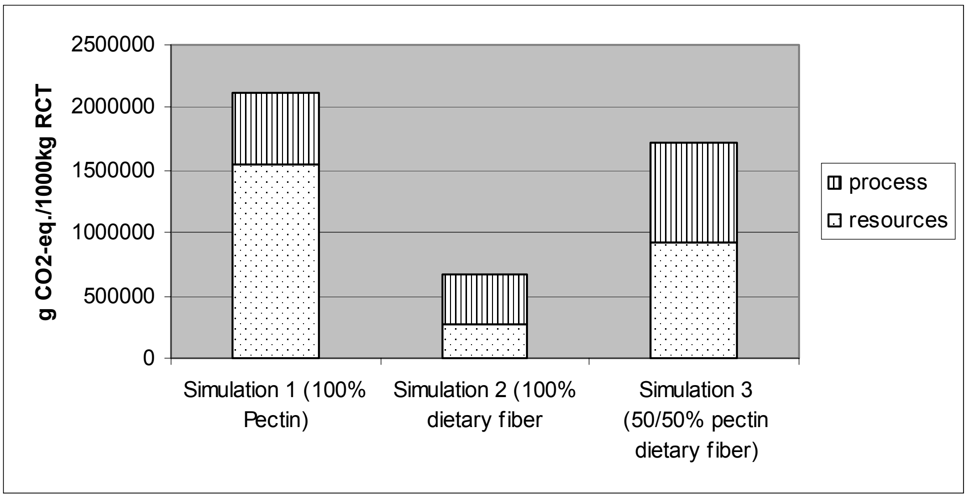

Figure 16 GWP from using 1000 kg RCT as input to the novel product production

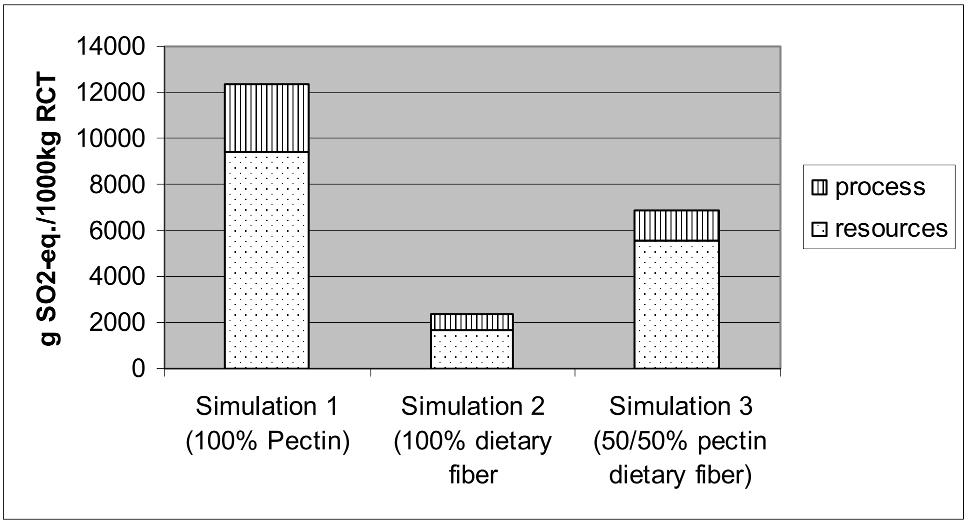

Figure 17 Acidification from using 1000 kg RCT as input to the novel product production

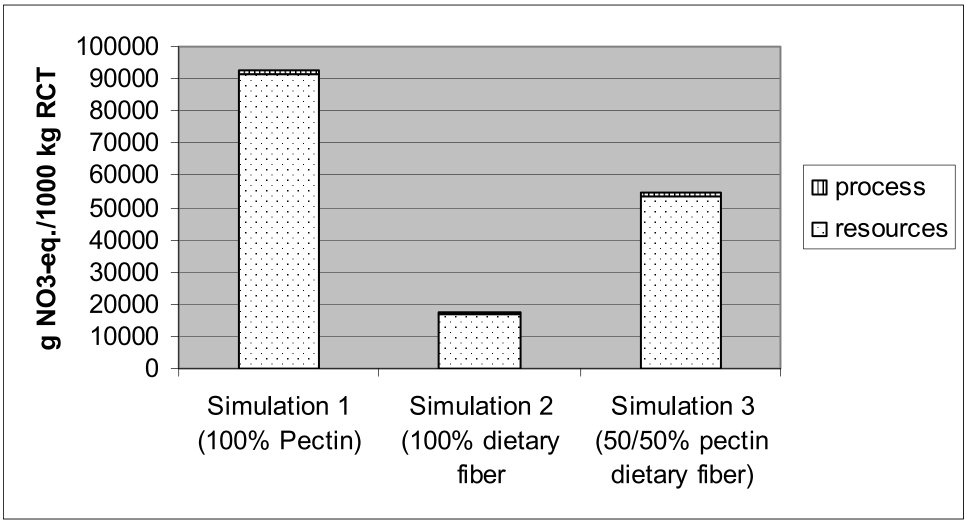

Figure 18 Eutrophication from using 1000 kg RCT as input to the novel product production

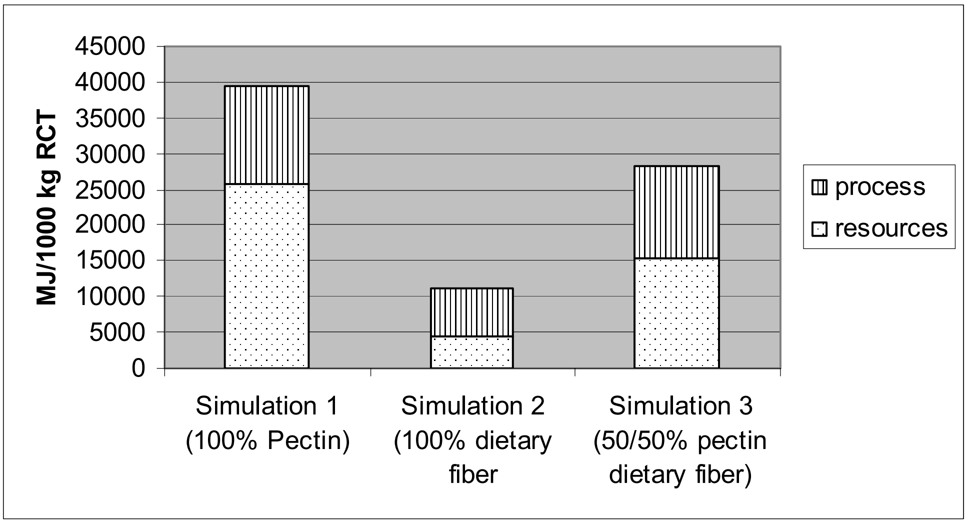

Figure 19 Primary energy from using 1000 kg RCT as input to the novel product production

More detailed information, such as a dominance analysis follows below. Since no information about MHR production was found, the feed-back flow was disabled. Impact is divided in the categories process, resources waste and transport. The process category contains everything that is consumed directly in the process, e.g. energy. The main exception is resources. The resources category contains the resources that are used. RCT has no impact, but the chemicals and enzymes belong to this category. These compounds are no ingredients, but merely auxiliary products in the process. The enzymes and the acids leave the system in the product and the waste, and are considered to be used when they are added to the process. The alcohol on the other hand is recirculated from the product flow back to the process, but also leaves the system as losses. The alcohol was defined as belonging to the resources category, but was considered to be consumed when it left the system as waste. Environmental impact from alcohol is therefore not included in the waste category, where only waste in the form of weight from the flow is included. Where waste and transport (transport is only valid for the transport unit) do not contribute to impact they are excluded from the diagrams.

The first part of the process is the flow from transport to extraction and it is always the same, since it is only the X, Y and Z flows that are altered (Table 16). The distillation is the most dominant process unit.

Table 16 Environmental impact data on processing of 1000 kg RCT. Data is presented per process unit

	Resources GWP	Process GWP	Total	Resources Acidification	Process Acidification	Total
Stabilisation	0	41364,67	41364,67	0	65,94182	65,94182
Mill	0	47686,78	47686,78	0	76,02027	76,02027
Extraction	63,05199	11204,77	11267,82	0,299383	17,86217	18,16155
Distillation of alcohol from extraction	5744,551	258359,6	264104,1	35,25156	411,866	447,1176
storage of juice	0	7381,242	7381,242	0	11,76687	11,76687

	Resources eutrophication	Process eutrophication	Total	Resources Primary Energy	Process primary energy	Total
Stabilisation	0	78,70476	78,70476	0	674,3083	674,3083
Mill	0	90,73387	90,73387	0	777,3685	777,3685
Extraction	0,202028	21,31936	21,52139	1,301047	182,6551	183,9561
Distillation of alcohol from extraction	344,6158	491,582	836,1978	96,17185	4211,662	4307,834
storage of juice	0	14,04432	14,04432	0	120,3257	120,3257

The pectin flow when 100% pectin is produced

When 100% pectin is produced it is only interesting to look at the pectin flow, since the feed-back loop of pectin residue to the MHR-flow was disabled. The environmental impact is presented in Table 17. The freeze drying step is the most dominating process unit.

Table 17 Environmental impact data on processing of 1000 kg RCT. Phytochemical juice and pectin are produced. Data is presented per process unit

	Resources GWP	Process GWP	Total	Resources acidification	Process acidification	Total
Enzymatic treatment of pectin flow	49322,16	18139,54	67461,7	231,5116	28,9173	260,4289
Enzyme inactivation of pectin flow	0	18484,73	18484,73	0	29,46758	29,46758
Centrifugation of pectin flow	0	1113,226	1113,226	0	1,774658	1,774658
Optional freeze drying of matter from pectin flow	0	0	0	0	0	0
Alcohol precipitation and Sieving	0	75320,06	75320,06	0	120,0721	120,0721
Distillation of alcohol from alcohol precipitation	1299,668	11358	12657,67	7,975441	18,10645	26,08189
Freeze drying of matter from alcohol precipitation	1330234	855167,4	2185401	8163,009	1363,272	9526,281
Storage of pectin rich fraction	0	1815,387	1815,387	0	2,894014	2,894014

	Resources eutrophication	Process eutrophication	Total	Resources Primary Energy	Process primary energy	Total
Enzymatic treatment of pectin flow	1599,565	34,5142	1634,079	724,1999	295,7027	1019,903
Enzyme inactivation of pectin flow	0	35,17098	35,17098	0	301,3297	301,3297
Centrifugation of pectin flow	0	2,11814	2,11814	0	18,14731	18,14731
Optional freeze drying of matter from pectin flow	0	0	0	0	0	0
Alcohol precipitation and Sieving	0	143,3119	143,3119	0	1227,834	1227,834
Distillation of alcohol from alcohol precipitation	77,96713	21,61093	99,57805	21,75827	185,1531	206,9114
Freeze drying of matter from alcohol precipitation	79800,77	1627,131	81427,9	22269,98	13940,56	36210,54
Storage of pectin rich fraction	0	3,454145	3,454145	0	29,59362	29,59362

The dietary fiber flow when 100% dietary fiber is produced

When only processing dietary fiber, the pectin and MHR process units are not relevant. The impact related to dietary fiber process units is presented in Table 18.

Table 18 Environmental impact data on processing of 1000 kg RCT. Phytochemical juice and dietary fiber are produced. Data is presented per process unit.

	Resources GWP	Process GWP	Total	Resources acidification	Process acidification	Total
Freeze drying of cell wall material	0	107037,9	107037,9	0	170,6353	170,6353
Storage of dietary fibre	0	0	0	0	0	0
	Resources eutrophication	**Process eutrophication**	**Total**	**Resources Primary Energy**	**Process primary energy**	**Total**
Freeze drying of cell wall material	0	203,6615	203,6615	0	1744,884	1744,884
Storage of dietary fibre	0	0	0	0	0	0

The pectin and dietary fiber flows when 50% of each product is produced

The pectin and dietary fiber flows are presented in Table 19.

Table 19 Environmental impact data on processing of 1000 kg RCT. Phytochemical juice and 50% of each pectin and dietary fiber are produced. Data is presented per process unit.

	Resources GWP	Process GWP	Total	Resources acidification	Process acidification	Total
Enzymatic treatment of pectin flow	24661,08	9069,772	33730,85	115,76	14,45865	130,2145
Enzyme inactivation of pectin flow	0	9242,363	9242,363	0	14,73379	14,73379
Centrifugation of pectin flow	0	832,0978	832,0978	0	1,326496	1,326496
Optional freeze drying of matter from pectin flow	0	0	0	0	0	0
Alcohol precipitation and Sieving	0	37660,03	37660,03	0	60,03605	60,03605
Distillation of alcohol from alcohol precipitation	649,834	5679,002	6328,836	3,99	9,053227	13,04095
Freeze drying of matter from alcohol precipitation	665116,9	427583,7	1092701	4081,50	681,6361	4763,14
Storage of pectin rich fraction	0	907,6934	907,6934	0	1,447007	1,447007
Freeze drying of cell wall material	0	53518,94	53518,94	0	85,32	85,33
Storage of dietary fibre	0	0	0	0	0	0

	Resources eutrophication	Process eutrophication	Total	Resources Primary Energy	Process primary energy	Total
Enzymatic treatment of pectin flow	799,7826	17,2571	817,0397	362,10	147,8514	509,9513
Enzyme inactivation of pectin flow	0	17,58549	17,58549	0	150,6649	150,6649
Centrifugation of pectin flow	0	1,583237	1,583237	0	13,56449	13,56449
Optional freeze drying of matter from pectin flow	0	0	0	0	0	0
Alcohol precipitation and Sieving	0	71,65593	71,65593	0	613,917	613,917
Distillation of alcohol from alcohol precipitation	38,98356	10,80546	49,78903	10,88	92,57654	103,4557
Freeze drying of matter from alcohol precipitation	39900,38	813,5657	40713,95	11134,99	6970,279	18105,27
Storage of pectin rich fraction	0	1,727073	1,727073	0	14,79681	14,79681
Freeze drying of cell wall material	0	101,8308	101,8308	0	872,4419	872,4419
Storage of dietary fibre	0	0	0	0	0	0

It is concluded that the freeze drying step is by far the most dominating process unit.

4.2 The scenarios

Even though the process simulations results may indicate that the production of dietary fiber is the most environmental friendly option, looking at the combined system may give a different result. It is already known how large impact the alternative product systems have on environment and now these linked systems will be assessed together. When RCT is not processed, i.e. when it is treated as animal feed instead, one still has to consider what novel products that are not being produced. For instance, if the production output would be phytochemical juice and pectin, then when RCT is treated as fodder these products need to be produced elsewhere. When RCT instead used to produce novel products, fodder needs to be produced elsewhere.

As seen in Figure 20 to Figure 23, processing RCT is the environmentally worst option. Only the 100% pectin and 100% dietary fiber simulations are presented.

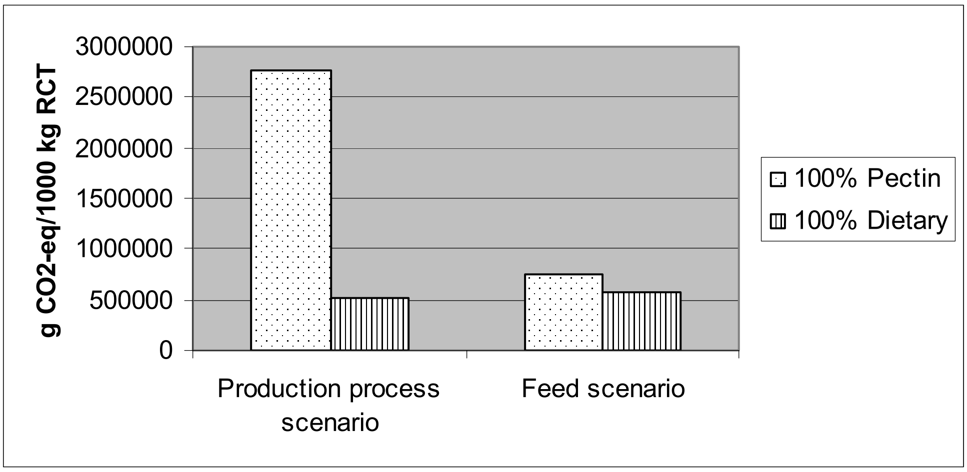

Figure 20 GWP in g CO_2-eq/1000 kg RCT

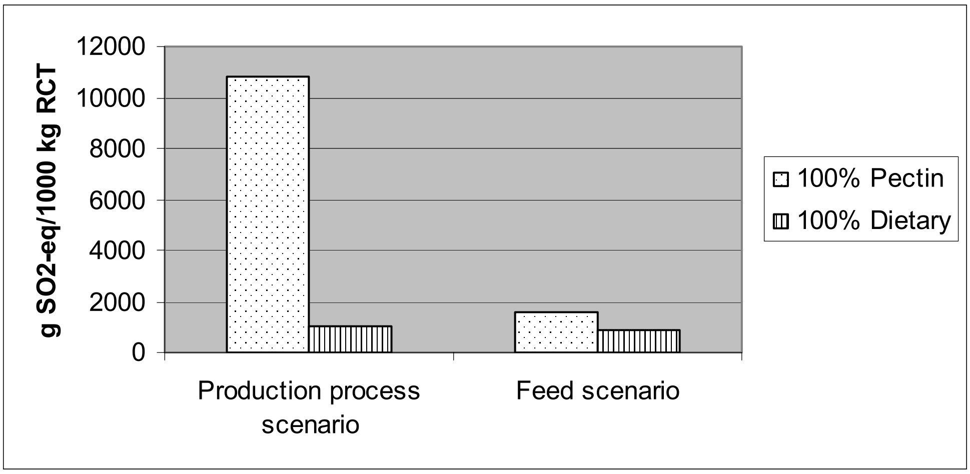

Figure 21 Acidification in g SO_2-eq/1000 kg RCT

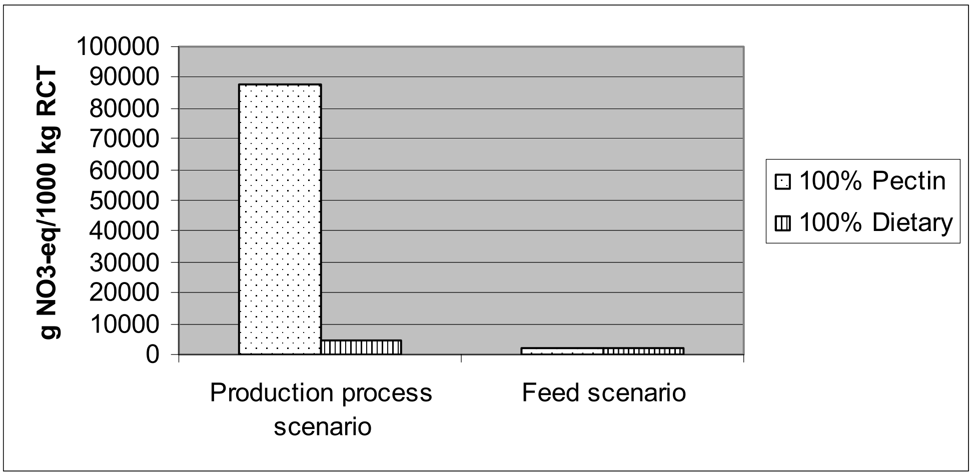

Figure 22 Eutrophication in g NO_3-eq/1000 kg RCT

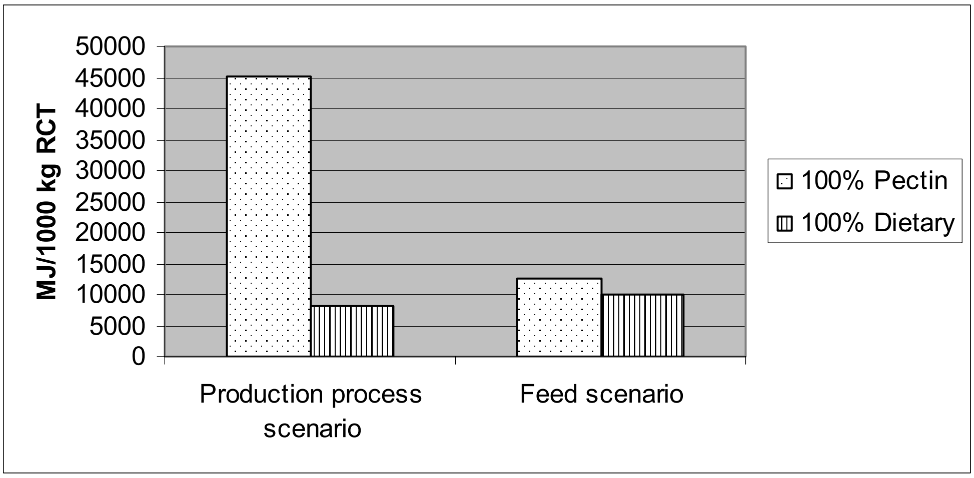

Figure 23 Primary energy in MJ/1000 kg RCT

5 Discussion

After the production modeling was finished, it was put into its context by designing three comparable scenarios. From the analysis of the scenarios it could be concluded to what purpose RCT was best used.

5.1 Production process modeling

The production process modeling consisted of choosing a program platform, scope of modeling and deciding on level of detail.

5.1.1 Choice of programming platform

It was decided that the model would be developed in Simulink Matlab. The reason for this was that Matlab was the current programming tool used in previous work at SIK and within REPRO. The programming in Simulink allowed a sort of semi object related programming, which involved strengths that for instance Excel lacked. One advantage of using Simulink was that the Simulink graphical user interface (GUI) could be used. It made it possible to represent the model similar to the flow charts used in LCA methodology. Process units could to a certain extent be copied and flows could be re-routed and snap to other process blocks. The GUI also had a built-in mask interface, which meant that by clicking on a process unit block, parameters could be altered without having to change the source code of the process unit. Another advantage of Simulink was that data structures were supported, which made the work with all variables a lot easier. Finally, Simulink supports embedded matlab code and calls to matlab functions, which made advanced calculations and use of functions possible.

Designing diagrams in Matlab proved to be somewhat difficult, but on the other hand Matlab has a function that writes matrix elements to an excel sheet.

When using a modeling program, then the model becomes a tool in itself, and becomes in a sense separated from the program.

5.1.2 Alternative programming platforms

Excel presents a simple interface and a straight-forward view of the sequence of the calculations. It supports the use of functions to a certain extent and it is easy to present data in diagrams, tables, etc. On the other hand Excel lacks the flow chart GUI possibility that Simulink has. It is also harder to keep track of variables since they are always stored in a cell and do not have a specific name.

Another alternative would be to use the Java platform (Java, 2008). Java technology is today used in almost any electronic information product. For instance, Matlab uses the Java platform to large extent. If Java programming was to be used to make this model, a model GUI would have to be programmed from scratch. However, one of the main reasons for Java's popularity is the vast library of classes that can be used. For instance, instead of programming a screen button, an existing class called JButton can be used and modified to suit the current application. This option would be the most resource demanding and time consuming, but on the other hand the most flexible one. If future projects with similar process modeling tasks are probable, it might be worth developing a tailor cut production process modeling program.

It is also possible to develop java programs and then use them together with Matlab, since Matlab supports the use of Java.

5.1.3 Object oriented programming

However, if the object oriented programming approach is to be utilized fully, data must be uniform and presented in a way that makes it possible to describe items of the same type in the same way. For example, if there is a class called ingredient that is described with attributes as "Name" and "weightInKilograms", then all previous lab results must have been carried out with that specific description of an ingredient in mind. If weights would have been measured in molar weight, then a new attribute to the class ingredient would have to be defined. In this case, it is possible to recalculate molar weight to kilograms, but in the worst case relevant data can be lost. In large projects such as, REPRO, this puts more demand on how pilot data is produced and how experiments before the modeling are carried out. How data is collected and what data that is needed must then be more accurately specified. Other examples of types that can be described as classes are process units, operations in the process units, process information that is sent from unit to unit, etc.

5.2 LCA discussion

A number of possible improvements have been suggested, which will reduce environmental impact drastically. Data quality and LCA assumptions are discussed and some of the assumptions may have to be reconsidered. It is further discussed that this report can be used as a guideline, structure or framework on how to analyse the scenarios. The different scenarios should continue being analysed and improved until data is accurate enough to give results that will answer in absolute numbers which scenario that is the most environmental friendly.

5.2.1 Sensitivity to system boundaries and allocation choices

The results of a LCA are influenced by the assumptions and decisions made in the goal and scope. The choices concerning functional unit and environmental impacts are obvious and easily observed, but other decisions are not that obvious. Assumptions and decisions concerning system boundary, type of input data and data quality have large impact on the results.

5.2.1.1 Allocation and system expansion

Inventory data may be calculated and presented in many ways. In, the ethanol and the alternative dietary fiber production, data sets are based on allocation. The ISO standard dictates that system expansion is preferred to allocation and that it should be used whenever several allocation procedures are possible (ISO14044, 2006). In the case of ethanol data, physical allocation (heat values of the two products leaving the ethanol system) was used when estimating environmental impact of ethanol. There were two main reasons for using physical allocation: First, the ethanol production does not belong to the foreground system. A system expansion requires a higher detail level in that sense that knowledge about yet another production system is needed, in this case the fodder system that produces fodder that is replaced by the feedstuff (Feedstuff is the residue from the distillation). It can be argued that since the ethanol system is not defined as belonging to the foreground system, it should not be focused on to such extent. Second, even though this is a more philosophical argument and assumes another time perspective, system expansion assumes that there is an outlet for the product in question. The ethanol industry grows constantly, which means that more feedstuff is produced. If the animal husbandry industry does not grow as fast, it will mean that feedstuff eventually will be burned instead of used as fodder. Once again time frame is important in the sense that in the future ethanol may not be that beneficial to produce.

Concerning the dietary fiber production, economical allocation was used to partition the impact between the products. This allocation was used because it was readily available and because of the fact that the dietary fiber production did not either belong to the foreground system. Concerning the enzymes, system expansion was used on the soil improver.

5.2.2 Data quality assessment

As discussed in section 3.2.1.3, average data was desirable in most cases, except for the production process scenario. Data should also be recent and represent the newest technologies used in industry. Below, a summary of the main sources of data is presented (Table 20). The sources are linked to an activity, and the publication year of the report and the geographic regions that data apply to is also included.

Table 20 The sources of data, age of data and the geographic origin of the data for each activity

Data category	Activity	Source of data	Data age (Publication date)	Geographic region	Reference
Novel products' production process	Freezing	Literature	2008	N/A	(Östergren, 2008)
	Milling energy	Literature	2008	N/A	(Östergren, 2008)
	Distillation	Literature	2008	N/A	(Östergren, 2008)
	Freeze drying	Literature	2008	N/A	(Östergren, 2008)
	Heating/cooling and mixing	Literature	2008	N/A	(Östergren, 2008)
	Centrifugation	Literature	function2004, constants 2007	N/A	(Bieler, 2004)
Auxiliary products	Ethanol production	Literature	2004	West Europe	(Bernesson, 2004)
	Isopropanol production	Literature	2004	Europe	(Althaus, Hischier et al., 2004)
	Ascorbic acid production	Literature (same as ethanol)	2004	(same as ethanol)	(Bernesson, 2004)
	Citric acid production	Literature (same as ethanol)	2004	(same as ethanol)	(Bernesson, 2004)
	Sodium citrate dihydrate production	Literature (same as ethanol)	2004	(same as ethanol)	(Bernesson, 2004)
Alternative productions	Animal feed production	Literature	2004	Sweden	(REPRO, 2008)
	Compost of organic waste	Literature	2003	The Netherlands	(REPRO, 2008)
	Alternative production of dietary fiber	Site-specific	2004	Sweden	(REPRO, 2008)
	Alternative production of phytochemical juice	Site-specific	1999	Sweden	(REPRO, 2008)
	Alternative production of pectin	Literature	2007	N/A	(REPRO, 2008)

The data on the production of novel products were obtained from literature and are approximations of real systems. Since the model did not represent a site-specific production, these data were considered appropriate and accurate to meet demands mentioned in section 3.2.1.3.

Concerning the data on ethanol production, they were put together by using average data when it was possible and site-specific data on Swedish ethanol production when no average data was available. Since the ethanol was assumed to come from Sweden, the data met demands in section 3.2.1.3.

There was less information found on the other auxiliary products, but since isopropanol were not used in the results of this report and since the other products were only used in small amounts, these data were considered to be sufficient.

How the amount of a novel product, organic waste or RCT is expressed in an amount of another product, e.g. the equivalent function of 1 kg phytochemical juice expressed in kg carrot juice is not a straight-forward problem. The juice contains many compounds that can be used in a range of applications. In this study the relation of dry weight was used, and the function of the dry weight of phytochemical juice was assumed to be equal to the function of the dry weight of carrot juice. Another way of assessing function could be to analyze the anthocyanins in the juices as colorants. Then the function would be related to the absorbency of the colorant, and the function of the product could be expressed in that way. Carrots like red cabbage contain anthocyanins, so therefore the carrot juice could still be a substitute for phytochemical juice, but substituted on a different basis (Colarome, 2008). To be able to interpret results in a better way, it must be defined if it is the phytochemical juice as product or if it is the anthocyanin that is to be substituted.

The quality of data representing alternative production of novel products is considered to be sufficient, except for alternative production of pectin. There were only one site-specific set of data on the energy mix, from an unpublished source. If further investigations of alternative production of pectin would prove that it was more energy demanding than first thought, the findings would be in favour for the production scenario. The alternative production of pectin affects the feed scenario, since the environmental impact of the pectin production can not be neglected compared with the carrot juice production.

No data on alternative MHR production was found, which was why the benefits of running the MHR production was not assessed. Data of MHR production should be found since MHR has the highest potential.

5.2.2.1 Marginal and average values

The process is not run a shorter period, but long time enough under continuous operation to let the energy system stabilize. The process may be increased in the future, but energy supply will always meet “average data demand”. That is why average electricity data has been used.

A change of energy consumption when performing a change-oriented LCA implies that marginal data will be used. In Sweden the marginal mix consists mostly of coal and fossil based energy. This means that increased energy consumption and the use of marginal data will result in a seemingly larger impact on environment. But what if the energy consumption decreases? Then the use of marginal data would result in that fossil fuel that was never really used would appear to “not be used”. That is why average data is considered to be the only relevant data in this case.

5.2.3 Improvement assessment

Since this study is mainly about assessing the potential of processing RCT into novel products, main focus of improvement assessment should be on the process.

As was illustrated in Table 17, the freeze drying operations in the process were dominant in that sense that they were both energy demanding and resource demanding (main contributor of resources is the alcohol which exits the system). Alternative process operations should be considered, and should be investigated whether it is possible to recirculate the alcohol from the freeze drying back into the system.

If the alcohol is completely recirculated it can be considered to have no environmental impact, i.e. if an infinite amount of RCT is processed then the environmental impact of producing the ethanol per processed RCT would be non-existent. Figure 24 to Figure 27 shows the process results when the freeze drying operations have been replaced with simple evaporation operations. In practice, the only difference is that aggregation energy from steam to water is used instead of sublimation energy.

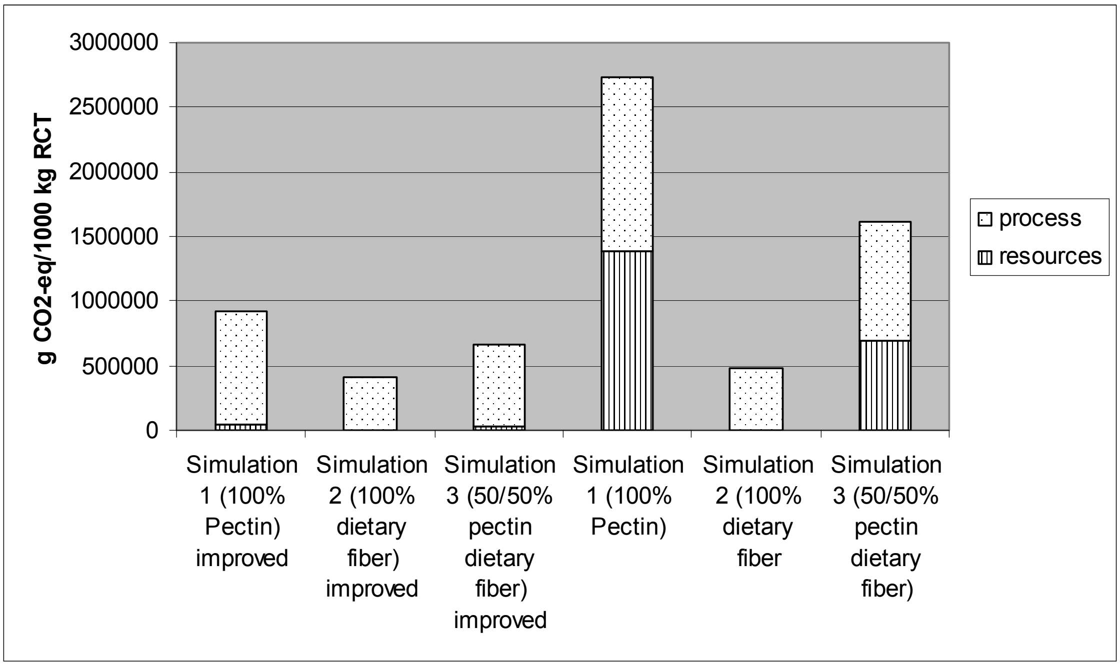

Figure 24 GWP of the process before and after improvements

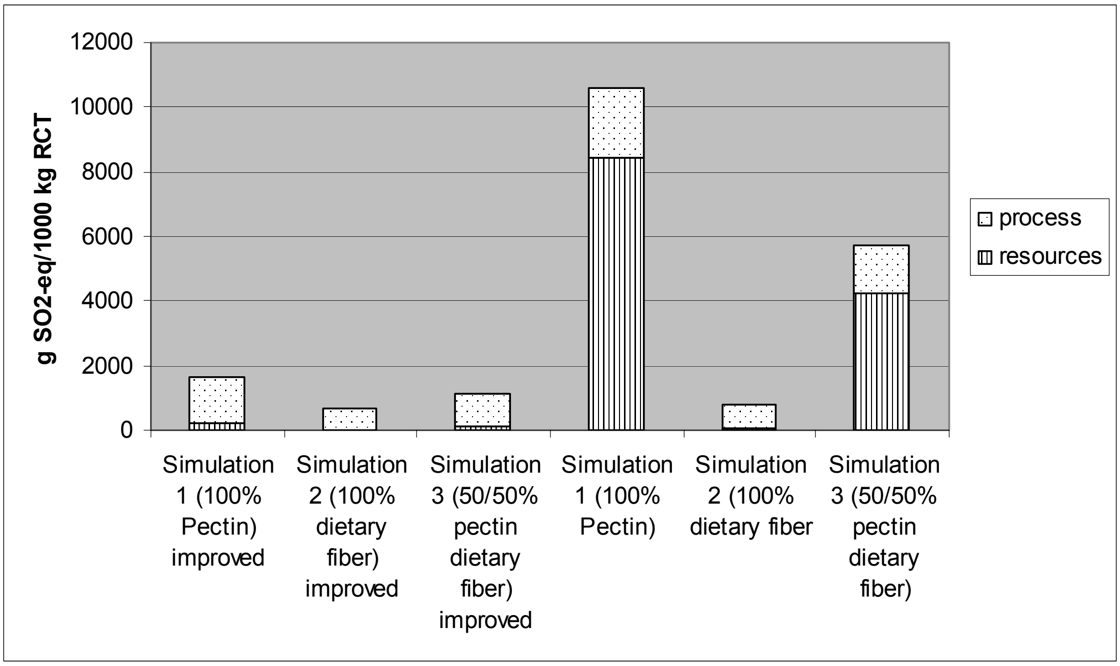

Figure 25 Acidification of the process before and after improvements

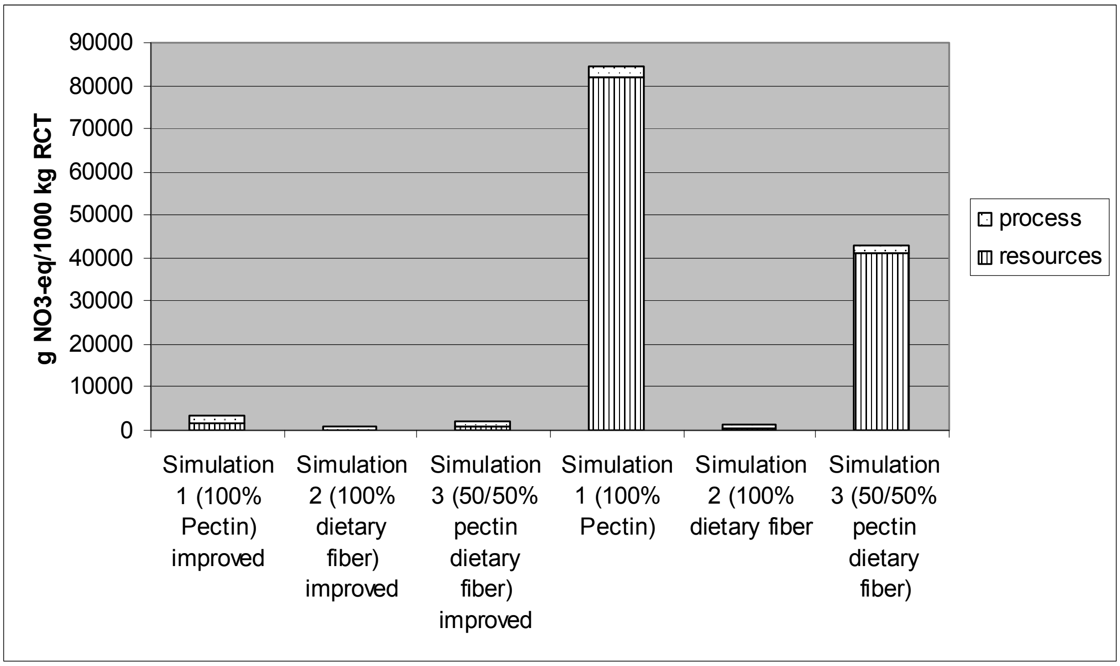

Figure 26 Eutrophication of the process before and after improvements

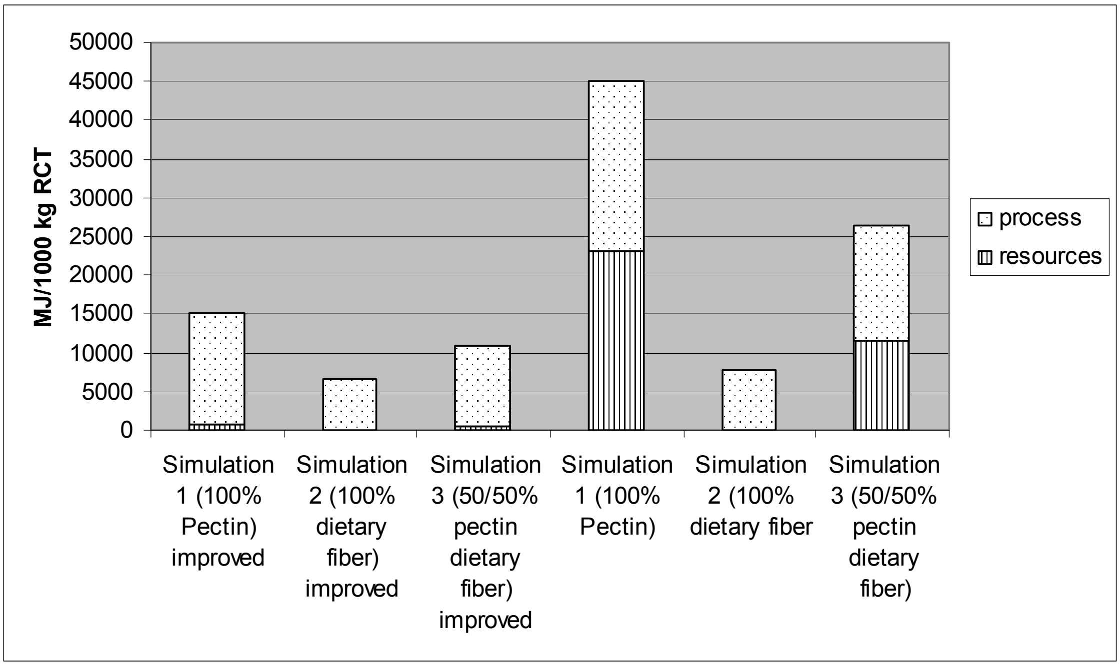

Figure 27 Primary energy of the process before and after improvements

Worth noting regarding eutrophication is that the new dominating impact comes from the enzymatic treatment of pectin flow (Figure 28). The resources that dominate the most are presented in Table 21. The chemicals dominate the most, and it is recommended to improve the chemical data quality. The freeze drying steps still dominate the other impact categories.

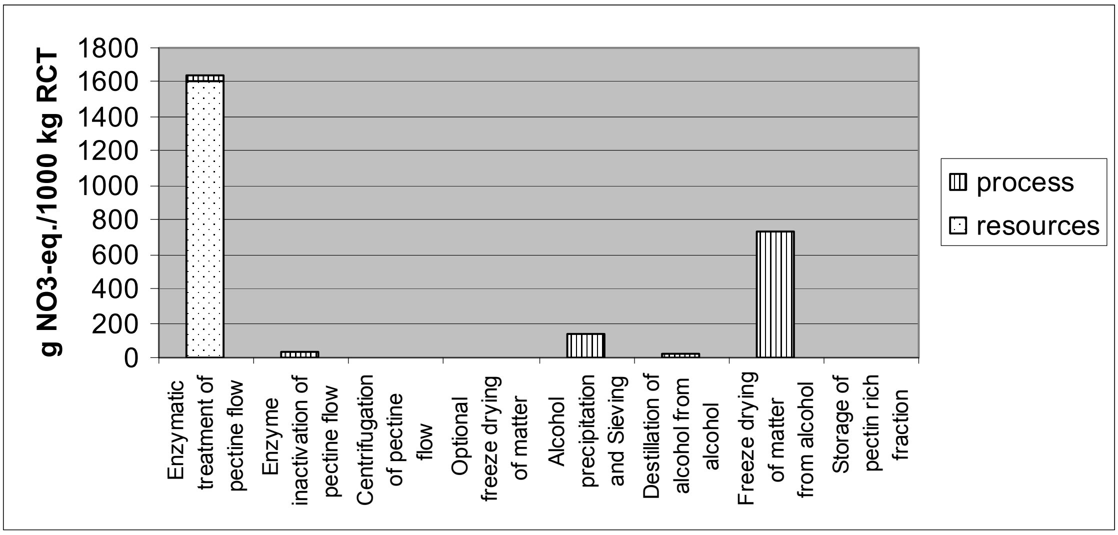

Figure 28 Eutrophication when setting the flows to 100% pectin

Table 21 The resources part of the enzyme treatment bar in Figure 29

Resource	Amount [kg resource]	Eutrophication [g NO_3-eq/kg resource]	Result [g NO_3-eq]
water	1505	0,000966	1,4541611
Cellulyve	0,19	6,95	1,3205
Neutrase	4,59	6,95	31,9005
Citric acid	9,96	59,75	595,11
Ascorbic acid	0,92	59,75	54,97
Trisodium citrate	15,316	59,75	915,131
Total			1599,886161

The scenarios with new improvements of the production process are shown in Figure 30 to Figure 33.

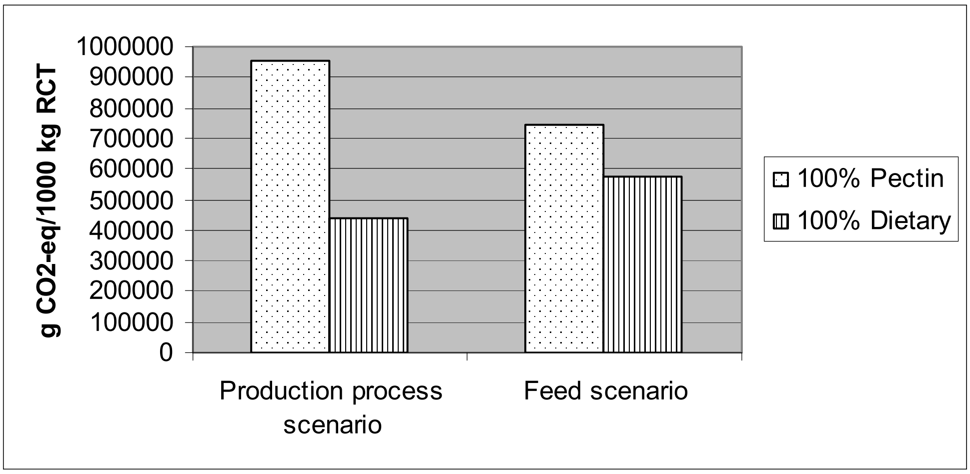

Figure 30 GWP of the scenarios with the new improvements of the production process

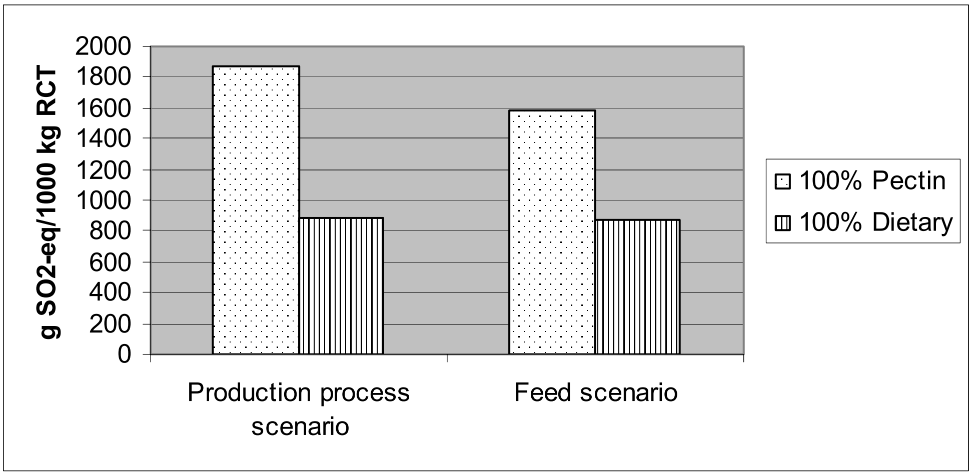

Figure 31 Acidification of the scenarios with the new improvements of the production process

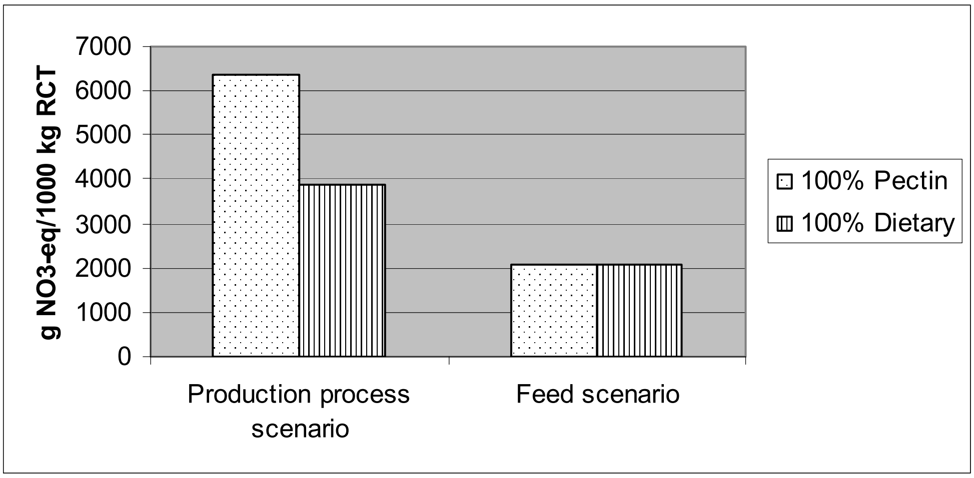

Figure 32 Eutrophication of the scenarios with the new improvements of the production process

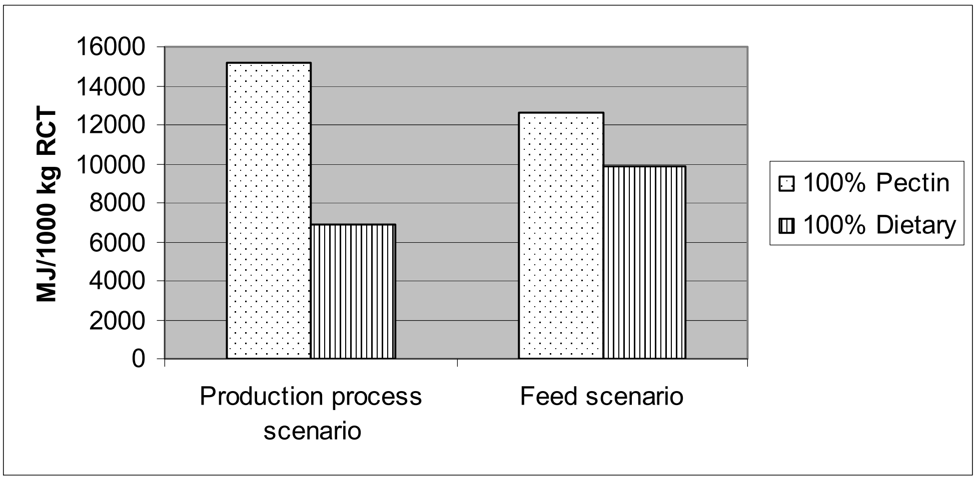

Figure 33 Primary energy of the scenarios with the new improvements of the production process

The process may prove to be beneficial to be put into operation in the future, but is now not optimized. Dietary fiber from the process is compared to the beet-pulp process, and neither beet-pulp nor RCT is considered to have any environmental impact. The difference lies in that the beet-pulp process is already put into operation, and is already in a later development stage and more optimized. From what is known from the pectin production, alcohol is used in a similar way to extract pectin. Obviously this process was deemed beneficial enough to be put into operation, and this is why more effort should be put into the optimization of the RCT process. Finally, the prerequisites of the pectin and RCT should be analyzed. The pectin process uses peels from apples etc. It is possible that apple peels contain more pectin or are easier to extract pectin from than RCT.

If electricity is replaced with natural gas whenever heating is required (electricity is seldom used for heating in industrial applications), the environmental impact is decreased further (Figure 34) and (Figure 35).

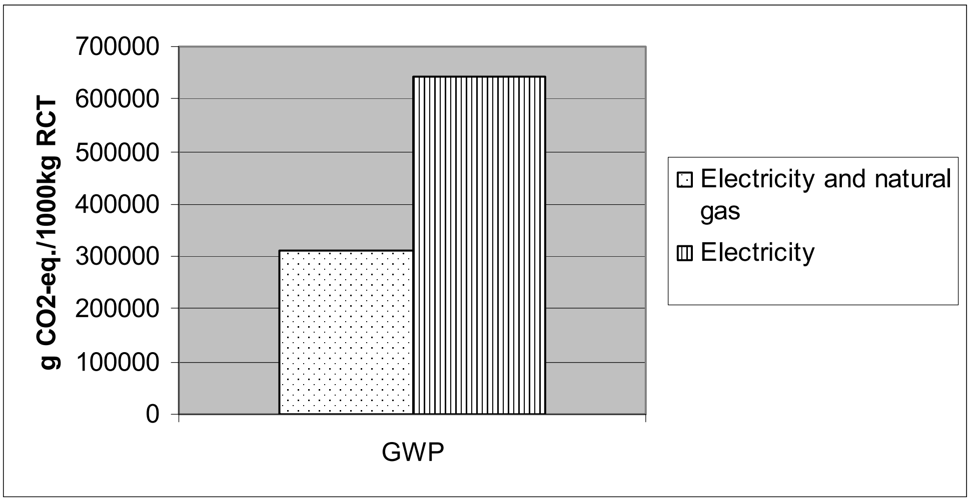

Figure 34 Primary energy consumption for the production when juice and 50% each of pectin and dietary fiber is produced

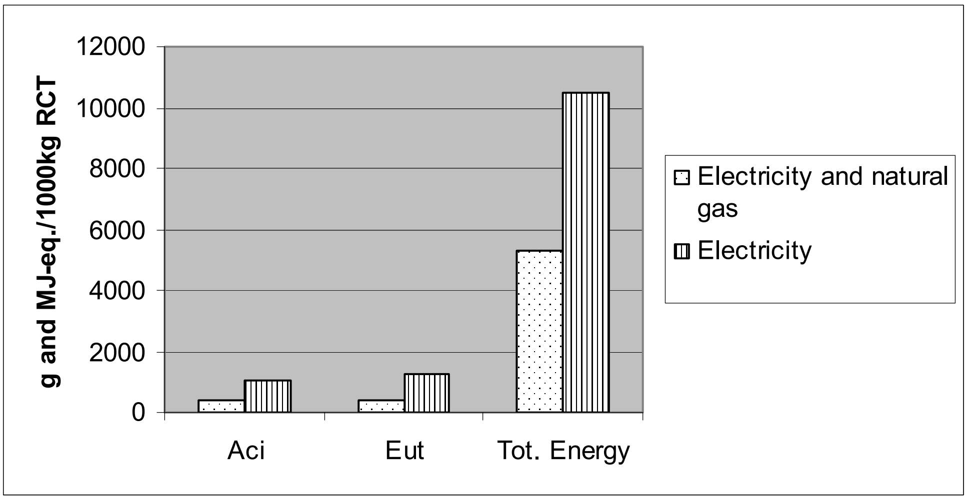

Figure 35 Primary energy consumption for the production when 50% each pectin and dietary fiber is produced

These potential improvements with gas used for heating make the process scenario more feasible (Figure 36 to Figure 37).

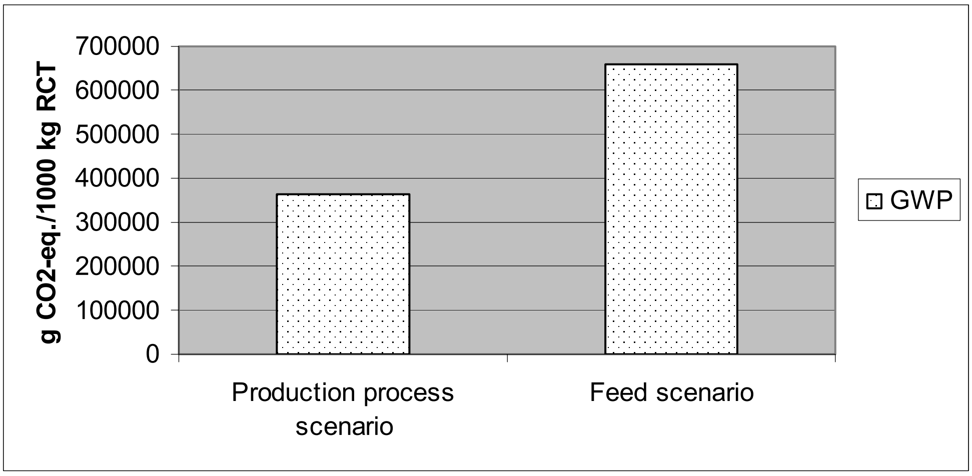

Figure 36 The production and the feed scenario when juice and 50% each of pectin and dietary fiber is produced and gas is used for heating

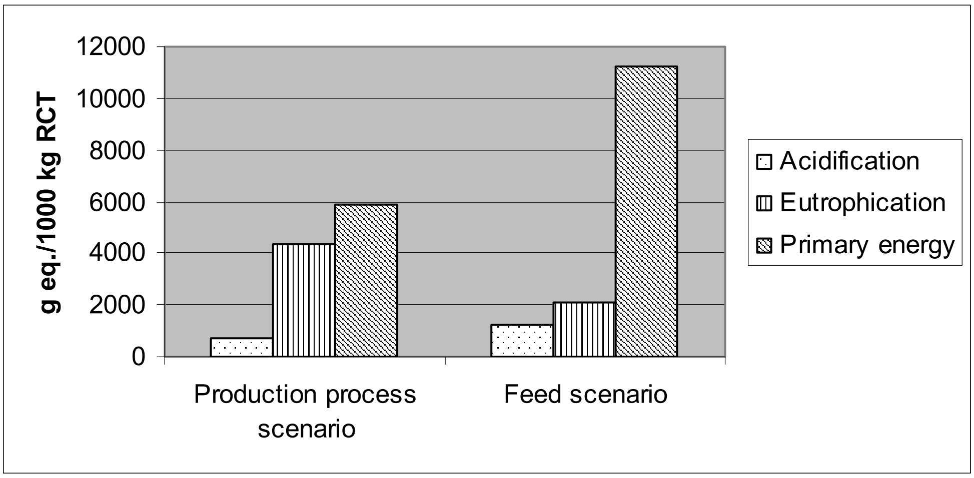

Figure 37 The production and the feed scenario when juice and 50% each of pectin and dietary fiber is produced and gas is used for heating

Considering the economical side MHR is known to have potential, while dietary fiber has the same value as the cost for composting it (Östergren, 2008). Pectin is considered to be of average worth, i.e. more than dietary fiber but less than MHR. Therefore, the alternative production impact and benefits of MHR production should be further investigated.

The relative results of the improvements of the production were considered more reliable than the results of the scenarios. This was because process data was considered to be more reliable than alternative novel products production data.

6 Conclusions

The industry producing new products from the red cabbage trimmings was modelled. The model included environmental impact assessment, as well as microbiological and economical analysis. A GUI was developed that made the model an important tool in the process development. Simulation options were possible to set by using the GUI provided features. Improvements of the production were suggested.

The models for evaluating environmental impact of the fodder production and compost facility were made.

The scenarios were designed and to make the scenarios comparable, models of the alternative production of novel products had to be made, i.e. when the RCT was not used to produce novel products these products had to be produced elsewhere. The scenarios can be used as a framework for the scenarios and should be developed further.

The environmental impact of processing RCT into novel products was compared with the other scenarios with the improvements it showed future potential. The suggested improvements in the discussion may be seen as a best case scenario, but it is possible that even more enhancements are reasonable. The results presented in section 4 are the results from the simulations based on the goal and scope and can be seen as the worst-case scenario.

The aim of this work was to evaluate potential environmental benefits of utilizing the red cabbage trimmings as high value food compounds or ingredients, compared to treating it as waste or fodder.

The potential environmental benefits of utilizing red cabbage as high value food compounds or ingredients, compared to treating it as fodder is considered to be promising. This work and the scenario analysis that has been carried out should be considered as a framework or a methodology that can be used to further evaluate potential.

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Appendix A

Input data for the production process model

The following tables present the input data to the process model. Each table represents one of the data categories used in the model.

Environmental impact data

	GWP-100	Acidification	Eutrophication	Total energy
Electricity, W. European system (g eq./MJ)	135	0.68	0.35	3.2
Electricity, S. European system (g eq./MJ)	135	1.9	0.72	3.08
Electricity, N. European system (g eq./MJ)	3	0.01	0.01	1.34
Electricity, The Netherlands system (g eq./MJ)	194.46	0.31	0.37	3.17
Natural gas (g eq./MJ)	67.9	0.0567	0.0591	1.19
Transport, local, 28 tonnes (g eq./(km*tonnes))	0.324	0.00156	0.00252	0.00375
Water (g eq./kg)	0.301553	0.00143183	0.00096622	0.0062224
Ethanol (Transport from Sweden included 800 km) (g eq./kg)	1003.5	6.158	60.2	16.8
Citric acid, sodium citrate, ascorbic acid (Transport from Germany included 400 km) (g eq./kg)	963.14	5.87	59.75	16.11
Isopropanol (isopropanol from Germany included) (g eq./kg)	1792.57	11.54	8.25	62.81
Enzymes (Transport excluded because of small amounts) (g eq./kg)	4940	15.8	6.95	61.2

Red cabbage

Initial amount RCT [kg]	1000
Initial dry matter content [%]	8.8
Initial uronic acids [g/kg]	98
Initial neutral sugars [g/kg]	503
Initial anthocyanins [g/kg]	5.4
Initial glucosinates [g/kg]	12.3

Costs

Electricity [€/kWh]	0.12
Transport [€/km]	0.0304
Transport fixed [€/kg]	0.0024
Water [€/m^3]	1.5
Ethanol [€/kg]	0.6
Isopropanol [€/kg]	1
Citric acid [€/kg]	1.65
Tri sodium citrate [€/kg]	2
Ascorbic acid [€/kg]	2.18
Neutrase [€/kg]	14
Cellulyve [€/kg]	42.50
Rapsidase [€/kg]	9

Enzymes

Neutrase [kg/kg drymatter process flow]	0.12
Cellulyve [g/kg drymatter process flow]	5
Rapsidase [g/kg drymatter process flow]	10

Chemicals

Citric acid per amount buffer; Pectin flow [g/kg]	13
Tri sodium citrate per amount buffer; Pectin flow [g/kg]	20
Ascorbic acid; Pectin flow [g/kg]	0.6
Citric acid per amount buffer; MHR flow [g/kg]	6
Tri sodium citrate per amount buffer; MHR flow [g/kg]	6
Ascorbic acid; MHR flow [g/kg]	0.6

Microbiology

Initial concentration of bacteria in RCT [cfu/g]	10000
Initial concentration in water [cfu/g]	0.1
D_{90} [minutes]	20
Temperature related to D_{90} [°C]	90
Z [°C]	13
B	0.00076
C	1571.5
T_{min} at maximum growth rate [°C]	0.036
T_{min} in lag phase [°C]	3.275

Output data from the production process model

Table 22 Amounts of products and valuable components produced when Z is set to 100%

	Pectin	**MHR**	**Dietary fiber**	**Phytochemical juice**
Total weight [kg]	9,335528	0	0	645,5931
Dry matter content [%]	0,94	0	0	7,7
Uronic acids [kg]	22,07538	0	0	20,58
Neutral sugars [kg]	16,5087	0	0	316,89
Anthocyanins [kg]	0	0	0	2,349
Glucosinates [kg]	0	0	0	11,07

Table 23 Amounts of products and valuable components produced when X is set to 100%

	Pectin	MHR	Dietary fiber	Phytochemical juice
Total weight [kg]	0	0	39,88472	645,5931
Dry matter content [%]	0	0	96	7,7
Uronic acids [kg]	0	0	77,42	20,58
Neutral sugars [kg]	0	0	186,11	316,89
Anthocyanins [kg]	0	0	0,108	2,349
Glucosinates [kg]	0	0	0,615	11,07

Table 24 Amounts of products and valuable components produced when X is set to 50% and Z is set to 50%

	Pectin	MHR	Dietary fiber	Phytochemical juice
Total weight [kg]	4,667764	0	19,94236	645,5931
Dry matter content [%]	0,94	0	96	7,7
Uronic acids [kg]	11,03769	0	38,71	20,58
Neutral sugars [kg]	8,254351	0	93,055	316,89
Anthocyanins [kg]	0	0	0,054	2,349
Glucosinates [kg]	0	0	0,3075	11,07

Process scenario description

Model description

The model is made in Simulink, Matlab and uses embedded Matlab.

The process block called “inputdata for process” is defined as the first process unit. It is not a real process unit, but the block in which all input data to the model is stored. Data is stored in the following categories:

- Red cabbage; The initial weight, dry matter concentration and valuable components is stored.
- Microbiological activity; The initial amount of bacteria, constants to growth and reduction functions, choice if they are persistent to alcohol etc. is stored.
- Costs; Costs of all chemicals, enzymes, energy etc. is stored.
- Environmental impact; Environmental of all chemicals, enzymes, energy etc. is stored.
- Energy system; Choice of electricity grid is stored (The Netherlands, Western Europe, Northern Europe, Southern Europe), if an alternative energy source is used and what type it is (Natural gas, wood chips etc.).
- Enzyme amounts; The amounts of enzyme per weight of mass flow in the model are set.
- Chemicals; Here the choice between ethanol and isopropanol is stored.

The input data is added to a matlab structure called globalData, after that globalData has been declared. Data in globalData are general for the whole process and sent from process unit to process unit. The other structure processData contains more specific data concerning the process units in the process. In “inputdata for process” processData is declared, and then copied to processDataOut. ProcessData is thought to be data from previous process unit, and processDataOut is representing actual process data for current process unit. Since “inputdata for process” is the first process unit, processData is not used. Initial amount of RCT, initial amount of valuable components etc. is stored in processDataOut. ProcessDataOut is then renamed to a name specific for that process unit and is sent to the output port of that process unit. Then the process data is sent to the input port of the next process unit, AND sent to Matlab workspace for later use. In the next process unit, the input process data is stored as processData and copied to processDataOut, which is then set to zero. Fields belonging to ProcessDataOut is then used to store data for this process and so on.

When the model has been simulated, Simulink calls a Matlab function called fpost that takes all previously stored copies of processDataOut and globalData as input arguments. Then fpost calls other functions that calculate costs, environmental impact, concentrations, losses etc. and store the data in a new, bigger structure. This structure is called DFP (data for process), and is a vector which elements contain structures equal to the structure processData. Then plot functions are called, which plot the results in Matlab figure windows. Finally all data are put into an excel chart.

Description of model functions used by the process model

The model uses some functions in order to calculate heating, freeze and mixing energy. It also uses a function that calculates microbiological activity.

Tank heating/cooling and mixing function

The function fsetTankEnergy returns the required energy in kWh, and takes eight input arguments (Table 25).

Table 25 Input arguments to the function

(1) Total weight (kg)
(2) Time (minutes)
(3) Start temperature (˚C)
(4) End temperature (˚C)
(5) Power number (PBT)
(6) RPM (rounds/minute)
(7) Mixing (Boolean)
(8) Temperature change (Boolean)

In the functions there are some constant basic assumptions (Table 26).

Table 26 Basic assumptions regarding dimensions, temperatures etc.

(9) Relation between inner diameter and height	1.085184 (Di/h)
(10) Relation between inner diameter and mixer diameter	10/24 (Dm/Di)
(11) Room temperature or outside temperature	20 (˚C)
(12) Density of total weight	1000 (kg/m^3)
(13) Maximum volume of a tank	1 (m^3)
(14) Losses depending on tank insulation	15 (W/ m^3/°C)
(15) Specific heat capacity of matter	4200 (J/kg/°C)

Since a tank has a maximum size, the number of tanks used will be dependent on how much input weight or volume that is to be processed. The required tank size is then calculated by dividing the matter volume with the number of tanks.
Then tank dimensions are calculated, followed by the energy calculations depending on how (7) and (8) are set:

$$energylosses = (6) \cdot (outerarea) \cdot abs((4) - (11)) \cdot (2)$$

$$tempenergy = (15) \cdot volume \cdot (12) \cdot abs((4) - (11))$$

$$totalenergy = \frac{((energylosses + tempenergy) \cdot numberof\tan ks)}{1000 \cdot 3600}$$

$$mixingenergy = \left(\frac{\left(\left((5) \cdot (12) \cdot \frac{(6)^3}{60} \cdot Dm^5 \right) \cdot (2) \right)}{1000} \right) \cdot numberof\tan ks$$

Then the sum of the calculated energies is returned (Östergren, 2008).

Freeze room function

The function works similar to the tank function, i.e. there are some inputs (Table 27), and some assumptions regarding density and specific heat capacity (Table 28). Then the freeze room volume is calculated to estimate capacity, and outer area is calculated in order to estimate losses (Östergren, 2008).

Table 27 Input arguments to the function.

(1) Wet matter weight (kg)
(2) Total weight (kg)
(3) Type of stabilization method: Freezing or steam blanching (Boolean)
(4) Time (days)
(5) Start temperature (˚C)
(6) End temperature (˚C)

Table 28 Assumptions related to the function regarding dimensions, temperatures etc.

(7) Relation between inner diameter and height	1.085184 (Di/h)
(8) Relation between inner diameter and mixer diameter	10/24 (Dm/Di)
(9) Room temperature or outside temperature	20 (°C)
(10) Density of total weight	1000 (kg/m^3)
(11) Maximum volume of a tank	1 (m^3)
(12) Losses depending on freeze room insulation	0.15 (W/ m^3/°C)
(13) Specific melting energy of matter	334 (kJ/kg)
(14) Specific heat capacity for solid state of matter	2 (J/kg/°C)
(15) Specific heat capacity of water	4200 (J/kg/°C)
(16) Efficiency	0.6

Energy for cooling and freezing the wet matter:

$$w_{coolingfreezing} = (1) \cdot ((15) \cdot ((5) - 0) + (13) + (14) \cdot (0 - (6)))$$

Energy losses:

$$w_{losses} = outerarea \cdot (12) \cdot ((9) - (6))$$

Allocation:

$$w_{Allocation} = \frac{\frac{(1)}{roomcapacity} \cdot w_{losses} \cdot (4) \cdot 24 \cdot 3600}{1000}$$

Sum of energies that are added to the process, transformed to kWh:

$$w_{Addedenergy} = \frac{(w_{coolingfreezing} + w_{Allocation})}{(16) \cdot 3600} \cdot 1.1$$

Centrifugation function

The centrifugation model is represented by a linear function:

$$E^P_{i,Z,EI} = P^F \cdot m_{su} \cdot t_F + (P^O + P^{Pu}) \cdot t_O - 0.2 \cdot P^{Br} \cdot m_{So} \cdot t_{Br}$$

$E^P_{i,Z,EI}$ is the total production dependent electricity consumption of a centrifuge, P^F is the power required for the feed in kW/t suspension, m_{Su} is the suspension in tons per batch, t_F is the feed time in s, P^O is the power consumption during operation in kW, P^{Pu} is the power consumption of the pumps in kW, t_O is the operation time in s, P^{Br} is the break power in kW/t solids, m_{So} is the mass of solids in tons per batch, and t_{Br} is the breaking time in s (Bieler, 2004).

The total weight that enters the centrifuge is used to set m_{Su}, and the total weight of the solid phase is used to set m_{So}. The rest of the variables are constant, and data on centrifuge definition is from (REPRO, 2008) in Table 29.

Table 29 Constants regarding the centrifugation function.

P^F	0.75
t_F	30
P^O	15
P^{Pu}	2
t_O	600
P^{Br}	1.8
t_{Br}	120

Distillation function

The distillation function uses the variables in Table 30, and the characteristics of it are depending on the desired output alcohol concentration.

Table 30 Input arguments, constants and output arguments of the distillation function

Mass fraction alcohol in	*Xf*
Mass fraction alcohol distilled	*Xt*
Mass fraction alcohol undistilled	*Xb*
Reflux (Recondensation)	0.6
Distillation energy for ethanol (kJ/kg)	838
Distillation energy for water (kJ/kg)	2424
Total flow that enters distillation tower	*F*
Total flow that leaves top of distillation tower	*D*
Total flow that leaves bottom of distillation tower	*W*

Mass balance gives:

$$D + W = F$$

and

$$W = F \cdot \frac{X_f - X_t}{X_b - X_t}$$

Then, *D* can easily be calculated.

The reflux and the specific heat capacity variables are set differently depending on which alcohol that is distilled.

$$w = D \cdot (reflux + 1)\frac{(1 - X_t) \cdot 2424 + X_t \cdot 838}{3600},$$

where *w* is the energy in kWh (Östergren, 2008).

Micro biology function

The bacterium that was modeled was Bacillus cereus, and the growth and reduction functions were given by (REPRO, 2008). The function can be called several times in each process unit, and the user defines if there will be growth or a reduction of bacteria. It can also be set whether the bacteria are resistant to alcohol or not. It can also be set if the bacteria will have a lag phase. A lag phase is when the bacteria are passive and no growth occurs. Every time that the function is called the actual amount of bacteria, the lag time that is left, the time and the interval, the start and the temperatures are used as an input arguments. All temperature shifts are assumed to be linear in relation to time, and the time interval decides how accurate the temperatures samples will be (Figure 38).

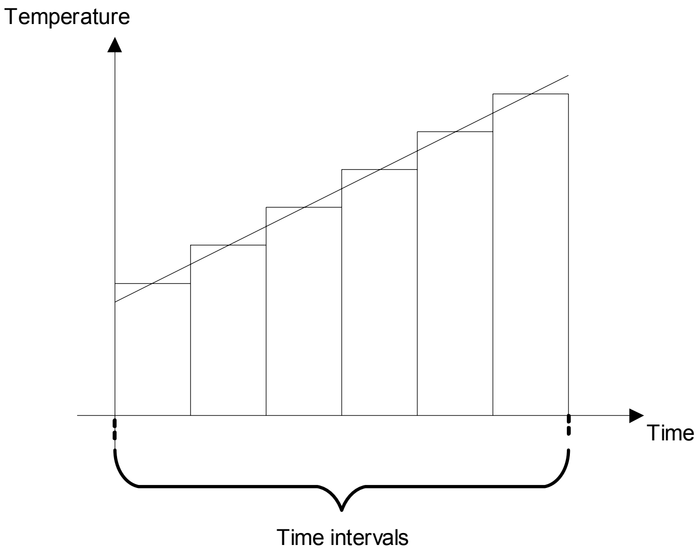


Figure 38 Approximation of temperature under a period of time

Growth

$$N_t = N_0 \cdot e^{\mu(t-\lambda)},$$

where N_t is the number of cfus (cfu; colonial forming unit) by the time t, N_0 is the initial amount of cfus, μ is the maximum growth rate and given by

$$\mu = b(T - T_{\min})^2$$

and λ is the lag phase and given by

$$\lambda = \frac{c}{(T - T_{\min})}.$$

If $N_t > 10^8$ cells/ml growth is halted.

Reduction

$$N_t = N_0 \cdot 10^{-\frac{t}{D_T}},$$

where N_t is the number of cfus (cfu; colonial forming unit) by the time t, N_0 is the initial amount of cfus and $D_T = D_1$ is the reduction rate, given by

$$T_2 = T_1 - Z \cdot \log\left(\frac{D_2}{D_1}\right)$$ where $D_2 = D_{90}$ (reduction time at T_2 = 90 °C)

A 6 to 8 log reduction if the ethanol concentration is > 70% can be set.

Description of process units

Each process unit gets input data from process before (the structures processData and globalData) and from the GUI. Since there are three sets of variables in processData used to keep track of weights, one has to be certain of what set or sets that are used in the current and the previous step. Depending on what phase a flow in a process unit is defined as, regular, solid or liquid, a different set of variables will be used. The sets store information of dry matter, wet matter, water, alcohol, dry matter content and total weight. For example, the milling unit uses the regular set for input and output, and the extraction step uses the regular set for input and generates both a liquid and a solid phase. Thus, both the solid and the liquid set are used for output. In the GUI, each process unit has a user input data window. All units have some types of user input data in common:

- Losses, in percent of output mass.
- Recovery of valuable components, in percentage of input valuable components. The recovery of each of the valuable components can be set.
- Microbiological status can be set to no activity, growth or reduction. Depending on how the status is set the, following variables will be used differently.
    - Post process storage time, is used only for calculating bacterial activity.
    - Post process storage temperature, is used for the same reasons as Post process storage time.
    - MO contamination is the possible contamination of the same bacteria. The value is added to current amount of bacteria before current process data is calculated.
    - MO lag is used for setting a lag time, i.e. the time before any growth occurs.

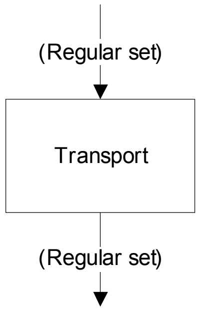
In most cases where both a liquid and a solid phase occur, there will be a set of user input data for each phase. One general exception is microbiological activity. In some process units there are losses independent of parameters from the user input data window, mainly in the freeze drying processes where wet matter exits the process, and in centrifugation of MHR where the solid residue goes to waste.

The figures below represent the process units. The tables represent variables that are only valid for the process unit and that can be set by the user. They are not referred to in the text.

Main flow

Transport

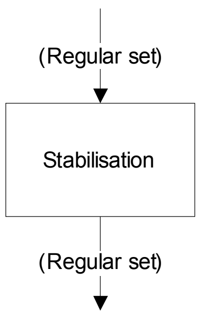
The material is transported from the farm to the location of the process.



Product loss, (%)	0
Transport time, (minutes)	60
Transport temperature, (˚C)	0
Distance, (km)	50
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	100
Glucosinates recovery, (%)	100
Microbiological status	Growth
Post process storage time, (min)	30
Post process storage temperature, (˚C)	20
Microbiological contamination, (cfu)	0
Microbiological lag	No

Stabilization

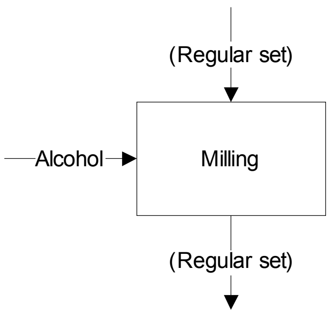
In stabilization, there are three options: The RCT can be either frozen, freeze dried or steam blanched for a period of time. Depending on choice of stabilization method, the valuable compounds degenerate more or less.



Type of stabilization method	Freezing
Product loss, (%)	0
Stabilisation time, (days)	42
Transport temperature, (˚C)	0
Start temperature, (˚C)	50
End temperature, (˚C)	
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	100
Glucosinates recovery, (%)	100
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Milling

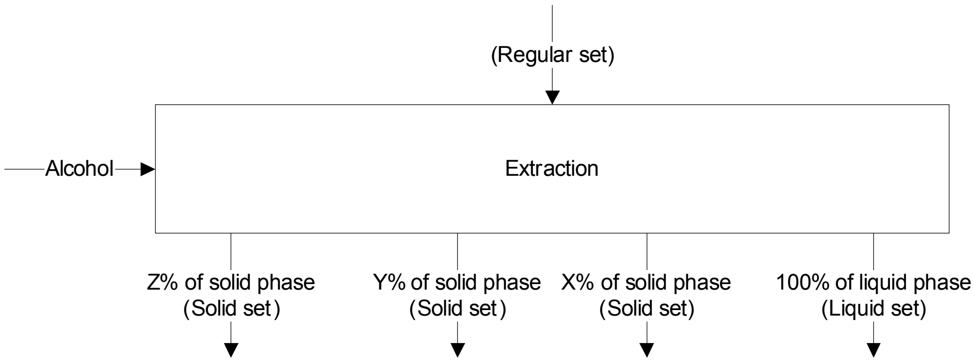
Meanwhile the RCT are milled, alcohol solution is added until the slurry concentration is 70% of alcohol.



Product loss, (%)	0
Capacity, (kg/h)	100
Start temperature, (˚C)	-20
End temperature, (˚C)	-3
Electric power, (kW)	8.8
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	100
Glucosinates recovery, (%)	100
Microbiological status	No activity
Organism resistance to alcohol	No
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Alcohol extraction

The slurry is filtrated in three steps. After the first filtration the liquid phase is put to the side and more alcohol is added to the solid phase. It is then filtrated again and more alcohol is added to the solid phase. After the last filtration, liquid phases from all of the three steps are sent to distillation. The solid phase is sent to processing of either dietary fiber, MHR or pectin, depending on how the proportion of the three flows is set.

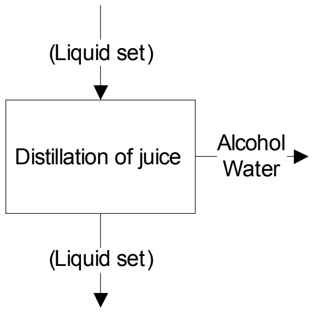


Product loss, (%)	0
Temperature step 1, (˚C)	-3
Temperature step 2, (˚C)	20
Temperature step 3, (˚C)	20
RPM, (rounds per minute)	50
Power number, (PBT)	1.2
Mixing time per step, (minutes/step)	15
Uronic acids recovery in liquid phase, (%)	21
Neutral sugars recovery in liquid phase, (%)	63
Anthocyanins recovery in liquid phase, (%)	50
Glucosinates recovery in liquid phase, (%)	90
Uronic acids recovery in solid phase, (%)	79
Neutral sugars recovery in solid phase, (%)	37
Anthocyanins recovery in solid phase, (%)	2
Glucosinates recovery in solid phase, (%)	5
Microbiological status	No activity
Organism resistance to alcohol	No
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Juice flow

Distillation of juice

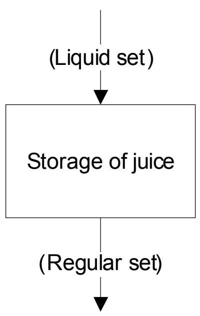
The juice is heated, depressurized and distilled. There is a possibility to evaporate the product to lower water content as well as evaporate the remaining alcohol.



Product loss, (%)	0
Time, (minutes)	0
Start temperature, (˚C)	20
End temperature, (˚C)	35
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	87
Glucosinates recovery, (%)	100
Evaporate water	No
Dry matter content of juice, (%)	7.7
Microbiological status	No activity
Organism resistance to alcohol	No
Post process storage time, (min)	0
Post process storage temperature, (˚C)	35
Microbiological contamination, (cfu)	0
Microbiological lag	No

Storage of juice

The juice is cooled and then stored.

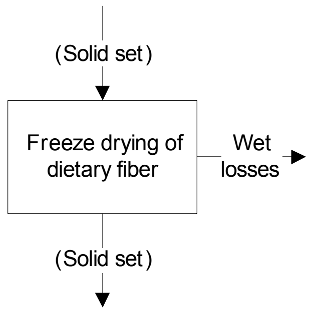


Product loss, (%)	0
Storage time, (days)	14
Start temperature, (˚C)	35
Storage temperature, (˚C)	4
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	100
Glucosinates recovery, (%)	100
Microbiological status	Growth
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Dietary fiber flow

Freeze drying of dietary fiber

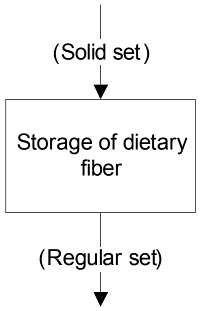
The solid phase from the extraction is first frozen and then the water and the alcohol are sublimated under low pressure.



Product loss, (%)	0
Operating time, (minutes)	480
Start temperature, (˚C)	20
End temperature, (˚C)	-20
Dry matter content, (%)	96
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	100
Glucosinates recovery, (%)	100
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Storage of dietary fiber

Because of its low water activity this product does not to be stored at a low temperature.

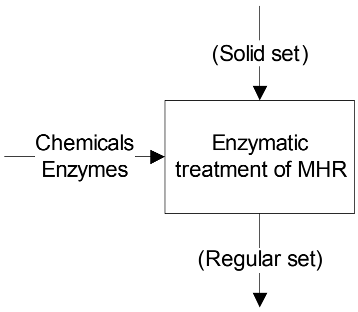


Product loss, (%)	0
Storage time, (days)	60
Storage temperature, (˚C)	20
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	100
Glucosinates recovery, (%)	100
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

MHR flow

Enzymatic treatment, MHR

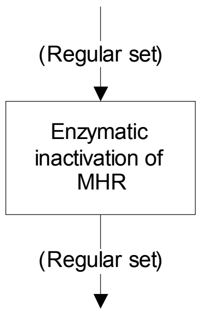
A buffer of citric acid, tri sodium citrate and ascorbic acid is prepared. The solid residue from the extraction is then diluted with the buffer. Then the slurry is heated, and a pectinase enzyme is added under constant stirring.



Product loss, (%)	0
Start temperature, (˚C)	20
End temperature, (˚C)	50
RPM, (rounds per minute)	50
Power number, (PBT)	1.2
Mixing time, (minutes)	240
Uronic acids recovery, (%)	94
Neutral sugars recovery, (%)	115
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Enzyme inactivation, MHR

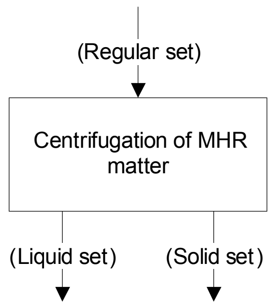
The slurry is heated and stirred for a period of time.



Product loss, (%)	0
Start temperature, (˚C)	50
End temperature, (˚C)	90
RPM, (rounds per minute)	50
Power number, (PBT)	1.2
Mixing time, (minutes)	30
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	Death
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Centrifugation, MHR

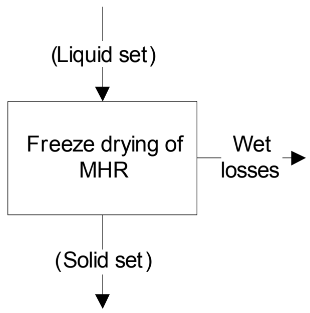
The slurry is then separated into a solid and a supernatant. The solid is considered as waste and will not be processed further.



Product loss, (%)	0
Operating time, (minutes)	10
Operating temperature, (˚C)	90
Uronic acids recovery in liquid phase, (%)	70
Neutral sugars recovery in liquid phase, (%)	64
Anthocyanins recovery in liquid phase, (%)	0
Glucosinates recovery in liquid phase, (%)	0
Uronic acids recovery in solid phase, (%)	30
Neutral sugars recovery in solid phase, (%)	36
Anthocyanins recovery in solid phase, (%)	0
Glucosinates recovery in solid phase, (%)	0
Microbiological status	Death
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Freeze drying of MHR

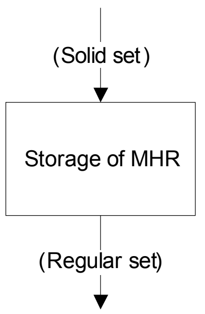
This process unit is similar to the previous freeze drying, except for that it is slightly more energy consuming because of the matters higher water content.



Product loss, (%)	0
Operating time, (minutes)	480
Start temperature, (˚C)	40
End temperature, (˚C)	-20
Dry matter content, (%)	94
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Storage of MHR

The MHR is stored at room temperature, due to low water activity.

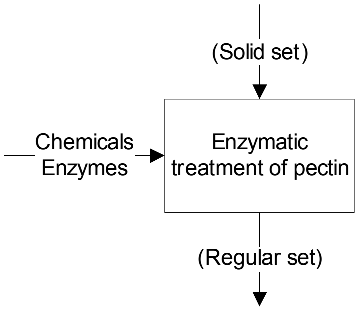


Product loss, (%)	0
Storage time, (days)	60
Storage temperature, (˚C)	20
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Pectin flow

Enzymatic treatment of Pectin flow

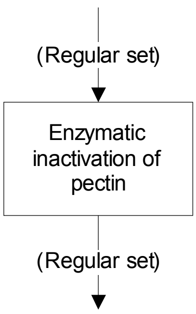
A buffer of citric acid, tri sodium citrate and ascorbic acid is prepared. The solid residue from the extraction is then diluted with the buffer. Then the slurry is heated, and protease and cellulase is added under constant stirring. For protease, Neutrace is used, and for cellulase Cellulyve is used.



Product loss, (%)	0
Start temperature, (˚C)	20
End temperature, (˚C)	50
RPM, (rounds per minute)	50
Power number, (PBT)	1.2
Mixing time, (minutes)	240
Uronic acids recovery, (%)	73
Neutral sugars recovery, (%)	88
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Enzyme inactivation of pectin flow

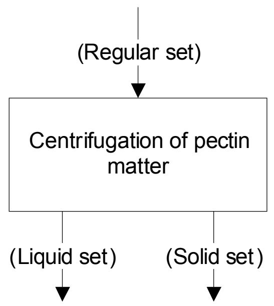
The slurry is heated and stirred for a period of time.



Product loss, (%)	0
Start temperature, (˚C)	50
End temperature, (˚C)	90
RPM, (rounds per minute)	50
Power number, (PBT)	1.2
Mixing time, (minutes)	30
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	Death
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Centrifugation of pectin flow

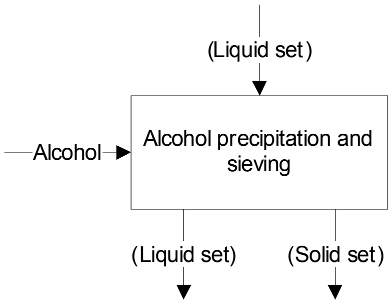
The slurry is then separated into a solid and a supernatant. The solid phase can be processed further, as feed to the MHR flow, and the liquid residue will continue as the main flow.



Product loss, (%)	0
Operating time, (minutes)	10
Operating temperature, (˚C)	90
Process solid residue as MHR	Yes
Uronic acids recovery in liquid phase, (%)	42
Neutral sugars recovery in liquid phase, (%)	24
Anthocyanins recovery in liquid phase, (%)	0
Glucosinates recovery in liquid phase, (%)	0
Uronic acids recovery in solid phase, (%)	58
Neutral sugars recovery in solid phase, (%)	76
Anthocyanins recovery in solid phase, (%)	0
Glucosinates recovery in solid phase, (%)	0
Microbiological status	Death
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Alcohol precipitation and sieving

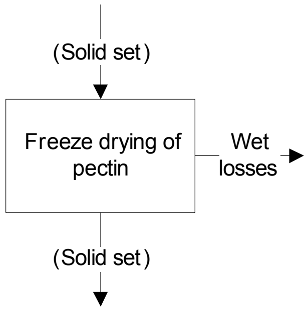
In this step the liquid phase from the centrifugation is separated into another two liquid and solid phases, under simultaneous adding of alcohol. The matter is sieved once. The output liquid phase goes to distillation, and the solid phase continues as the main flow.



Product loss, (%)	0
Start temperature, (˚C)	50
End temperature, (˚C)	4
Diameter, (m)	0.1
RPM, (rounds per minute)	50
Power number, (PBT)	1.2
Mixing time, (minutes)	1140
Uronic acids recovery in liquid phase, (%)	7
Neutral sugars recovery in liquid phase, (%)	58
Anthocyanins recovery in liquid phase, (%)	0
Glucosinates recovery in liquid phase, (%)	0
Uronic acids recovery in solid phase, (%)	93
Neutral sugars recovery in solid phase, (%)	42
Anthocyanins recovery in solid phase, (%)	0
Glucosinates recovery in solid phase, (%)	0
Microbiological status	No activity
Organism resistance to alcohol	No
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Freeze drying of pectin

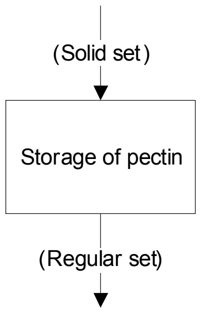
The solid matter from previous step is freeze dried, and sent to storage.



Product loss, (%)	0
Operating time, (minutes)	480
Start temperature, (˚C)	4
End temperature, (˚C)	-20
Dry matter content, (%)	94
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Storage of pectin

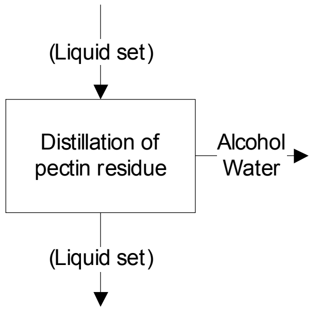
Here the material is stored at room temperature, due to low water activity.



Product loss, (%)	0
Storage time, (days)	60
Storage temperature, (˚C)	20
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Distillation of pectin residue

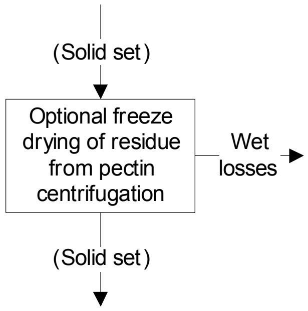
This process unit is similar to the other distillation processes.



Product loss, (%)	0
Time, (minutes)	0
Start temperature, (˚C)	4
End temperature, (˚C)	35
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	0
Glucosinates recovery, (%)	0
Microbiological status	No activity
Organism resistance to alcohol	No
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Optional freeze drying

This freeze drying is similar to the other freeze drying processes, but this one can be activated and deactivated.



Freeze-dry material	No
Product loss, (%)	0
Operating time, (minutes)	480
Start temperature, (˚C)	40
End temperature, (˚C)	-20
Dry matter content, (%)	96
Uronic acids recovery, (%)	100
Neutral sugars recovery, (%)	100
Anthocyanins recovery, (%)	100
Glucosinates recovery, (%)	100
Microbiological status	No activity
Post process storage time, (min)	0
Post process storage temperature, (˚C)	0
Microbiological contamination, (cfu)	0
Microbiological lag	No

Appendix B

Data collection of ethanol

The (Bernesson, 2004) report

The emissions data in Table 31 is obtained from table A21 in Bernessons report, and energy data is from table A22. Note that Cultivation of wheat and the fuel related operations has been excluded. Other data on cultivation of wheat are later added to the result. The energy data on steam related processes has been corrected.

Table 31 LCI results of 1 ha. Production and consumption of ethanol fuel has been excluded (Bernesson, 2004).

Production factor	CO_2 [g/ha]	CO [g/ha]	HC [g/ha]	CH_4 [g/ha]	NOx [g/ha]	SOx [g/ha]	NH_3 [g/ha]	N_2O [g/ha]	HCl [g/ha]	Particles [g/ha]	Input energy [MJ/ha]
Emissions, electricity, large-scale ethanol fermentation*	6336	14.54	2.34	39.59	12.12	10.5	0.18	0.57	0	2.02	1573.45
Emissions, steam (heat), large-scale ethanol fermentation*	4617	108.65	9.23	0.92	221.91	9.7	0	8.77	5.08	10.46	1600.56
Emissions, electricity, large-scale ethanol distillation**	3788	8.69	1.4	23.67	7.25	6.28	0.11	0.34	0	1.21	940.71
Emissions, steam (heat), large-scale ethanol distillation**	27114	638.08	54.23	5.42	1303.28	56.94	0	51.52	29.83	61.46	9399.52
Emissions, electricity, drying of distillers waste ***	10560	24.24	3.9	65.98	20.2	17.5	0.3	0.96	0	3.37	2622.42
Emissions, steam (heat), drying of distillers waste ***	31657	745	63.31	6.33	1521.66	66.48	0	60.15	34.82	71.76	10974.08
Total machinery, ethanol production, Swedish el. *	366	0.84	0.14	2.29	0.7	0.61	0.01	0.033	0	0.12	90.95
Building material, Swedish el. *	110	0.25	0.041	0.69	0.21	0.18	0.0031	0.01	0	0.035	27.39
Emissions, handling of waste water, Swedish el. *	1632	3.75	0.6	10.2	3.12	2.71	0.046	0.15	0	0.52	405.39
Emissions, production of chemicals for ethanol production *	7482	2.22	0.27	0.0032	24.5	34.9	0.1			2.37	121.07
Transport of chemicals for ethanol production *	309	0.32	0.18	0.0081	2.9	0.079		0		0.029	4.28

Transport of chemicals for ethanol production, machinery, Swedish el. *	1.4	0.0032	0.00052	0.0087	0.0027	0.0023	0.000039	0.00013	0	0.00045	0.35
Transport of wheat to ethanol production *	40292	40.2	23.19	1.06	379.18	10.32		0		3.82	558.33
Transport of wheat to ethanol production, machinery, Swedish el. *	150	0.34	0.056	0.94	0.29	0.25	0.0042	0.014	0	0.048	37.31
Transport of distiller's waste from ethanol production ***	9632	9	5.43	0.25	92.04	2.47		0		0.92	133.47
Transport of distiller's waste from ethanol production, machinery, Swedish el. ***	29	0.066	0.011	0.18	0.055	0.048	0.0008	0.0026	0	0.0091	7.13
Total; ethanol fermentation - transport of distiller's waste from ethanol production (0)	144075	1596.19	164.33	157.54	3589.42	218.97	0.75	122.52	69.73	158.15	28496.41

The production of wheat was 5900 kg/ha, and the production of ethanol was 0.296 kg ethanol/kg wheat. Data from bottom of Table 31 calculated to represent the emissions of 1 kg wheat are presented in Table 32.

Table 32 LCI results of producing 1 kg wheat. Cultivation of wheat is excluded.

[kg wheat]	CO_2 [g/kg]	CO [g/kg]	HC [g/kg]	CH_4 [g/kg]	NOx [g/kg]	SOx [g/kg]	NH_3 [g/kg]	N_2O [g/kg]	HCl [g/kg]	Particles [g/kg]	Input energy [MJ/kg]
Total; ethanol fermentation - transport of distiller's waste from ethanol production	24.41956	0.2705	0.02785	0.0267	0.60838	0.03711	0.000128	0.02077	0.012	0.02681	4.8299

Then environmental impacts were calculated by using the weights from (Ecoinvent, 2003), and are presented in Table 33.

Table 33 Environmental impact data on the production of 1 kg ethanol. Cultivation of wheat is excluded.

	GWP g CO_2 / kg wheat	Acidification g SO_2 / kg wheat	Eutrophication g NO_3 / kg wheat	Primary energy MJ/kg wheat
Total; ethanol fermentation - transport of distiller's waste from ethanol production	31.80508882	0.473617266	0.821772705	4.8299

In Table 34 the cultivation data from Table 3 are added. The data represents 1 kg ethanol.

Table 34 Environmental impact data on the production of 1 kg ethanol.

	GWP g CO_2 / kg ethanol	Acidification g SO_2 / kg ethanol	Eutrophication g NO_3 / kg ethanol	Primary energy MJ/kg ethanol
Total; Cultivation of winter wheat - transport of distiller's waste from ethanol production	1517.717034	9.184435911	97.53494016	25.37543455

After that, physical allocation is used to partition impact between the distiller's waste and the ethanol (For ethanol, the lower heat value of ethanol fuel is used). Transport impact is also added (Table 35).

Table 35 Environmental impact of producing 1 kg ethanol when physical allocation is used.

	GWP g CO_2 / kg ethanol	Acidification g SO_2 / kg ethanol	Eutrophication g NO_3 / kg ethanol	Primary energy MJ/kg ethanol
Total; Cultivation of winter wheat - transport of ethanol to consumer	1003.514357	6.158089034	60.19621962	16.7999122

Process production results

GWP	Simulation 1 (100% Pectin)	Simulation 2 (100% dietary fiber)	Simulation 3 (50/50% pectin dietary fiber)
resources	1386663	5807.603	696235.4
process	1347946	474136.8	911041.6
Sum	2734610	479944.4	1607277
Acidification	**Simulation 1 (100% Pectin)**	**Simulation 2 (100% dietary fiber**	**Simulation 3 (50/50% pectin dietary fiber)**
resources	8438.047	35.55095	4236.799
process	2148.84	755.8491	1452.344
Sum	10586.89	791.4001	5689.143
Eutrophication	**Simulation 1 (100% Pectin)**	**Simulation 2 (100% dietary fiber**	**Simulation 3 (50/50% pectin dietary fiber)**
resources	81823.12	344.8178	41083.97
process	2564.744	902.1425	1733.443
Sum	84387.86	1246.96	42817.41
Primary energy	**Simulation 1 (100% Pectin)**	**Simulation 2 (100% dietary fiber**	**Simulation 3 (50/50% pectin dietary fiber)**
resources	23113.41	97.4729	11605.44
process	21973.62	7729.167	14851.39
Sum	45087.03	7826.64	26456.84

Alcohol recirculation and evaporation instead of freeze drying improvements

GWP	Simulation 1 (100% Pectin) improved	Simulation 2 (100% dietary fiber) improved	Simulation 3 (50/50% pectin dietary fiber) improved
resources	49385,21	63,05199	24724,13
process	876563,2	410017	643565,6
Sum	925948,4	410080,1	668289,7
Acidification	**Simulation 1 (100% Pectin) improved**	**Simulation 2 (100% dietary fiber) improved**	**Simulation 3 (50/50% pectin dietary fiber) improved**
resources	231,811	0,299383	116,0552
process	1397,38	653,632	1025,945
Sum	1629,191	653,9314	1142,001
Eutrophication	**Simulation 1 (100% Pectin) improved**	**Simulation 2 (100% dietary fiber) improved**	**Simulation 3 (50/50% pectin dietary fiber) improved**
resources	1599,767	0,202028	799,9846
process	1667,841	780,1414	1224,515
Sum	3267,608	780,3434	2024,5
Primary energy	**Simulation 1 (100% Pectin) improved**	**Simulation 2 (100% dietary fiber) improved**	**Simulation 3 (50/50% pectin dietary fiber) improved**
resources	725,5009	1,301047	363,401
process	14289,34	6683,914	10491,12
Sum	15014,84	6685,215	10854,52

Scenario results

The production scenario

100% pectin

	Production process	Feed	Total
GWP	2735749	25232.14	2760981
Acidification	10592.3	233.9898	10826.29
Eutrophication	84391.59	3086.616	87478.2
Primary energy	45110.4	159.1399	45269.54

100% Dietary fiber

	Production process	Feed	Total
GWP	480193.3	25232.14	505425.4
Acidification	792.5845	233.9898	1026.574
Eutrophication	1247.831	3086.616	4334.446
Primary energy	7831.63	159.1399	7990.769

Alcohol recirculation and evaporation instead of freeze drying improvements

100% pectin

	Production process	Feed	Total
GWP	927087.8	25232.14	952320
Acidification	1634.605	233.9898	1868.595
Eutrophication	3271.332	3086.616	6357.948
Primary energy	15038.21	159.1399	15197.35

100% Dietary fiber

	Production process	Feed	Total
GWP	410328.9	25232.14	435561
Acidification	655.1158	233.9898	889.1056
Eutrophication	781.2137	3086.616	3867.829
Primary energy	6690.205	159.1399	6849.345

The feed scenario

100% pectin

	Alternative production of phytochemical juice	Alternative production of pectin	Total
GWP	547050.50	197728.4	744778.85
Acidification	668.55	916.5183	1585.07
Eutrophication	1645.27	411.4659	2056.74
Primary energy	9499.96	3130.658	12630.62

100% dietary fiber

	Alternative production of phytochemical juice	Alternative production of dietary fiber	Total
GWP	547050.50	30391.75	577442.25
Acidification	668.55	200.5803	869.13
Eutrophication	1645.27	442.5569	2087.83
Primary energy	9499.96	362.3248	9862.28