CHALMERS
UNIVERSITY OF TECHNOLOGY

Integrating a Biogas Digester into a Household Environment

Master’s thesis in Product Development

HAMPUS BERGMAN

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

PREFACE

This report is the result of thesis for the master's program of Product Development at Chalmers University of Technology.

I want to thank all the people I have been in contact throughout the span of the project for their valuable input. Furthermore I want to thank my family and loved ones for their support and encouragement.

Finally I want to direct a special thanks to my examiner Ulrike Rahe as well as my supervisor Isabel Ordoñez for their big support and guidance throughout the project.

Göteborg 2016

Hampus Bergman

ABSTRACT

Biogas is a renewable resource that can be used in several applications, high sustainability and the wide availability of substrate makes it a technology with a promising future. The goal of this thesis project was to develop a concept that would integrate a biogas digester into a household environment. This was done by conducting a pre-study through customer visits, expert interviews and a survey to collect knowledge about the subject matter and to collect customer needs. The pre-study was followed by a concept development phase where new concepts were generated and then evaluated and lastly eliminated. Concepts were removed in two steps where the first one removed a number of them which were then evaluated more thoroughly. Then in the second elimination step a single most promising concept was chosen to be further developed. The final concept then had its architecture and industrial design finalized as well as materials selected. The result of the thesis is a biogas reactor system that can easily be integrated into a household environment to provide a sustainable way of recycling organic household waste.

CONTENTS

1 **INTRODUCTION**

1.1 BACKGROUND OF THE PROJECT

This thesis project was a collaboration between Chalmers University of Technology, University of Borås and FOV Fabrics AB. At University of Borås they had in a collaborative effort with FOV Fabrics AB developed a novel textile that was suitable for producing biogas reactors, but the reactors that were produced with the textile were simple and their intended market was mainly developing countries. In an effort to find a use for the textile in another market this thesis project was initiated.

1.2 BIOGAS TECHNOLOGY

There is a large market for biogas technology in today's society, but depending on what part of the world considered the technology used can differ greatly in scale. In rural parts of China and India it is common having smaller biogas digesters, aimed to provide enough energy for cooking food. Whilst in a country like Sweden larger biogas plants is the norm, often on the scale that can cover the recycling needs of entire municipalities. In Sweden the applications also differs from the aforementioned markets, where biogas is often used for heating households or used as a propellant in a vehicle.

The technology is based on decomposition of organic matter by utilizing different bacteria in an anaerobic environment, this will produce biogas which consists of methane, carbon dioxide, a small degree of hydrogen sulfide as well as some trace elements. The organic matter added, often referred to as substrate, can be from different sources; common substrates include manure, sewage, kitchen waste, or other organic matter that can be obtained in bulk.

1.3 OBJECTIVES

The objective of this thesis was to develop a concept that integrates a biogas production system into a household environment.

1.4 DELIMITATIONS

The complexity of the problem and the fact that it had to be integrated into a household could affect the degree of which the concept could be finalized. It was not likely that the final outcome would be a plug-and-play solution, it would probably have to be installed into a household at a custom-basis.

2 METHOD

The work structure for this project was largely based upon the product development process described by Ulrich and Eppinger (2012, p. 12-16) in their book Product Design and Development. The development process of the project spanned over five different phases and they will be presented in this chapter with each of their respectively sub-steps to follow in more detail. The five different main phases of the development process that were used in this project are (in chronological order): Pre-Study, Concept Development, System-Level Design and Detail Design. The product development process presented by Ulrich and Eppinger (2012, p. 12-16) includes additional main phases after Detail Design called Testing and Refinement and Production Ramp-Up. Since the scope of this project was to develop a concept and not to deliver a finished product, Production Ramp-Up was left out of the project; the Testing and Refinement phase was not completed due to resource constraints. Furthermore the first main phase of Ulrich and Eppingers' suggested process was named Planning, but for this thesis the first phase was named Pre-Study since it did not precede the start of the project as in the case with the Planning phase described by Ulrich and Eppinger. Similarly several of the steps in the different main phases was also excluded, the steps that were not included in the process were all deemed to not add significant value for the outcome of the thesis.

2.1 PRE-STUDY

The purpose of this phase was to prepare for the Concept Development phase that would follow, where the actual generative work of the thesis starts. There were multiple benefits associated with conducting the pre-study but one of the main perks was to front load the knowledge acquisition required for the later phases of the project. This enabled important decisions to be made with more certainty and decreased risks thanks to the improved knowledge base (Wheelwright and Clark, 1992, p. 183).

One of the first step in the pre-study was to articulate the market opportunity. This was done to ensure that a customer existed that would find value in the product and therefore would be inclined to purchase it (Lindstedt and Burenius, 2003, p. 17). This enabled the market opportunity, its challenges, benefits and alternatives to become clearly synthesized from the early stages of the project.

The next step in the pre-study was to define what market segment that the project would aspire for, this step would be referred to as market segment delimitation by Ulrich and Eppinger (2012). The point of delimiting the market segment was to generate a support for correct decisions throughout the rest of the project, therefore it is crucial that this step is performed early on in the process (Wheelwright and Clark, 1992, p. 41). By limiting the market fewer needs would have to be considered and thus the end result could possibly become better tailored for the intended market which could lead to a more successful product. Since the market segment delimitation was performed early in the project it was based upon input from the different stakeholders and experts that were involved in the project.

Consideration of product platform and architecture was the next step in the pre-study phase. The terms platform and architecture can be multifaceted, in this project the definitions used by Meyer and Lehnerd (1997) was used; "A product platform is a set of common components, modules, or parts from which a stream of derivative products can be efficiently created and launched". Implementing a product platform would enable a more efficient development of derivative products and product variations as well as other advantages (Muffatto, 1999). However some drawbacks were also associated with platforms, for example increased weight or cost of components and products (Wickenberg, Stamlin, Persson & Börjesson, 2011). Using a platform solution could provide multiple advantages to the finished product, but it could also bring some drawback. This project did not use any specific method for deciding if a platform strategy was viable, the choice was based on weighing the perceived benefits and disadvantages. In other words, making a logically sound decision by analyzing the project problem, scope and the opportunities therein.

The next steps of the pre-study phase was the technology assessment and patent issues investigation. The reason for conducting these steps was to ensure that there were no knowledge gaps and to keep the project up to date with the prevailing state of the market. Furthermore investigating patents could be useful in the product development process, both to ensure that no unintentional intellectual property theft would occur, but it could also aid in finding technology that should be assessed.

The mentioned research was conducted by using search engines such as google and different patent databases that were present at the Chalmers library website (Chalmers bibliotek, 2014). The search words was documented as well as the results.

The usefulness of collecting customer needs arose when there was a perceived information gap for doing correct decisions in the development process, or as McQuarrie expressed it "The question is whether collecting information from or about customers could lead to a better decision." (2012, p. 3). This was certainly the case in this project, there were a considerable knowledge gap for making correct and trustworthy decisions. In order to acquire the knowledge that was lacking four different tools were used in this project; customer visits, expert interviews, a survey and a case study. They each served different purposes; the survey was mainly used as a confirmatory tool to find out how potentially future customers would prioritize different functions. Which was in line with how the method is presented by McQuarrie (2012). While the customer visits were used as an exploratory tool (McQuarrie, p.7) to find out about different issues or challenges that the customers had experienced. The expert interviews were mainly used as a substitution to a customer visit when the customer could not meet up face to face, but also once when a simple but specific question needed an answer. The case study's purpose was to gather raw data from the specific household, but also to interview the person in charge of the house about their views of the technology, similarly to an explorative customer visit. The last step of the pre-study was to establish target specifications, this was done with the help of the collaborative information that was gathered thus far. The different tools that were used in this step of the pre-study phase will be further explained hereafter.

Customer visits

Since the use of biogas digesters for single households were not a widespread practice, conducting the customer visits was done by going to biogas plants that were larger in scale. This was of course not the optimal source, but taken into account the novelty of the goal of the thesis it was one of the most valuable sources for the project. Furthermore the goal of doing these customer visits is to explore the possibilities and attain information about problems that might occur both in the development stage and in latter operation of the actual product. This was coherent with McQuarrie's view of what the goal of a customer visit should be (2012, p. 27). The perceived benefits of conducting customer visits as opposed to just conducting interviews was that the human to human interaction in the environment of the customer could lead to more in depth knowledge of the issue at hand. Thus it could potentially make the problem clearer for the interviewer than if the interview was conducted over the phone (McQuarrie, 2012, p.28).

Survey

The need for conducting a survey was evident since the project did not possess any quantifiable confirmatory data about customer's prioritization regarding different functions of a household biogas digester. The survey was carried out by calling villa owners in Sweden living outside of large cities or in the countryside. The interview was conducted by first introducing the interviewee to the subject of household biogas digester followed by a few questions about their own households energy use and recycling habits. Then lastly the interviewees were asked to rate the importance of seven different properties of a potential household biogas digester system. These ratings were later used in the project to motivate decisions in the concept evaluation and selection steps.

Expert interviews

The expert interviews conducted can be categorized into three different categories; biogas users, researchers and safety. All of the interviews were made with the intent to gather knowledge, either as a generative measure about problems that could arise or to answer specific questions (where the latter was applied when interviewing the safety expert). The different interviews were conducted in a similar fashion where questions were prepared prior to calling the interviewee.

Case study

The contact person for the project had measured environmental data in his villas basement. The contact was also potentially interested in testing a prototype if one were to be made. Therefore a case study was conducted both in order to gather data and get an exploratory data source i.e. similar to a customer visit. The case study was performed by meeting the interviewee at his place of residence, an interview guide was prepared beforehand and used. Furthermore the different environmental data were gathered, off of which the temperature was the most important.

Target specifications

The target specifications is to be seen as a preliminary goal to strive towards. They would later be revised, edited and set as final specifications in compliance to the process described by Ulrich and Eppinger (2012, p. 93-103). Establishing these specifications was done in four steps as listed below (for further details about the four sub-steps refer to Ulrich and Eppingers book):

1 Prepare the list of metrics

2 Collect competitive benchmarking information

3 Set ideal and marginally acceptable target values

4 Reflect on the results and the process

2.2 CONCEPT DEVELOPMENT

This phase was the starting point for the generative work carried out in the thesis, thus the core of the different concepts was created here (Ulrich and Eppinger, 2012). Some of which would be further developed into more mature forms while others would be filtered out early on if they were perceived as inferior. This process continued until the concept selection part where the remaining concepts were evaluated against each other under several criteria's to single out the most promising solution. By going from a large solution space with a high quantity of concepts and from that point work towards narrowing down the quantity could affect the outcome of the final concept chosen. This process was chosen since it can effectively widened the solution space and promote objectivity in the ongoing selection process (Wheelwright and Clark, 1992, p. 111-112). In contrast an opposite concept development process could be to decide very early on a solution and then spend the rest of the time testing and refining it, perhaps missing out on a superior end result. The three major steps used in this phase are concept generation, concept evaluation and concept selection which will be further explained below.

Concept generation

In an effort to saturate the solution space and avoid overlooking any technology the concept generation was performed in five steps. These five steps were derived from Ulrich and Eppingers' product development process (2012, p.120); clarify the problem, search externally, search internally, explore systematically and reflect on the solution and the process. Ulrich and Eppinger (2012, p. 119) argues that their five-step method reduces the risk of a few common problems such as: "Failure to consider carefully the usefulness of concepts employed by other firms in related and unrelated products." or "Failure to consider entire categories of solutions.". This was done by decomposing the generation process into different sub problems so as to make the generative work for each specific part easier. The different sub-steps will be presented below.

Clarify the problem

This was the first step of this method, in order to split the problem into sub problems a certain amount of understanding of the problem at hand was necessary. Also when dividing the whole into sub problems the understanding of the whole problem might be elevated, or in the words of the Ulrich & Eppinger (2012, p.120) "Clarifying the problem consists of developing a general understanding then breaking the problem down into sub problems if necessary.". When the problems have been split into different smaller parts, deciding which of them were the most critical sub problems and then focusing on those was an effort to create the best new concepts possible.

Search internally

This step in the concept development phase used the human resources involved in the process to brainstorm new ideas and concepts. Some guidelines for doing this was described by Ulrich and Eppinger (2012, pp. 127-130) and they can be summarized to: suspend judgement of concepts, generate a lot of ideas, i.e. quantity over quality. These tips were followed to make it easier to saturate the solution space of the problem. Some other generative methods was also used, such as making analogies, related stimuli and unrelated stimuli. These were all means to enable a more extensive generation of concepts.

Search externally

When searching externally the two major goals was to find existing solutions for both the overall problem and sub problems. This was done in two ways for this project; consulting experts and searching patents. The patent searching was already explained previously “technology assessment and patent issues investigation” and the same search results were used for both purposes. The second method for gathering information from external sources was the data gathered from stakeholders when dialogues were held, their advice and opinions were also used.

Explore systematically

Thus far in the project some concepts had already been generated, now these were explored systematically to enable even further saturation of the solution space. This was done by taking sub solutions from different concepts and combining them into new concepts.

Concept evaluation

The evaluation of the different concept was a lengthy process where the different concept were continuously scrutinized and weeded out until only a few remained. Alongside the evaluation the concepts also had to evolve, more detail and depth was often needed in order to judge if a concept was to be eliminated or kept in the concept pool. In order to filter down the number of concepts a screening matrix was used to rate and rank them, the ranking was based on the customer needs that were acquired in the survey performed earlier in the project. The concept screening method used is further explained in the supporting documents.

Alongside the process of narrowing down the different concepts they were also improved and made more detailed. This was done in multiple ways where the first step was to produce more detailed sketches of all the different concepts. These sketches were used when the first concept screening was done. Further into the process CAD models were made of two of the concepts to illustrate them further in detail. Physical prototyping was also a part of the procedure to test the feasibility of a couple of concepts.

A tool for assessing risks with the different concepts was used in the final concept selection. The tool that was used was a Failure mode and effect analysis, henceforth it will be called FMEA (Carlson, 2012). The point of the tool was to assess different aspects of failure modes intrinsic to specific concepts, rate them and from those ratings calculate a risk priority number (RPN). The different aspect that were rated for each failure mode were severity, occurrence and ease of detection. More information about the tool can be read in the supporting documents chapter 6.4.

Estimating manufacturing costs was also an integral part of evaluating and rating the different concepts. This was however not done absolutely, but rather in relative fashion towards each other. Since the only function for the cost estimation thus far in the project was to rate the different concepts towards each other, estimating the costs absolutely would not add any perceived benefit.

The outcome of the concept evaluation is to have a better understanding of the concepts advantages and disadvantages as the next step is to choose one of these concepts for further development.

Concept selection

The accumulated data from the concept evaluation phase was reviewed to decide which concept that was the most promising. To aid in the process of selecting the final concept a weighted selection matrix (Ulrich and Eppinger, 2012, pp.154-158) was used. This tool allowed for a methodical and detailed evaluation of the concepts and in comparison to the selection matrix used previously it is more precise. The criteria's were weighted to prioritize some criteria before other, this affected the final outcome by for example making an important customer need weigh as much as two less important ones. The weights were derived from both the customer survey performed in the pre-study and later tweaked with the knowledge gathered through the project. More information about the weighted selection matrix can be read in the supporting documents chapter 6.2. The outcome of the concept selection step was a final concept, next phase in line is the system-level design which will further develop the chosen concept this phase will be explained in the next chapter.

2.3 SYSTEM-LEVEL DESIGN

The System-Level Design phase consisted of several different steps that aimed to finalize the foundation for the chosen concept. The first step consisted of assessing different product options followed by further developing the product architecture, setting the final specifications and further refine the final concept.

The first step of the system-level design phase was to develop a plan for product options, which would comprise the different derivative product versions and accessories that were needed. The different needed options were explained and solutions for them were reflected upon.

Development of the product architecture was then finalized, this encompassed design choices of specific parts that would affect the interfacing parts. As well as what kind of parts that could be bought off-the-shelf and what parts that needed to be manufactured.

The target specifications that were already set previously in the project were in this stage of the process re-evaluated. This enabled the specifications to be adjusted to the chosen concept and thus they could be made more accurate.

The final step in the system-level design phase was to evaluate the need for and refine the industrial design of the chosen concept. The need for industrial design was assessed in order to find out how important it would be for the product, and what value it would add to the customer (Lindstedt and Burenius, 2003). For this project the products aesthetic needs was gauged and based on that a few parts industrial design was changed, these parts geometry were later finalized in the detail design phase.

2.4 DETAIL DESIGN

This phase involved three different steps, where the first one was to define the part geometry, the second was to select the materials and the third one was to estimate the manufacturing cost of the concept. To define the geometry the CAD program Catia was used. For selecting the materials for the different parts the program CES was used. The third step was to estimate the manufacturing cost of the finished product and this was done by comparing the cost of similar parts to come up with a rough cost estimation in a range.

The first step of the detail design phase was to define the part geometry, this was done by utilizing the CAD program Catia v5 to sketch and model the geometries of the different parts. This enabled accurate sketches and renders of the concept and its parts to be produced. More information about the program can be found in the supporting documents.

The second step of the phase was to decide upon what material to use for the different parts. The material selection was conducted by first stating the different demands put on the materials for specific components, then a material was found that could withstand those demands. One important software was used for the majority of materials selected, the program CES was used to compare different materials properties against each other. This made the comparison process efficient and clear.

Estimating the manufacturing cost was the final step of the phase, an absolute manufacturing cost estimation was performed by using the knowledge gathered throughout the project. Assessing the manufacturing cost of the parts that was needed to be manufactured was done by comparing the parts to similar already existing parts and other available data. Parts that could be bought off-the-shelf where the plan was to do so were also estimated in a span, based on the cost on the market. All these data points were added up and a total cost estimation was produced ranging in a span from the maximum cost to the minimum.

3 RESULTS

The results will be presented in the same order as the method were described. This is to ensure that the reader can more easily refer back to the method part of the report to see the reasoning behind why a step in the process is performed and what the outcome should reflect.

3.1 PRE-STUDY RESULTS

From examining the market opportunities it was found out that small scale biogas digesters were commonly used in rural parts of some Asian countries (Chen, Yang, Sweeney and Feng, 2010). The digesters was mostly used for providing fuel for gas stoves and not as often for heating up water. Contrastingly in western societies small scale biogas digesters were not found to be commonly used, the reasons for this could be several, one plausible explanation could be that it did not exist any solution that was good enough. The hassle of actually setting up and utilizing a small scale biogas production process would outweigh the perceived benefits. If a product would be able to make become an attractive option for recycling a household's organic waste into biogas it was deemed that the market would exist, as long as the benefits of the product would outweigh the negatives. This thesis was decided to focus on developing technology that would make it easier to implement a biogas digester into a household, a complete system that would enable the user to recycle its household's organic waste.

When considering what market segment that the project would focus on there were mainly five different stakeholders whose opinions were considered. The stakeholders and experts were the examiner of the thesis Ulrike Rahe, the supervisor Isabel Ordoñes, Professor Mohammad J. Taherzadeh from University of Borås, PhD student Karthik Rajendran from University of Borås and Fredrik Johansson from the company F.O.V. Fabrics AB. The input from the mentioned stakeholders as well as the original scope of the thesis led to the decision that the intended market segment was going to be villa houses in the Nordic climate. The main motive for focusing on that market was that it was unexplored and that it has a high purchasing power.

When considering the product architecture that could be used it was noted that the architecture would be heavily influenced by the problem, and the presumed solution space that would emerge from the concept generation step of the project. Since the problem was well defined the solution space could, to a certain extent, be imagined even before a lot of work had been put into generating new concepts. Constraints like that there had to be a reactor that contains organic waste, as well as some way to insert the organic matter into the reactor. There also had to be a way to remove the depleted slurry that would be produced as a byproduct. And lastly the need to be able to extract the produced biogas so that the product can actually be used. All of these functions would have to be present in the final concept in order for it to be a feasible concept.

The organic waste input would have to be used frequently, and so would the water input. Therefore an effort was made to integrate them into the household to a larger extent than for example the slurry output, which could possibly be emptied with several months in between (depending on the size of the reactor). Furthermore the biogas output had a large need to be fully automated i.e. it would always have to be ready for use, either for warming up water or other tasks. Another function that also was needed for an efficient biogas production was a way to atomize the organic waste, one of the obvious ways of doing this was to macerate the food waste before it would be fed into the biogas reactor. To enhance the usability of the system, it would further be advantageously to integrate the maceration of the organic waste in the system. This enhanced usability would further constrain the interface of the architecture.

Then there could be other functions in use. For example, sensors that could detect when to empty the slurry in the reactor, if the emptying function is actuated automatically.

The architectures of the upcoming concepts was thus far in the project believed to have a large degree of constraints already applied to them as a result of the scope of the thesis. Even so, there were a lot of different paths that could possibly be one that led to the best concept. So in an effort to try and explore as large of a solution space as possible constraints were not intentionally put on the architecture and the reflection from this chapter was mainly used as inspiration for when to search internally when generating concepts in chapter 3.2.

While considering if effort should be put into making concepts that could act as a platform two main factors were considered: the time constraint of the project and the added complexity that could be the end result of developing a product with a platform architecture (Ulrich and Robertson, 1998). In addition to this, the nature of the scope and thus the natural architectural restrictions that was discussed above, makes some parts of the architecture seem very likely to be developed into having slot-interfaces, as defined by Karl Ulrich (1995, p. 426). Which could greatly influence the ease of developing the architecture into a platform, an example would be the ease of rescaling the biogas reactor. With the benefits of developing a technology into a platform solution considered versus the added complexity, weight, cost and development time all in mind a decision was made to not make an effort into developing a platform concept. But the possibility that the architecture of the final concept might still become very easy to make into a platform solution still exists and this will be further reviewed in the discussion part of the thesis.

The use of biogas digesters for household purposes was not found to be a common occurrence in the western world, it was however more prominent in rural parts of China and India (Rajendran, Aslanzadeh, Johansson and Taherzadehl, 2013). From the research it was found that the most common biogas digester in China was the fixed dome variant, where the pressure in the dome would build up as the amount of biogas increased. The biogas could later be siphoned as long as the pressure would allow. A big problem with this type of reactor were that it was often made of bricks and other porous materials, which could lead to gas leakage and ground pollution. In India the floating drum type biogas digester was found to be a popular design that could pressurize the gas at a constant level since the volume of the biogas container would vary with the gas amount. The design had some problems with oxidation of the steel drums that are often being used. Furthermore another digester design called plug-flow was researched, in this design the substrate supposedly flows through an elongated reactor, this works similar to a fixed dome variant. This reactor would often be made out of more modern materials such as polymers, but this had been shown to have some disadvantages since the polyethylene used would easily be cut. In the article Experimental and economical evaluation of a novel biogas digester (Rajendran et al., 2013) the authors also presented biogas production estimations derived from experimental data. By using a method that potentially could be equivalent to the one that would be used in this project the article authors claimed that a biogas reactor in a household of 4-6 persons could produce 34$m^3$of biogas per month (measured at atmospheric pressure).

Waste disposal units or garbage disposals are commonly used in several parts of the world and comes in a multitude of varieties. They operate by grinding and pulverizing the food waste together however it needs both water and electricity to operate (Down the sink 2015).

Patents that were found and investigated are presented below, the search words that were used can be found in the supporting documents.

Introducing Screw for Biogas Plants

The Introducing Screw For Biogas Plants (Vogelsang 2014) patent was used to load substrate into a biogas reactor, but it would be suitable for a higher loading rate than what will be used in this project.

Lightweight assemblable appliance and respective method for production of biogas and liquid fertilizer

This patent presented an interesting solution for feeding the organic waste (Efrati, Teller, Lanzer, Miller, Eilon & Zak, 2014) where a sink was used in conjunction with a grinder. The solution would be too large and too expensive for just being used in a single household though.

Biogas production from a flexible digester

This flexible biogas digester (Wanhjihia, 2014) was intended for outdoor use and was made to be more easily installed thanks to the flexible digester construction. The constructions is generally similar to other small scale biogas production solutions that already are in use.

The next step of the pre-study was to collect the customer needs and later use the collected data to establish target specifications. The methods that was used for collecting customer needs were customer visits, expert interviews, case study and a survey.

Customer visits

Karl-Johan Gunnarsson - Skottorps Säteri

The biogas digester at this dairy farm was used to facilitate energy needs for some households and the farm itself. It produced 4.5GWh of energy each year where one third was electricity, the mesophilic digestion of the process was mainly fed with cow manure and some residual organic waste from the dairy process. Karl-Johan also mentioned that the biogas digester was sensitive to a decreased outside temperature, which lead to a lowered efficiency. The system had been repaired on several occasions, the moving parts of the stirrers but also the pump had then been fixed. Karl-Johan said that he would want additional temperature gauges if he could change anything in the system.

Safi Hadi - Gryaab

Gryaab is the municipal water purification plant for Gothenburg and some of the surrounding municipalities. The only kind of biogas substrate they accept is toilet waste and the plant receives 1Mm^3 of mixed slurry each year, of off which 2.5% is dry weight. The digestion process is mesophilic and they produce 70GWh worth of energy each year. Safi Hadi also pointed out that Gryaab have low levels of hydrogen sulfide, which is directly dictated by the substrate that they use. Safi explained that this is due to lack of co-digestion, the homogeneousness of the substrate leads to less hydrogen sulfide. Gryaab also performs a lot of their maintenance moving parts such as pumps and valves. Over time increased levels of fat in their substrate has led to increased risks of their pipes clogging up. Safi Hadi emphasized the importance of accurately dimensioning the pipes which the slurry would be pumped through. Gryaab keeps the temperature in the digester process by heating up the slurry that is added into reactor as well as utilizing a heat retention loop. One of the most important lessons from the visit at Gryaab was the large safety demands that they had on the plant.

Jörgen Fredriksson & Robert Lippens - Ragn Sells Heljestorp

Ragn Sells operates a biogas plant that mainly uses substrate from household waste, however a fraction of the substrate is residual products from fish industry. Their process is thermophilic and they produce 150.000 Nm^3 of biogas each month, which translates to an estimated 12 GWh worth of energy each year (6.5kWh/Nm^3). The components that are prone to wear out the fastest are the pumps, and since the process utilizes co-digestion the wear is both abrasive and corrosive. Jörgen and Robert stressed that a biogas production system will always consist of compromises, there will always be a trade-off between efficiency and reliability; finding a good balance between these factors are important. They also mentioned that the process at Ragn Sells Heljestrand is very robust but not particularly efficient and this is due to two main reasons. That the company prioritized robustness when the plant was constructed and the fact that newer and more efficient technology exists on the market today.

Expert interviews

Fredrik Joelsson - Öresundskraft

Öresundskraft is currently not producing any biogas, but have prior experiences with siphoning biogas from landfills. The landfills worked by preparing the ground, then filling it with organic waste and covering it up. Then to extract the gas they siphoned it with a negative pressure. The landfill had problems with corrosion, tubes for the biogas had to be changed after a ten year period. Furthermore connections to wells had plaster that got filled up with hydrogen sulfide and had to be remade. Fredrik Joelsson also mentioned the biggest disadvantage with producing biogas with this process was the smell that could spread if there were any leaks or if the siphoning of the gas somehow stopped.

Marcus Möller - NSR Helsingborg

NSR is a waste management company that operates in the north west of Scania in the south of Sweden. They use mesophilic digestion of substrate from different food industries, for example waste products from the animal industry. They produce 80 GWh of biogas for vehicles annually. The most important take away from the interview with Marcus Möller was to act proactively, and prepare for failures and operation stops.

Lars Synnerholm - MSB (Myndigheten för Samhällsskydd och Beredskap)

Lars Synnerholm was asked a question about what possibilities existed for producing and storing biogas indoors, more specifically in the basement of a household. To which he explained that there are very tight restrictions for this, and having a system which produces and stores the biogas indoors would be hard to get approved.

Case study

Rodrigo Ordoñez Pizarro

Rodrigo's household currently uses a gas water heater and does not sort their organic food waste, their basement is also situated underneath their kitchen. All of these factors would make it easy to test a prototype from this thesis in their household. Rodrigo also stressed the importance of the system ease of use, especially for everyday use. The case study was also comprised of some collected environmental data, figure 1 shows the temperature data from December the first 2014 to January the fourth 2015. The temperature fluctuates a bit, but never goes below 14°C. Just below 3831 m^3 gas, which could be translated to 42141 kWh of energy (Svenskt Gastekniskt Center, 2015). The amount of energy that could be produced if a biogas digester was installed in the case study would be approximately 3009 kWh. Which amounts to just above 7% of the yearly energy need for the household of the case study (Rajendran et al., 2013). The annual cost saving the case study would be able to generate would approximately be 2144 SEK (Öresundskraft, 2015).

[Volume consumed annually] x [Energy per volume natural gas] = [Energy consumed annually]

3831 x 11, 0 = 42141 kWh

[Volume produced monthly x 12] x [Energy per volume biogas] [Adjustment for methane content] = [Energy produced annually]

34 x 12 x 9, 67 x 0, 74/0, 97 = 3009 kWh

[Energy produced annually] / [Energy consumed annually] x 100 = [Percentage of energy need covered]

3009 / 42141 x 100 = 7, 1 %

[Energy produced annually] x [Energy cost] = [Annual cost saving]

3009 x 0, 7125 = 2144 SEK

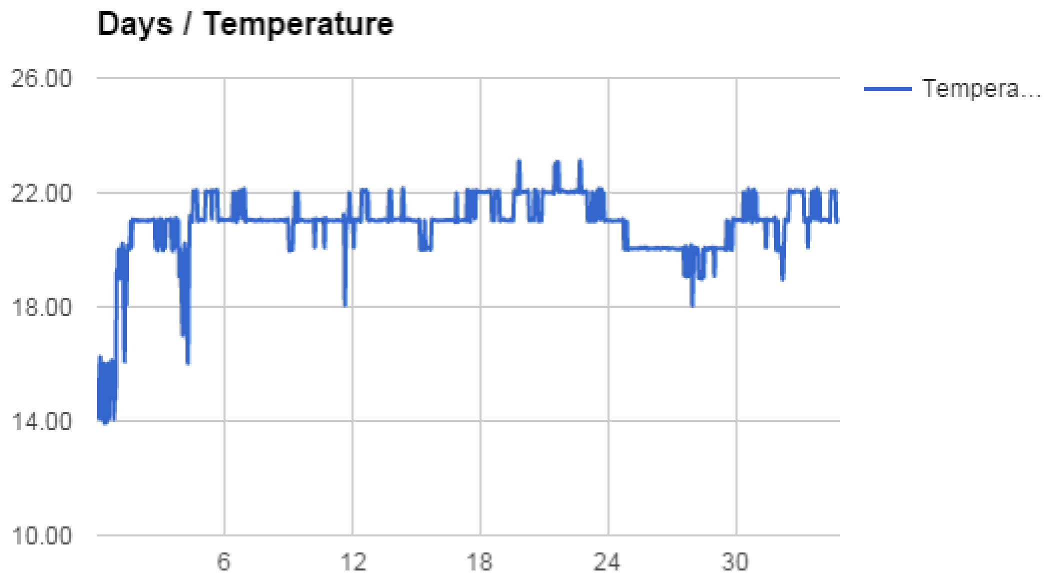


Figure 1 - Plot of temperature measurements *Y-axis - Temperature [°C]* *X-axis – Time [Days]*

Survey

A template with the questions asked during the survey can be found in the supporting documents. The seven different rated criteria that made up the confirmatory part of the surveys interviews were evaluated by calculating the mean score of the different criteria's. The outcome is shown in the list below as the highest rated criteria as the first:

1. Robustness
2. Easy to use at an everyday basis
3. Easy maintenance
4. Efficient biogas production
5. Small investment cost
6. It is easy to empty the slurry
7. The system is compact

The lowest rated criteria which was that the system should be compact, still had an average score of 3.95 which is 79% of the maximum score. The reason for this relatively high score could be that the people being interviewed had a negative attitude towards the technology and thus put very high demands on it. For instance if the customer is not motivated to learn how to sort and dispose of their household waste in a different way than they are currently doing. A product that is supposed to change their habits have to provide enough value for the customer to overcome the lack of motivation (Lindstedt and Burenius, 2003). This was said by a few of the interviewees when the interviewer commented on the consistency in high scores.

Target specifications

The target specifications were most often set by estimating a value from the knowledge that had been accumulated thus far in the project.

Metric No.	Need No.	Metric	Importance	Units	Marginal Value	Ideal Value
1	1	Should not be destroyed by corrosion over a specific time	5	years	10	Never
2	1	All fluid and mass containers in the system that needs to, should withstand the control pressure	5	mbar	150	450
3	2	Maceration demands few actions	5	Number of actions	5	2
4	2	Feeding time	5	s	360	10
5	3,6	Max time to empty slurry	4	s	3600	300
6	3	The reactor capacity	4	m^3	1	2,5
7	3	The maximum amount of biogas that is allowed to escape when the slurry is emptied	4+1	Nm^3	0,05	0
8	3,4	Number of actions to adjust reactor temperature	4	List	4	0
9	5	System manufacturing cost	3	SEK	50000	10000
10	6	Ease of emptying slurry	2	List	6 steps	0 steps
11	7	Space that the system occupies	2	m^2	12	2

Table 1 -Target Specifications Table

3.2 CONCEPT DEVELOPMENT RESULTS

Concept generation

The results from the concept generative phase of the project will be covered in this chapter.

Clarifying the problem

The first step of the concept generation was to clarify the problem at hand, the theory and information will be summarized in this chapter. The general understanding of the problem was summarized by first looking at the anaerobic digestion process and then pointing out some specific problems about the household setting it was supposed to be implemented into. When looking at the anaerobic digestion process it was found that it uses microorganisms to break down biodegradable organic waste into methane, CO_2 and some less prominent by-products (Rajendran et al., 2013). All of this happened in an environment free from oxygen, or in other words an anaerobic environment. In order to assure that the reactor environment was oxygen free it would have to consist of some other medium that did not solve well with oxygen. Water was the obvious choice for this task. The use of water would affect the density and viscosity of the post digestion slurry by-product, the slurry's attributes would be dependent upon the pre digestion substrate's particle size and composition. Another aspect of anaerobic digestion considered was that the activity of the microorganisms were affected by the temperature in which they reside. Optimal biogas production rate was found out to be achieved at around 38°C; at temperatures below the optimal production rate it would continuously decline until it would reach a complete stop at the freezing temperature. However through that range of efficiency the yield would theoretically be the same if enough time for digestion would be given for the microorganisms to digest the substrate (Taherzadeh, 2015). In order to make use of the produced methane the system had to be able to extract the gas. After the substrate had been digested into slurry it would need to be removed from the reactor. Furthermore the system would probably need to have to be subjected to periodical maintenance. Another factor that was consider were the suggested implementation into a household environment and the information from Lars Synnerholm at MSB; storing the biogas inside of a household should be avoided as to minimize risks. Thus far in this chapter the general outline of the thesis’s problem have been covered, in the next paragraphs several sub-problems will be highlighted.

One of the most restricting sub-problems that was considered, was the need to open up the reactor. Either for maintenance or emptying the actual slurry, the complication of this was that the biogas methane could not be allowed to freely escape into the environment, at least not in uncontrolled amounts. This was not only an efficiency related concern since trace compounds such as hydrogen sulfide could have health implications if people were to be exposed to it.

Furthermore hydrogen sulfide was found to act as a corrosion catalyst if it come into contact with material that were susceptible to corrosion (Roberge, 2008). This restricted the amount of materials that could be used in the finished product, at least it limited the materials used in the interior of the system.

The need to move several different types of mass throughout the system was also evident, at the same time the system should be kept sealed from the outside. The usual solution applied for this problem was found to be to transport the mass through pipes. It was deemed probable that this solution would be used in some of the concepts for this project. However during the customer visit at Gryaab, Safi Hadi pointed out that clogging can be an issue depending on some factors of the system as previously mentioned. These factors include composition of the mass that was to be transported as well as the diameter and length of the pipes. But in contrast to the process at Gryaab, there would be other demands on a small scale household digester process. The driving force most commonly found in small scale systems was to utilize the mass equilibrium between the input and the output of the chambers of the system. Considering these two polar opposites it was deemed probable to have a mass equilibrated biogas reactor system in a household environment. But the system would have to be designed in a way to avoid the risk of clogging the pipes by for instance dimensioning the diameter of the pipes as Safi Hadi mentioned.

In order for the digestion process to be efficient the organic waste needs to have a sufficiently small particle size, since a smaller particle size translates into a larger surface area for the microorganisms to react with (Fredriksson and Lippens, 2015); pulverizing the organic waste is a requisite for an effective digestion process. Logistically the easiest way of atomizing the substrate would be to do it before feeding it into the reactor chamber so as to avoid unnecessary re-processing of already atomized substrate.

Concept generation

After clarifying the problem the generative part of the concept generation started, the concepts were generated through the three different steps explained in chapter 2.2, namely searching internally, searching externally and systematically exploring. After the generation process was completed the concepts that could easily be deemed as non-feasible were removed, the remaining concepts are presented below and will be presented in more detail in this chapter.

1. Indoor reactor
2. Well reactor
3. Well reactor with gas holder
4. Well reactor with integral gas holder
5. Outdoor reactor
6. Triple chamber
7. Indoor reactor with pump
8. Well reactor with pump
9. Well reactor with gas holder and pump
10. Well reactor with integral gas holder and pump
11. Triple with pump
12. Automatic with compressor
13. Automatic
14. Well with compressor
15. Well automatic

Before going into detail about the 15 different concept some commonly found solutions that was shared between several concepts will be explained. The first commonly used solution developed was how the biogas outlet operates. When observing the first of the five different reactor setups in figure 2 the large yellow pentagon represents the biogas reactor, the top of the reactor was shaped to funnel the gas to the center of the reactor roof. From this point a red line can be seen in the figure that was directed upwards, this represents a pipe that transfers the biogas to a gas holder (depicted as a red square with rounded corners). The green line represents an input pipe for the organic waste, the organic waste was designed to be loaded from the sink which can be seen as a gray square in figure 2.

On the second reactor setup in figure 3 the inside of the reactor chamber was depicted. The reactor was designed to be loaded with both water (represented by the blue area) organic waste (green area) and depleted organic waste (brown area). The rest of the inside of the reactor was depicted with red, this was a representation of the biogas that would be collected here when produced. The problem with this design was that it would allow the biogas to escape up throughout the organic waste feeding pipe. This would however be avoided if the water level was raised as depicted in figure 4. The same figure also shows how the water level would rise up through the organic waste input pipe. This effect was due to the fact that the pressure had increased when the biogas was accumulated in the reactor and this would in turn push up the water level in the organic waste input pipe. In figure 5 a drainage pipe had been added to let excess water leave the reactor. This was done to automatically control the water level inside the system, and keep it at a constant elevation. This would in turn make it easy to maintain a constant pressure level for the biogas.

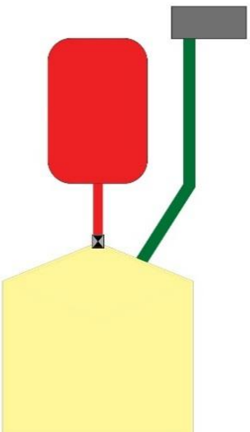


Figure 3

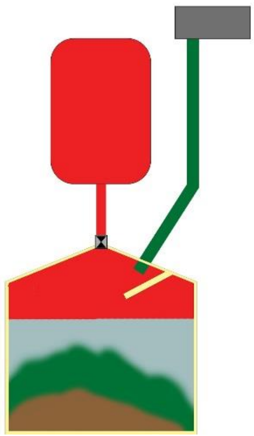


Figure 2

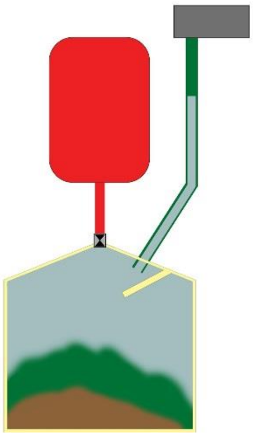


Figure 4

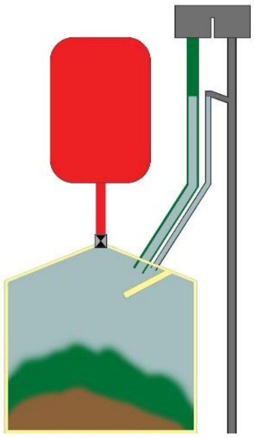


Figure 5

Figure 6 depicts another commonly shared function used in different concepts. The function added a crimson red pipe attaching to the ordinary red pipe at the right side of the picture. This pipe was designed to act as an alternate gas source that connects to the main gas system via a pressure gauge. The pressure gauge acts by lowering the pressure of the gas that would be received from the outside of the house, lowering the pressure of the gas was needed since home utensils that use gas operate on lower pressures than the gas delivered to the house. Both of these two common solutions will be found in some form in most of the concepts that will be presented in this project.

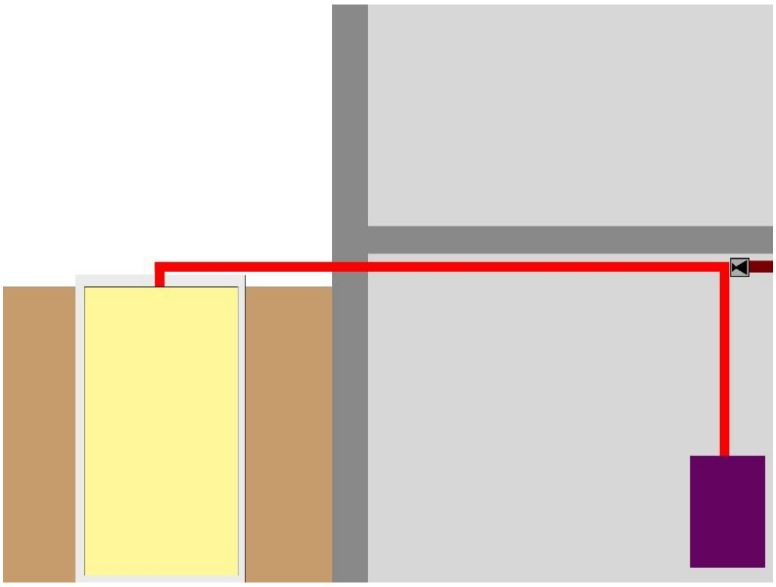


Figure 6 – External gas source illustration

Indoor Reactor -*Concept 1*

Concept 1 (figure 7) solved the challenge of keeping a high enough temperature for a mesophilic digestion by positioning the reactor part of the system inside of the household and therefore utilizing the relatively high temperature already existent in that environment. Also in order to adhere to the restriction of not storing large amounts of biogas inside the household the biogas was led outside to a gas holder through a gas pipe (depicted as a red line in figure 7. The concept was generated with a preferred placement in mind, underneath a kitchen. This would enable simple solutions for making an easy feeding system for the organic waste into the reactor chamber, through for instance a sink (this solution is depicted as a green line in figure 7). The organic waste input pipe was also seen as the perfect place for installing a waste disposal unit that atomizes the substrate, especially considering that off the shelf solutions are commonly installed in this configuration. The waste disposal unit would have an operating interface from the inside of the kitchen. The off-the-self solutions usually operate by having water flowing through the WDU when it would be active and then feeding the organic waste to macerate it. When this water would be added to the reactor chamber it would balance out the in-flow by utilizing a water drainage pipe to let the necessary amount of water out into the ordinary sewage drain (figure 7). The water levels of the system would differ when considering the reactor level versus the water drainage pipe and organic waste input pipe's water levels, the water level in the reactor will be the lowest. The biogas was collected in the top of the concepts reactor by having the roof of the reactor act as an upside down funnel, just past this connection with the system was a valve that could be closed off. The point of the valve was to ensure that the reactor could be opened without the risk of biogas leaking into the reactor and out of into the atmosphere; by having a buffer of water above the valve a margin of error was built into the system.

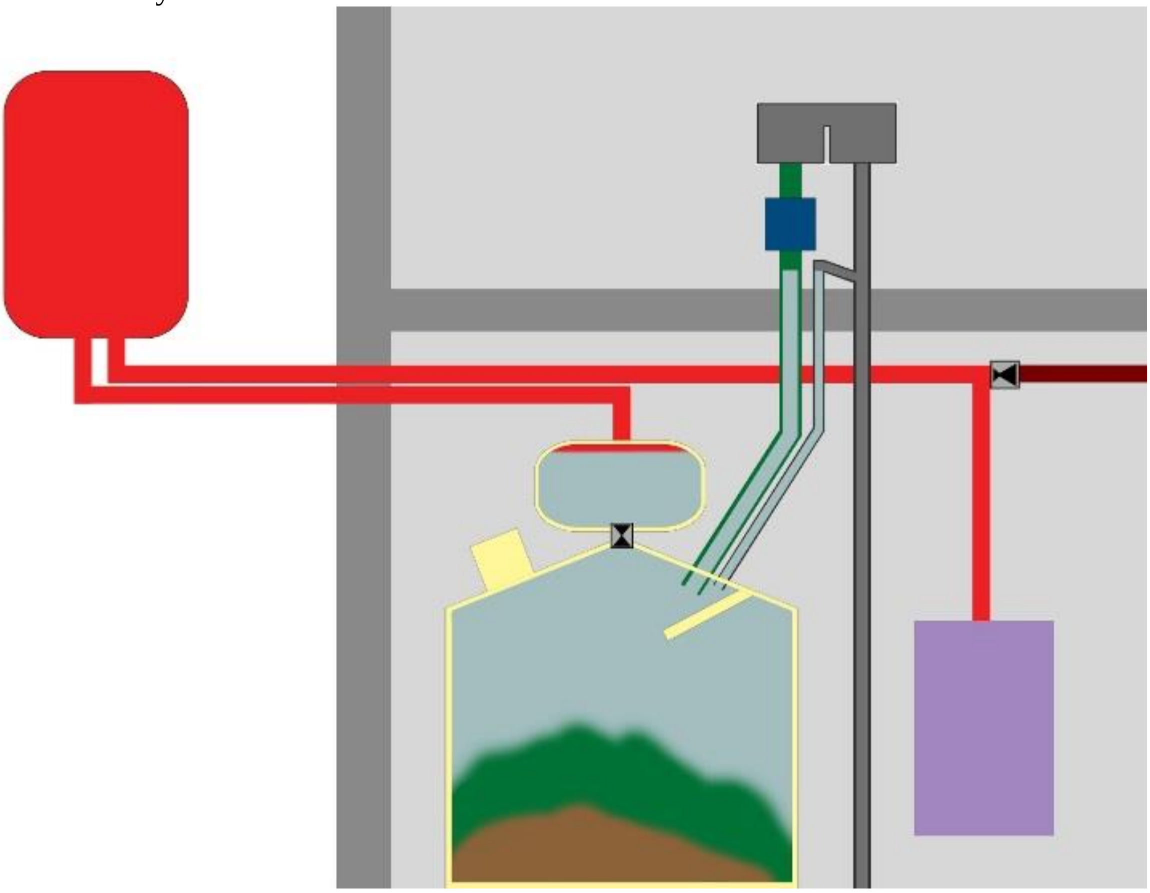


Figure 7 - Concept 1: Indoor Reactor

When the valve is closed off the reactor could be then be opened and emptied out for cleaning or other maintenance. The reactor would therefore have to store all of the slurry that had been produced until it was actually opened up and emptied. The interval for emptying the reactor would be dependent of reactor size and load rate of organic substrate.

Well Reactor -*Concept 2*

In the well reactor concept (figure 8) the reactor was positioned outside the household, in a hole in the ground like just like the name implies. The two main advantages of this strategy was firstly that it takes up less available space if it is underground and outside. The second advantage was that by lowering the reactor into the ground it would be able to utilize the geothermal energy to help raise or maintain an elevated temperature needed for producing biogas. This was seen to be true especially in comparison to placing the reactor on ground level. However the geothermal temperature data that was found showed lower temperatures than in for instance the basement that was investigated in the pre-study. The macerated organic waste was supposed to be transported from the kitchen via a pipe that was led through the ground and would end up in the biogas reactor. The slope of this transport pipe will have a lower angle than the corresponding one found in the first concept (Inside reactor). Furthermore the water level would be balanced in similar fashion as in concept 1; there would be a water output pipe that would automatically drain water to balance the mass equilibrium. Another similarity would be the use of a water buffer to enable safe and leakage free opening and maintenance of the biogas reactor.

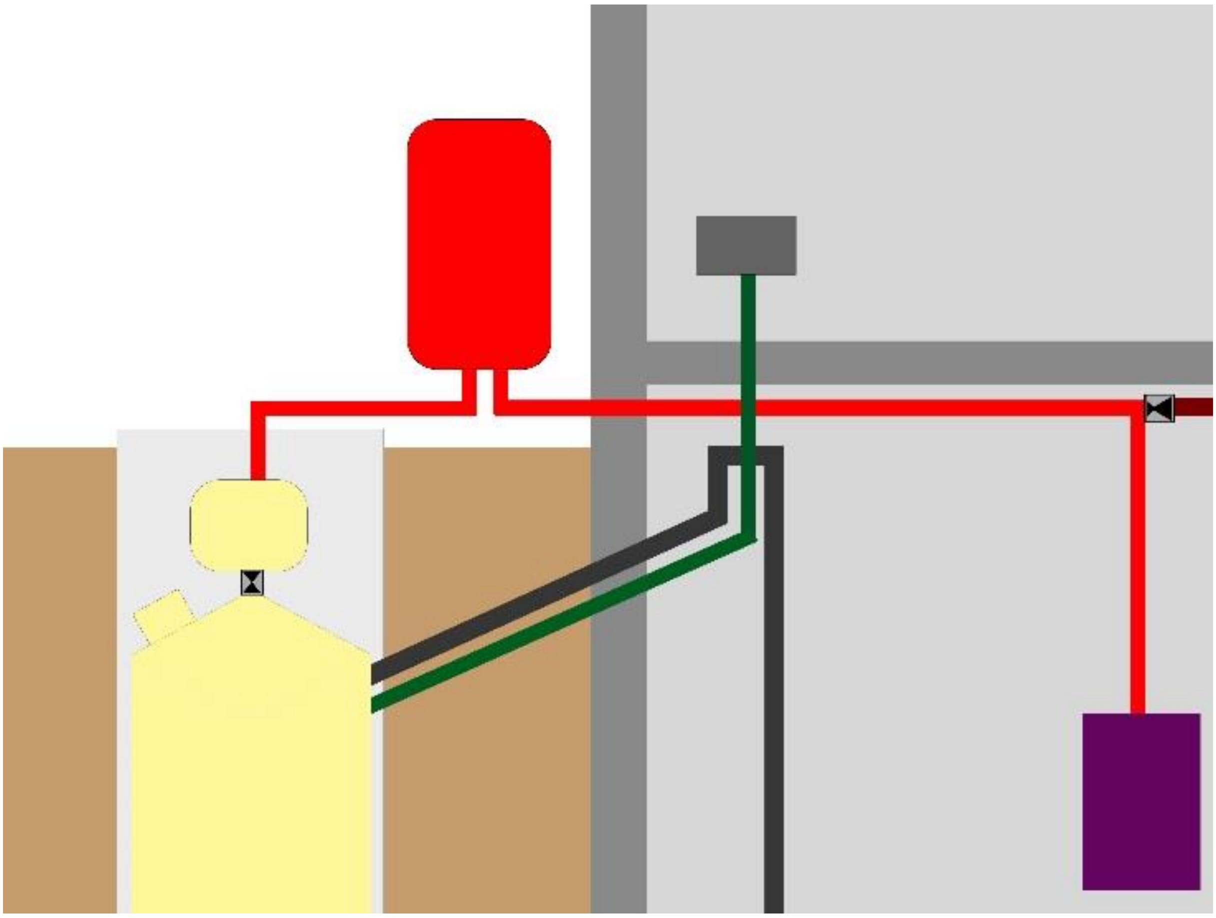


Figure 8 - Concept 2: Well Reactor

Well Reactor with Gas Holder -*Concept 3*

A main difference that was brought to the third concept in comparison to the previously presented concepts was that it does not have the same gas outlet closing solution. Therefore in order to ensure that no gas could leak when performing maintenance and similar activities, water had to be filled up to the close off valve. It should be noted that this could only be achieved if the pressure was lowered in the gas holder beforehand, which was to be achieved by combusting the biogas stored in the gas holder using a torch (depicted as a yellow square in figure 9). This would ensure that the methane would not leak out into the atmosphere and contribute to the greenhouse effect as discussed in previously. After this step would have been performed it would be safe to open up the reactor without risking any gas leaks, also note that when the gas holder was cut off from the downstream part of the system (the path leading back into the house) it will be pressurized so as to allow the gas to be torched.

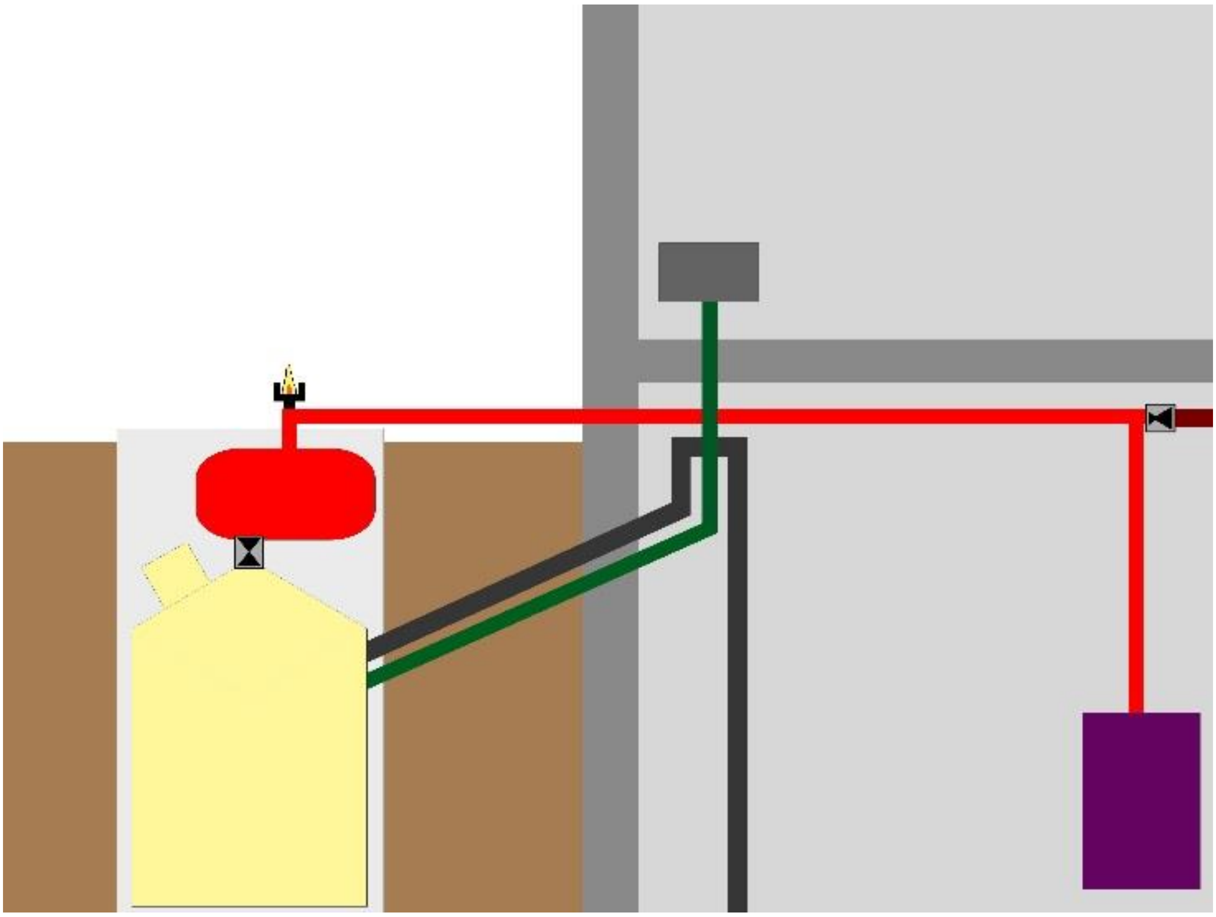


Figure 9 – Concept 3: Well Reactor with Gas Holder

Well Reactor with Integral Gas Holder -*Concept 4*

The fourth concept, Well Reactor with Integral Gas Holder (figure 10), has the same functionality that the gas holder had in the third concept but the solution in concept 4 was designed more integrated into the biogas reactor. With the integrated gas holder solution the reactor in itself was able to pressurize the gas to a constant pressure by weighting down on the flexible reactor hull; alternatively it could have a rigid hull with a flexible membrane on the inside that acts as a pressurizer. To clarify the concept the reader can imagine a weighted down below as a comparison. This concept enables the gas to be pressurized which in turn enables the gas to be burned up, similarly to the system in concept 3, via a torch. Which would enable safe access to the inside of the reactor in the case of maintenance. Other than that the concept was designed similar to concept number 3, the Well Reactor with Gas Holder concept.

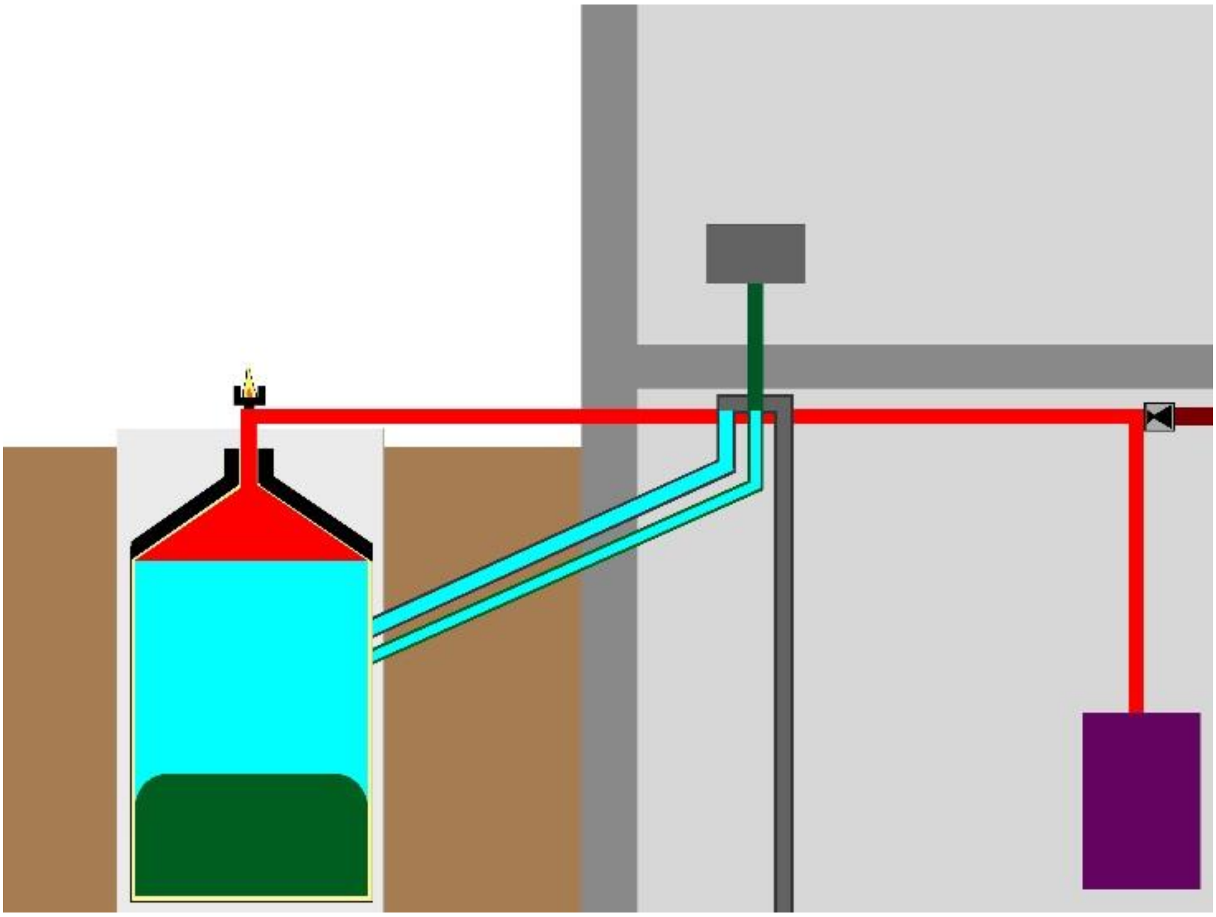


Figure 10 – Concept 4: Well Reactor with Integral Gas Holder

Outdoor Reactor -*Concept 5*

In the fifth concept (figure 11) which was named Outdoor Reactor the reactor chamber was placed on the ground where it was fed with organic waste by pumping it from the inside of the household basement. The pump was positioned approximately underneath the input of the reactor chamber in the vertical axis. This ensures that the substrate was pumped up into a pipe at a slope, which would ensure that no gas would go back through the organic waste inlet pipe since it was full of water or slurry. Having a pump in the system, directed into the reactor chamber also means that it could be pressurized. One way to utilize the pressurization mechanism was to pumping in excess water in order to further pressurize the biogas in the reactor chamber. Pressurizing the gas enables it to be and torched off easily which solves the problem of emptying the gas in the reactor before maintenance without releasing any of the volatile gases into the atmosphere. Since this concept was situated unprotected from the outside weather it demands a solution for maintaining an adequate temperature to support the mesophilic microorganisms that was to produce the biogas. The first step towards this would be to insulate the reactor; other mechanisms for raising the temperature is probably needed but in this early phase of the development no further effort was put towards developing a solution. This would later be found to not affect the outcome of the final concept as will become apparent later on.

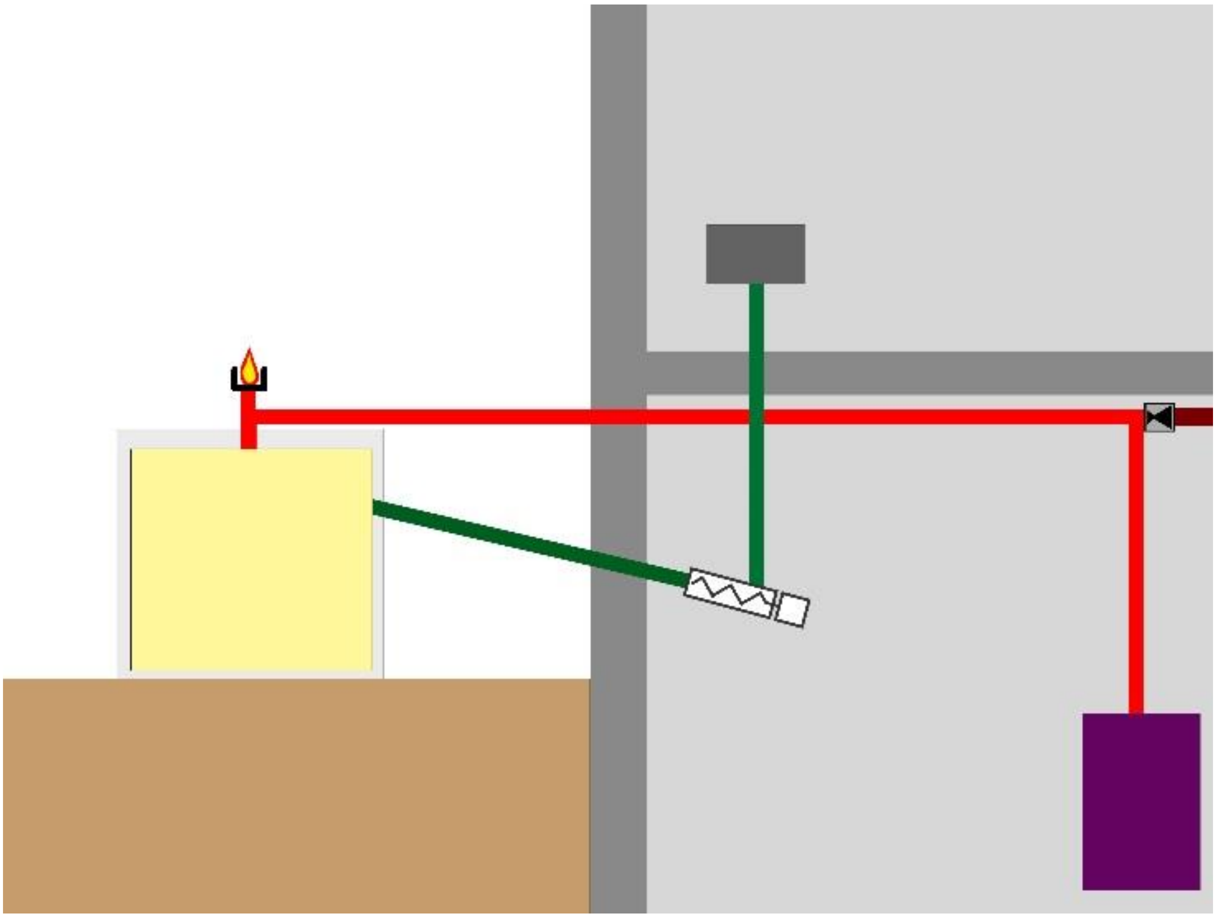


Figure 11 – Concept 5: Outside Reactor

Triple Chamber -*Concept 6*

The sixth concept (figure 12) was more or less a design iteration of the second concept (well reactor) with some minor changes. All the big components that was situated outside of the household in the Well Reactor concept, i.e. the biogas reactor, water buffer and gas tank was in the Triple Chamber concept placed underground in the well. This was also where the name Triple Chamber was derived from. Otherwise the concept was as pointed out previously very similar to the well reactor concept and operates in similar fashion.

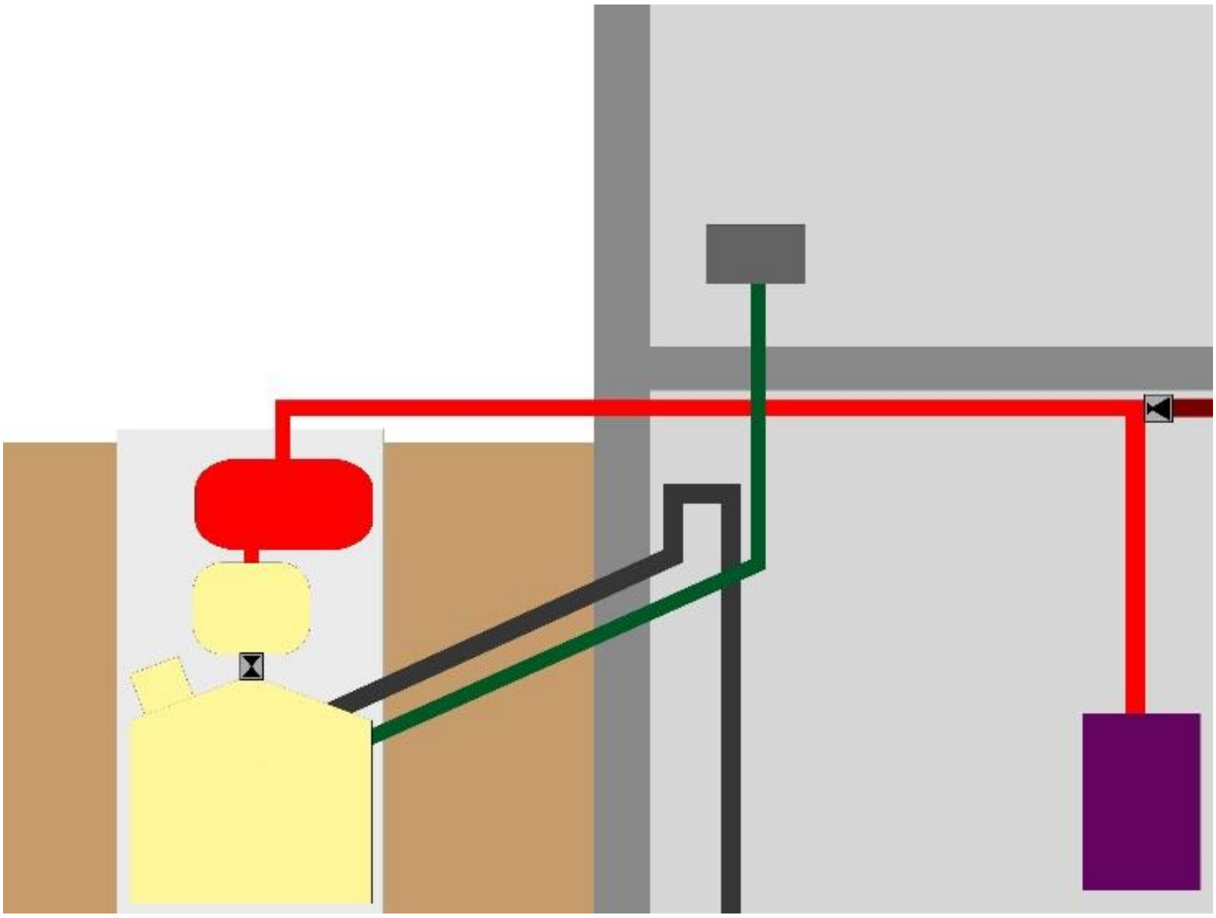


Figure 12 – Concept 6: Triple Chamber

Indoor Reactor with Pump -*Concept 7*

The seventh concept (figure 13) Indoor Reactor with Pump was derived from the Indoor Reactor concept but with some changes. The main change was that concept 7 was designed with the addition of a pump for feeding the organic waste into the biogas reactor. The reason for having this iteration of concept number one is that there are advantages and disadvantages to including a pump in the system and it was not trivial to decide if any of them were superior. The advantage of adding the pump would hopefully make the feeding of the organic waste more stable, while the disadvantage would be the increased complexity and cost of the system.

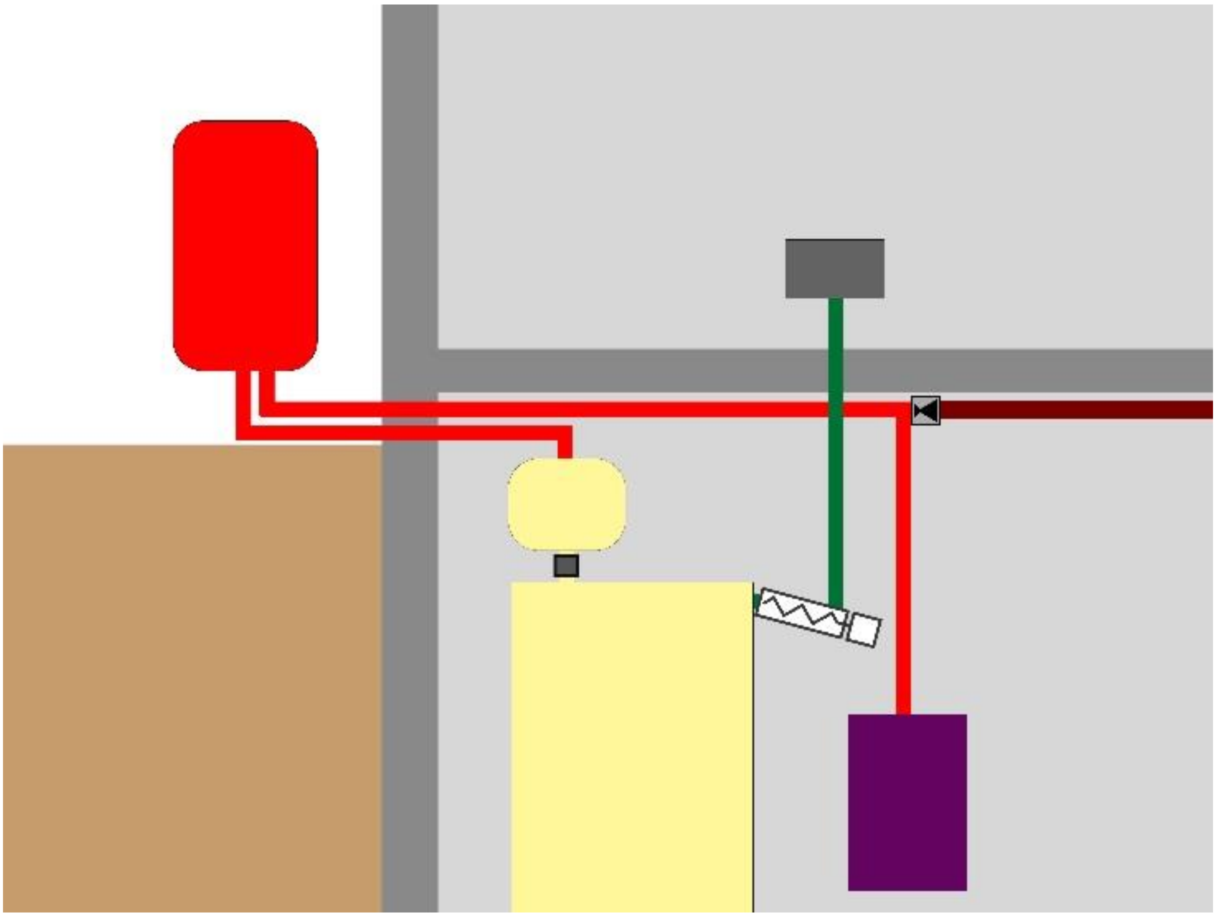


Figure 13 – Concept 7: Indoor Reactor with Pump

Well reactor with pump -*Concept 8*

The eighth concept (shown in figure 14) was an iteration of the previously presented Well Reactor concept but with minor changes. The Well Reactor with Pump concept differs by including a pump for feeding the reactor with the substrate and water. Similarly to the previously presented concept this design change was made to improve the reliability of the organic waste feeding, but it comes at the price of a more complex and costly overall solution.

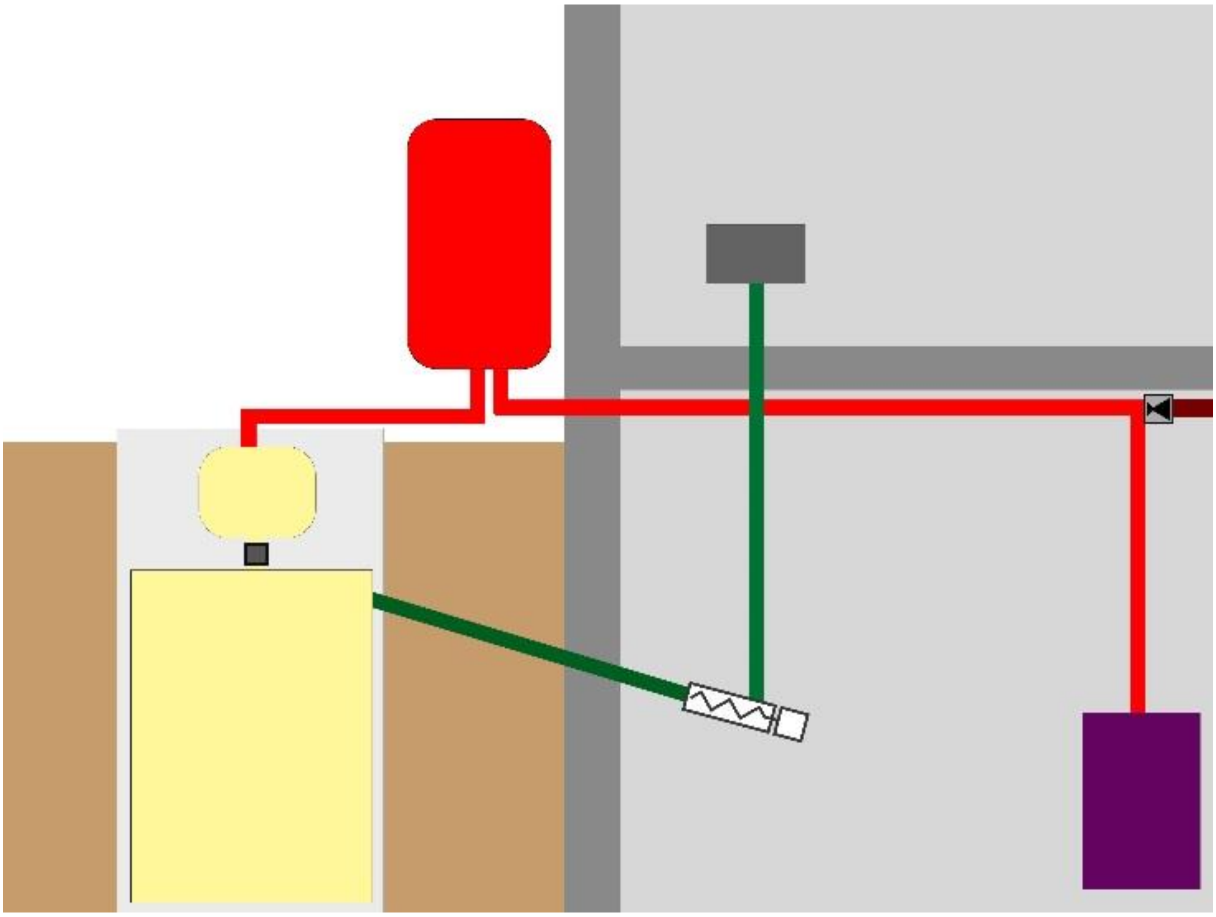


Figure 14 – Concept 8: Well Reactor with Pump

Well Reactor with Gas Holder and Pump -*Concept 9*

The ninth concept (figure 15) was derived from a previously presented concept, namely concept 3 the Well Reactor with Gas Holder. As the name implies a pump was added in this iteration of the concept. The design addition was made to affect the concept in the same way as the pump addition affected the previously presented Concepts 7 and 8, the same advantages and disadvantages exists in concept 9. However the Well Reactor with Gas Holder and Pump concept was also able to utilize the pump in another way, it was able to raise the water level in the reactor chamber by pumping in excess fluid. This is useful when the need arises to empty the reactor for maintenance, it would also be able to pressurize the biogas so that it can be torched off. Depending on what kind of pump that would be selected it could also be used to raise the water level enough to enable the same close off system that is being used in the indoor reactor concept. This would imply that the need for torching off the gas is eliminated making this a slightly more sustainable way of performing maintenance.

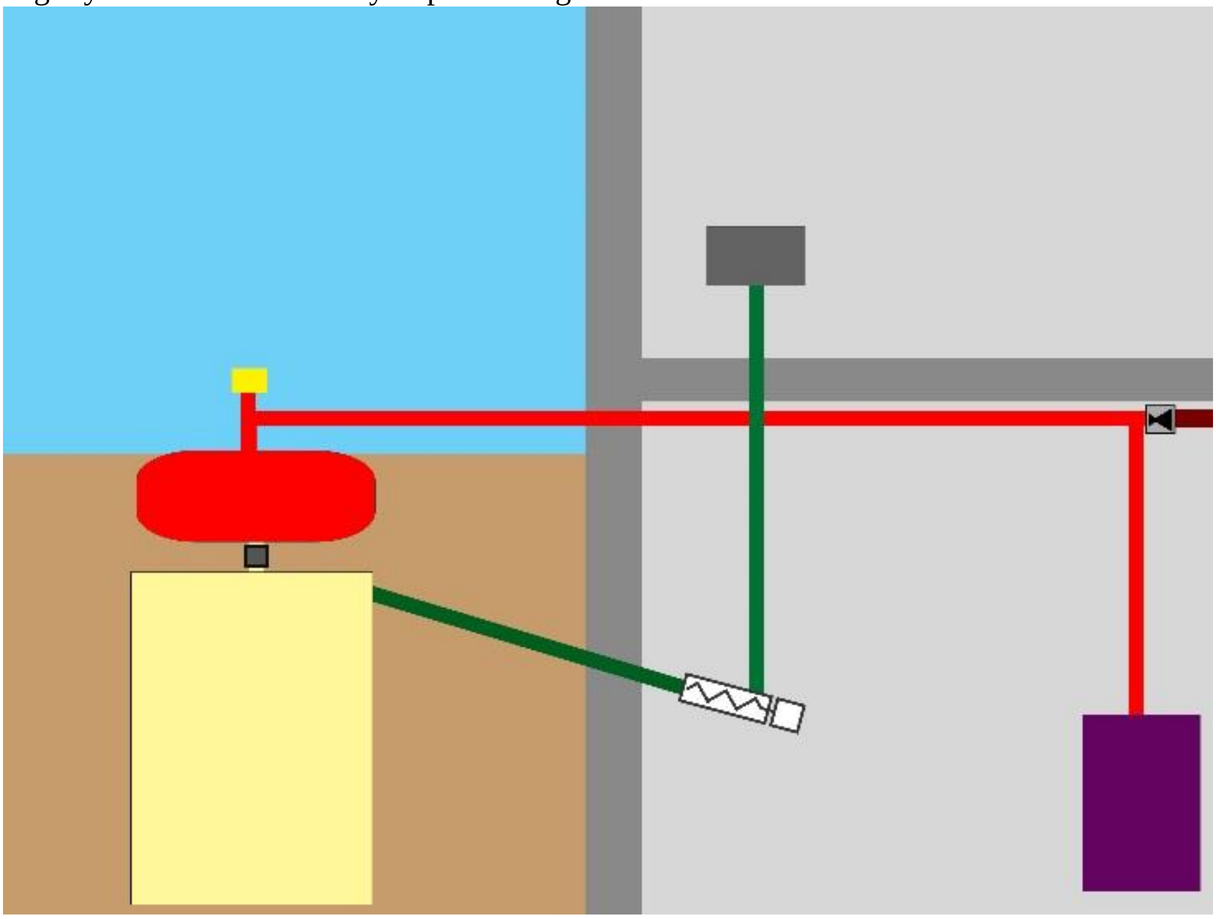


Figure 15 – Concept 9: Well Reactor with Gas Holder and Pump

Well reactor with integral gas holder and pump -*Concept 10*

Concept 10 as depicted in figure 16, was designed as an iteration of a previous concept with the addition of an organic waste slurry pump. The same train of thought was applied to this concept as was applied to the previously presented concept 9; i.e. the pump served both the purpose of feeding the organic waste but could also be used as a way to increase the pressure in the reactor chamber. This design enabled manipulation of the water level that would assist the evacuation of biogas from the system.

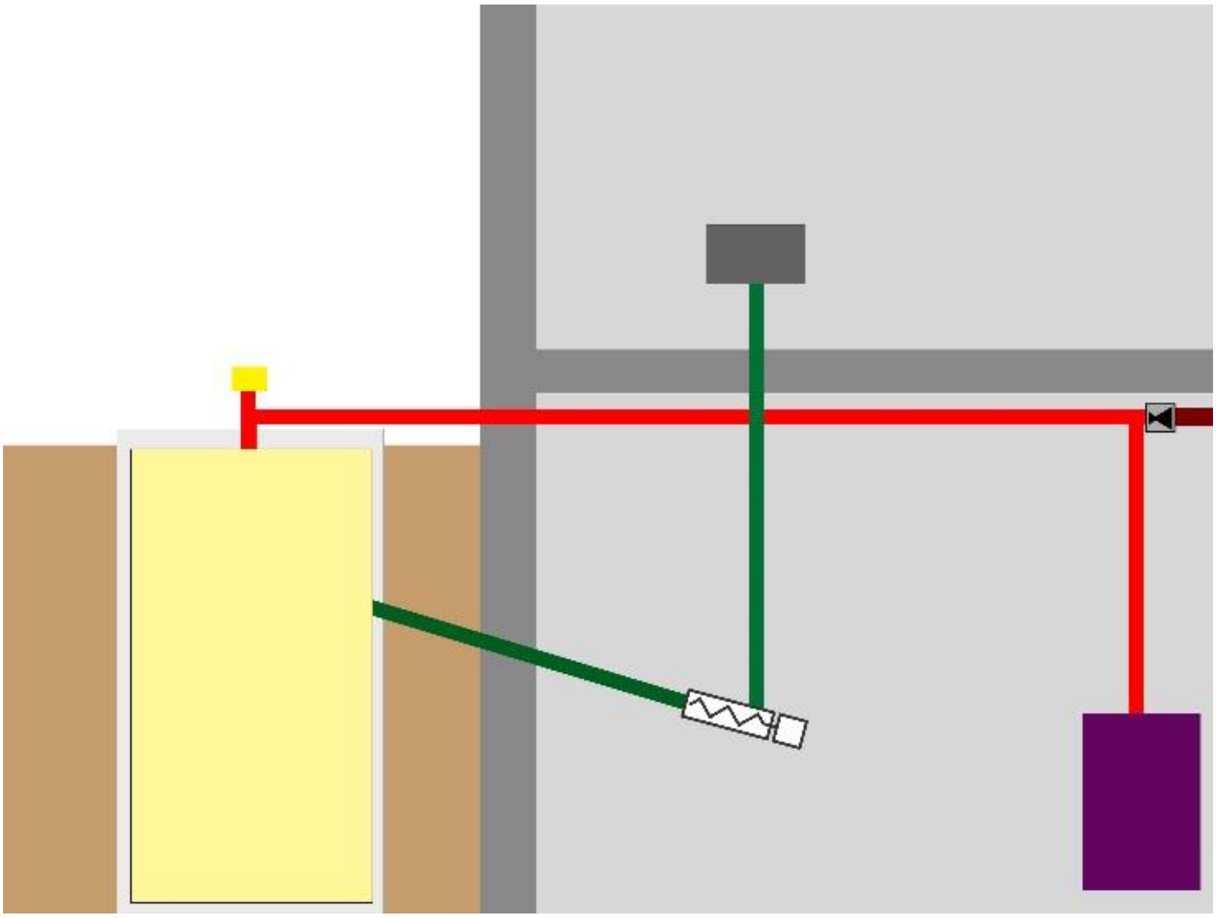


Figure 16 – Concept 10: Well Reactor with Integral Gas Holder and Pump

Triple with Pump -*Concept 11*

The Triple with Pump concept was derived from the Triple Chamber concept but with the inclusion of a pump to the organic waste feed as shown in figure 17. In this concept the addition of a pump was made to improve the input reliability of water and substrate, this concept cannot benefit from extra pressurizing of the reactor with the pump. There was no need for pressurizing the reactor chamber in this concept since it had another mechanism for hindering biogas leaks when opened (as described previously for concept 6).

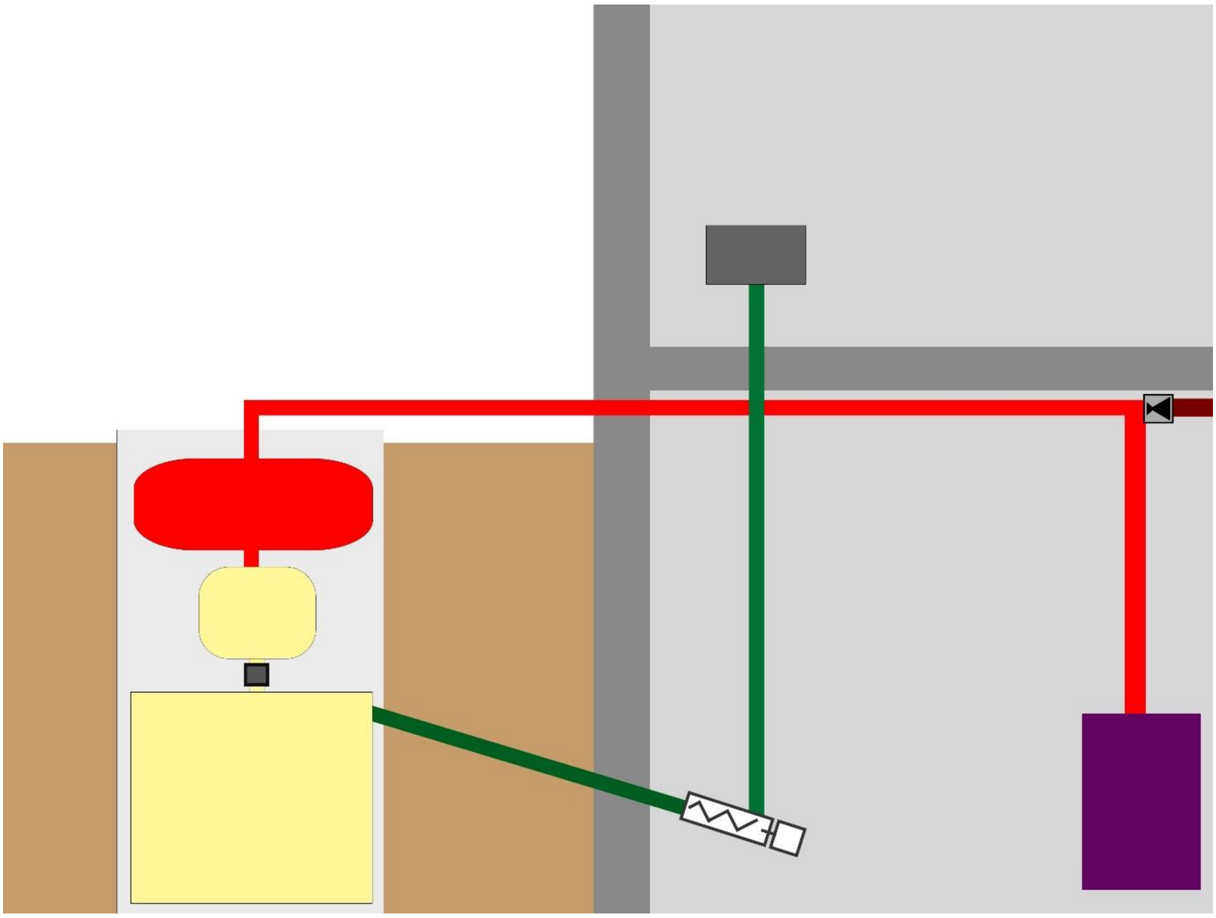


Figure 17 – Concept 11: Triple with Pump

Automatic with Compressor -*Concept 12*

The word "automatic" in the concept name refers to the fact that the slurry emptying mechanism was designed to be entirely self-regulated and automatic. This automatic function operates via the principle of mass equilibrium, when one unit of mass was added through the organic waste inlet the same unit of mass was forced out of the slurry outlet, the concept is illustrated in figure 18. In the beginning period of the operation cycle the slurry outlet was designed to only let out water until enough slurry had accumulated at the bottom of the reactor. This was function was implemented by placing the slurry outlet slightly above the bottom plane of the reactor floor. Having this minimum constant level of slurry in the reactor was to stabilize the microorganism culture found in the reactor Taherzadeh and Rajendran (2015). The slurry outlet was made to connect to an ordinary sewage system which conveniently would transport the depleted organic matter away. The function that the compressor in this system was designed to perform was to pressurize the biogas that had been produced. In order for this to be feasible there had to be a pressure indicator for the accumulated biogas and an actuator for the compressor that would start the compressor when it was needed. This also had the implication that the water, slurry and gas level will (relatively to each other) increase and decrease when the biogas was accumulated and thereafter evacuated, this fluctuation would be small and therefore the three surface levels only slightly fluctuate themselves.

The decreased need for long term storing of the slurry in the reactor (in comparison to the previously presented concepts) enabled the biogas reactor size to be decreased. The limiting factor for determining the size was with concept 12 changed from the volumetric amount of slurry that needed to be stored to the size that was needed in order to attain optimal efficiency. Or in other words, in order to ensure that the organic waste was sufficiently digested the reactor size and the corresponding flow-through time of the organic waste would have to be adjusted. Unfortunately no known models for determining the time it would take for the organic waste to flow through was found. Furthermore the actual optimal reactor size would vary greatly with the temperature in the reactor chamber and it could also be optimized towards on average utilize a smaller portion of the maximum theoretical yield as a trade-off for a more compact solution.

With all of these variables it would be extremely hard to optimize the flow through time of the organic waste, a compromise would have to be made; considering this overestimating the volume would be better than producing a reactor that was too small if efficiency is prioritized. This claim was furthermore supported by the fact that the mesophilic activity increases with increasing temperature, the microorganisms thrive in a temperature span. But in a sub-optimal temperature the activity would not completely stop, it would just be lowered. Thus the lowered digestion rate of the reactor would have to be compensated with an increased flow through time of the substrate, this would ensure that the organic waste would have time to sufficiently deplete.

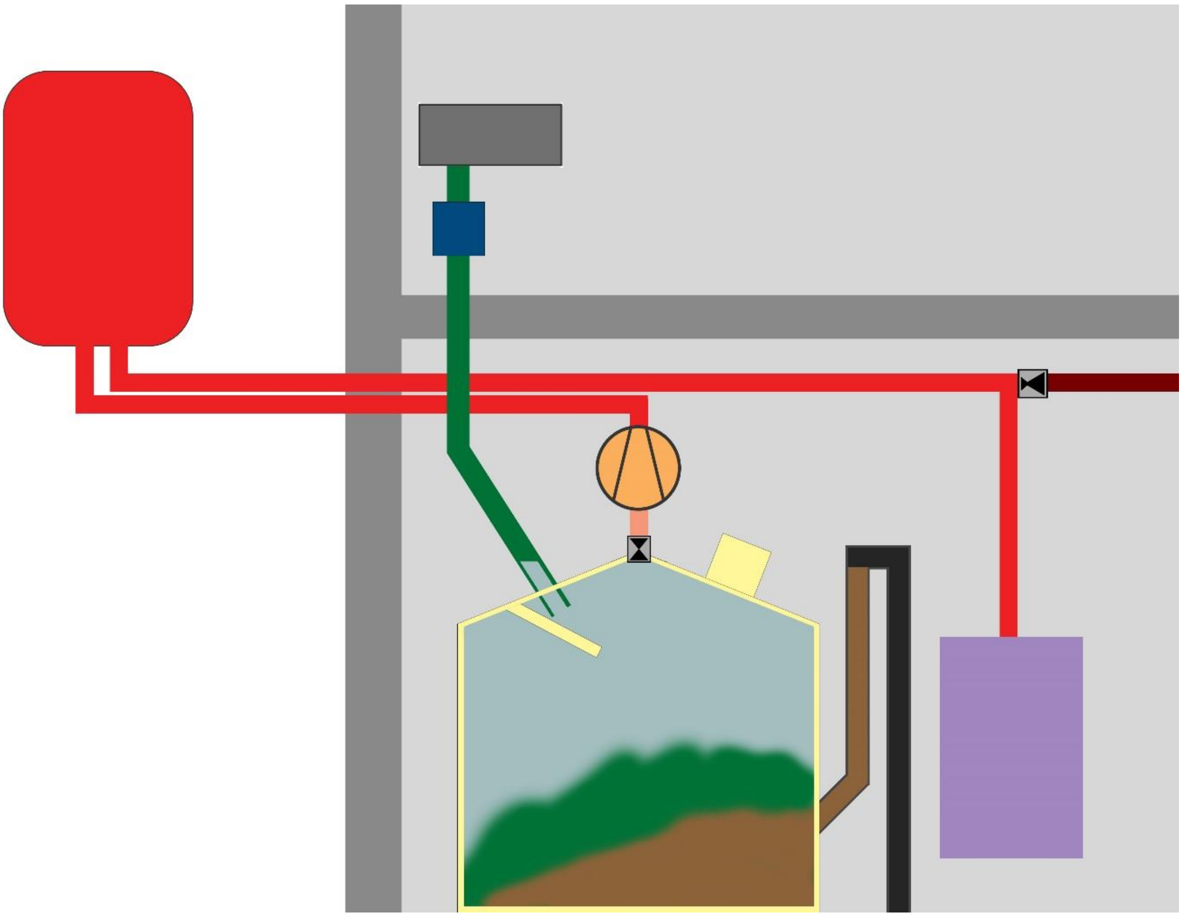


Figure 18 – Concept 12: Automatic with Compressor

The Automatic with Compressor concept was however also designed with a lot of similarities with other concepts that previously presented. One of these similarities was the close-off valve that can be used to open the reactor without risking gas leakage, another the gas holder that was placed on the outside of the household to decrease the risk of gas leaking into the household. Furthermore the organic waste was designed to be atomized and then fed through the input pipe similarly to what was presented in this beginning of this chapter.

Automatic -*Concept 13*

The concept Automatic was derived from concept 12 (Automatic with Compressor) but instead of utilizing a compressor for transportation of the biogas out of the reactor, it handles this similar to the Indoor Reactor concept. In other words: there concept was designed with a sealing mechanism for shutting off the flow from the reactor to the gas system. When the system was operating the biogas would always be pressurized which means that the water and slurry surfaces are higher up than the biogas level as depicted in figure 19.

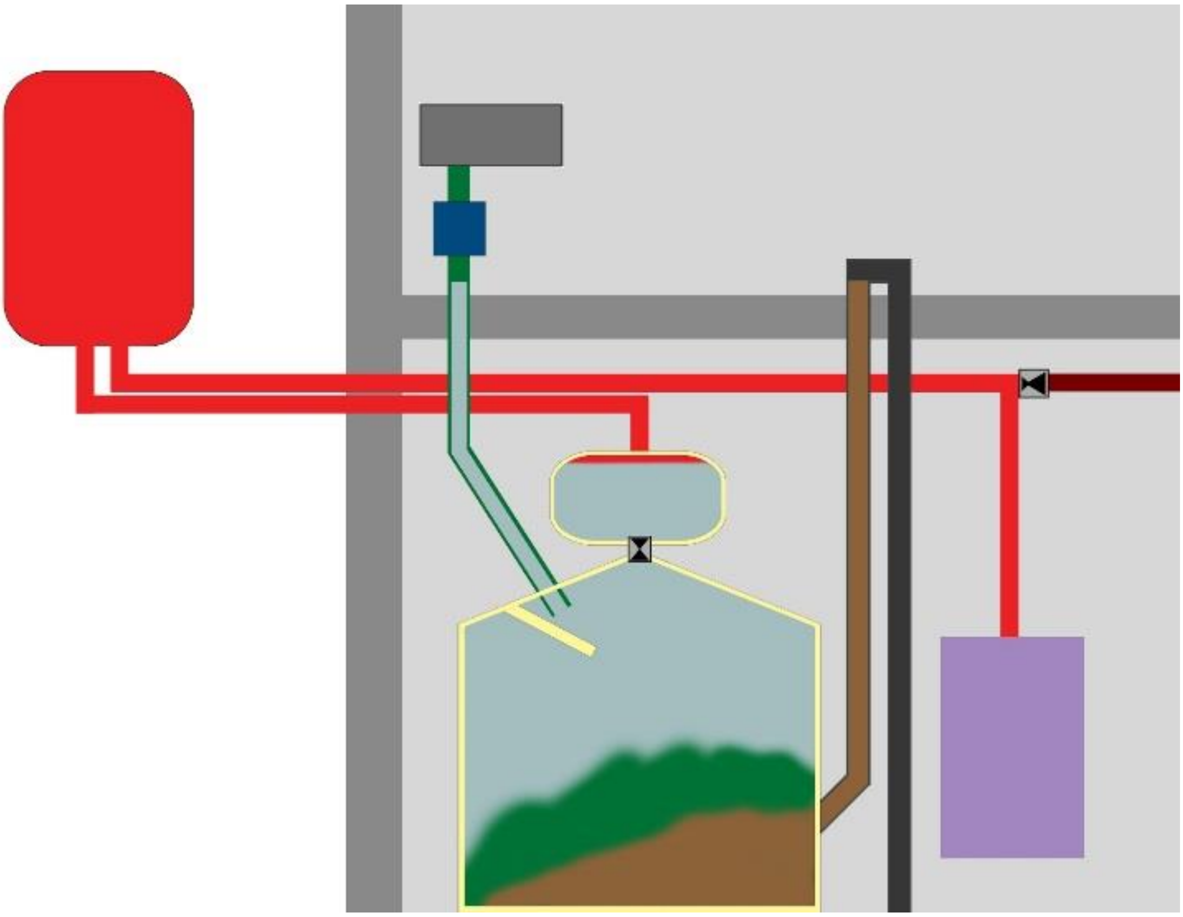


Figure 19 – Concept 13: Automatic

Well with Compressor -*Concept 14*

The Well with Compressor concept (figure 20) was a combination of the second and the twelfth concept; the concept consists of an automatic slurry emptying mechanism located outside in a well in the ground. The biogas was made to be accumulated with the help of a pump controlled by a gas gauge similarly as in concept 12. The bottom of the well could also be made to accept the actual slurry from the reactor, the slurry outlet pipe would then empty the slurry downwards. The rest of the features of concept 14 can be found in previously presented concepts. The organic waste would be fed through a pipe, the reactor could be closed when the need for maintenance occurs and organic waste would be pulverized just under the loading sink.

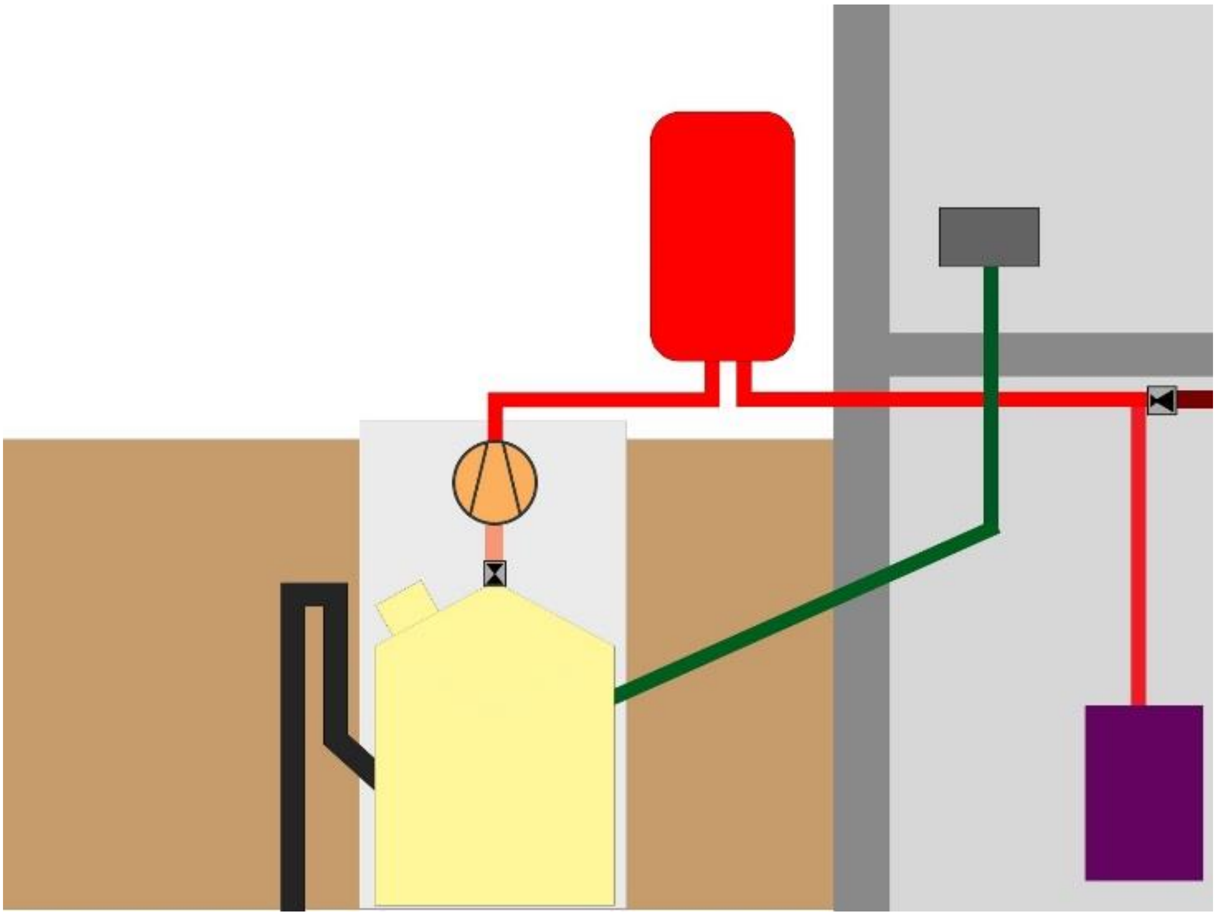


Figure 20 – Concept 14: Well with Compressor

Well Automatic -*Concept 15*

The Well Automatic concept (figure 21), was based upon concept 13 but similarly to concept 14 it was situated in a well outside of the household. The concept was made to function like concept 13 except for two differences; the substrate was made to travel from the loading sink out to the reactor in a pipe through the ground and the slurry output would be emptied underneath the biogas reactor instead. This concept demands a suitable well that the well was suitable and mostly viable if the well is pre-existent.

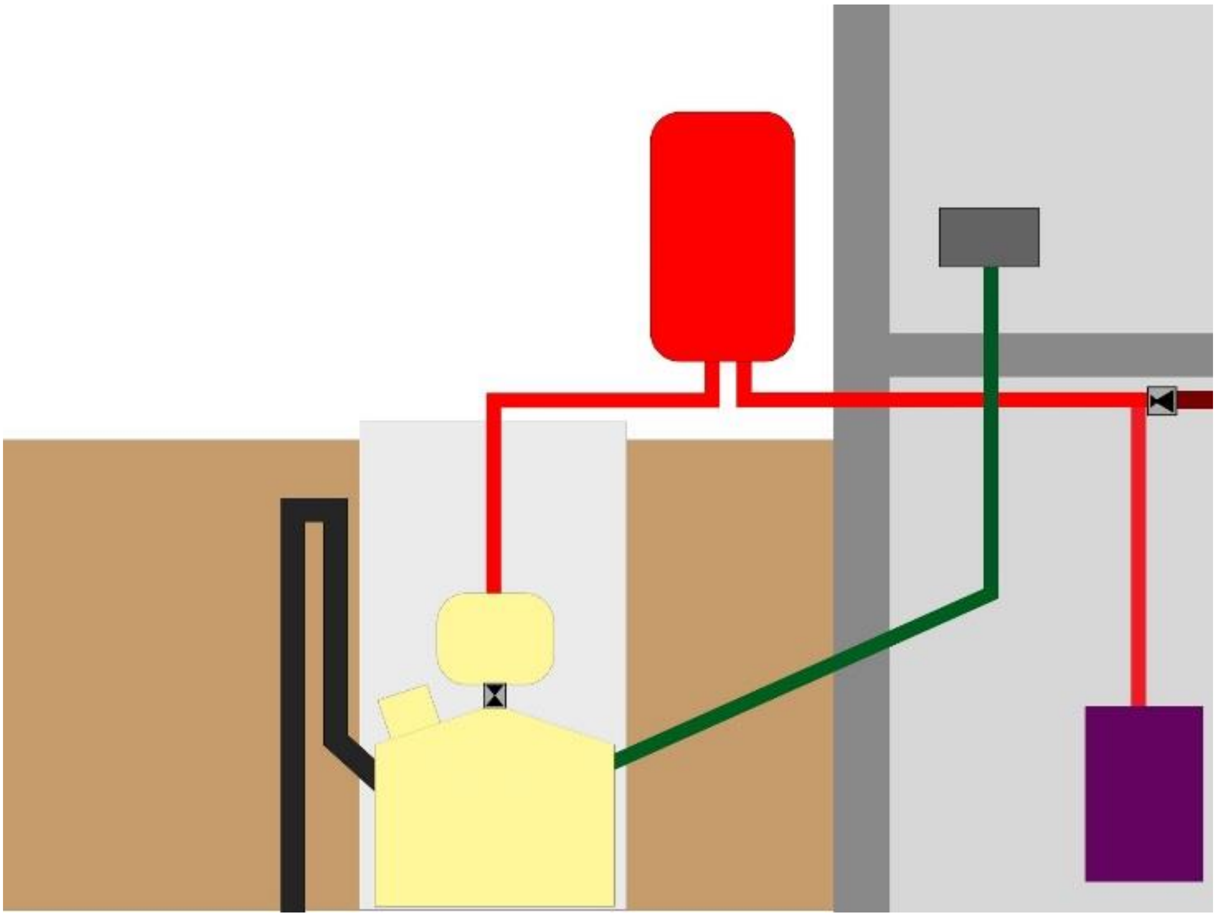


Figure 21 – Concept 15: Well Automatic

Concept evaluation

The first part of the concept evaluation was to screen the concept as explained in part 2.2.2 of this report, the concepts that passed the screening matrix are shown in table 2 (the complete matrix can be viewed in the supporting documents chapter 6.1).

	Indoor reactor	Well reactor	Well reactor with gas holder	Well reactor with integral gas holder	Triple chamber	Automatic with compressor	Automatic	Well automatic
It is robust and won't break or leak	+	+	+	0	+	-	+	+
The biogas digester is easy to use at an everyday basis	0	0	0	0	0	0	0	0
It is easy to maintain	+	0	0	0	0	+	+	-
The digester is effective at producing biogas	0	0	0	0	0	0	0	0
The investment cost is low	+	0	0	0	0	0	+	0
It is easy to empty the slurry	+	+	+	0	+	+	+	+
It does not take up much space indoors	-	0	0	0	0	-	-	0
It does not leak gas when it is emptied	+	+	0	0	+	+	+	+
Sum +'s	5	3	2	0	3	3	5	3
Sum 0's	2	5	6	8	5	3	2	4
Sum -'s	1	0	0	0	0	2	1	1
Net score	4	3	2	0	3	1	4	2

Rank	1	3	5	8	3	7	1	5
Continue?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 2 – Screening Matrix

The concept screening results left eight concepts remaining as seen in table 2, these were: Indoor reactor, Well Reactor, Well Reactor with Gas Holder, Well Reactor with Integral Gas Holder, Triple Chamber, Automatic with Compressor, Automatic and Well Automatic.

These eight concept were kept for continued evaluation while seven were discarded, the amount of concepts that were kept could be argued to be picked arbitrarily. However considering the time frame of the project it was deemed adequate. By inspecting the screening matrix, several conclusions could be drawn. Two of the screening criteria never had any influence on the result of this screening step, these criteria were that the biogas should be easy to use at an everyday basis and also the criteria that the digester should be effective at producing biogas. Both of these screening criteria were deemed of great importance for the project, but in the screening no relative merit was found for these criteria and therefore they were assumed to be redundant. Furthermore the Indoor Reactor concept and the Automatic concept both had the highest net score of four, while the Well Reactor and the Triple Chamber concepts each had three in net score. The shared advantages that the two concept that placed with the highest rank was that their maintenance was easy to perform and that their investment costs were low.

The feasibility of the different concepts were investigated by closely analyzing the different sub-concepts and assessing their functions, this also lead to that the majority of the sketches were redrawn in more detail. One concern that emerged from this analysis was that the mechanism for emptying the slurry automatically (that is used in concept 12, 13, 14 and 15) might clog up, depending on the viscosity of the slurry generated in the digestion process. With a high enough viscosity the risk that the slurry would clog up in the slurry output would be prominent, since higher viscosity increases the fluid's resistance to flow (White, 2008). However this risk could be mitigated by dimensioning the diameter of the output pipe so that it would be appropriate for use with the pressures and slurry composition that would be expected. There are however no known theoretical models for achieving this, so this would have to be estimated, prototyped, tested and refined in order to be sure about the reliability. Additionally the fact that there were a plethora of different biogas reactors that worked by the same mass equilibrium principle was seen as an attest to its feasibility.

Another feasibility issue that became a concern was the difficulty of determining the right size for the biogas reactors that require periodical maintenance and to know when to actually empty them. This problem was mostly a dimensioning issue though, and could be resolved with sufficient prototype testing and refinement of a physical true scale biogas reactor.

A further investigation regarding the concern that the slurry would clog up the system was performed with a miniature physical prototype of the sub-concept of having a reactor that automatically empties its slurry. A reactor was made with a water input and slurry output hoses attached. This was later tested and evaluated, the results of will be presented hereafter.

The prototype test was supposed to demonstrate two of the functionality of the finished biogas reactor. The first function was the concern about the previously mentioned risk for clogging of the automatic slurry output. The second concept demonstrated is that the pressure difference will be maintained through the system even if the fluid is flowing through the system, this principle is found in concepts 1, 2,3,4,6, 13 and 15.

The prototype consists of a container that has a mechanism for pressurizing itself, in this container two holes were drilled and tapped. Nipples were then attached to these holes and hoses were mounted onto the nipples. Now the test was carried out by cycling a slurry substitute through the already pressurized container which was halfway filled with water. The slurry substitute was durum wheat which in combination with the water became highly viscose.

Figure 22 depicts the prototype assembled with the internal chamber pressurized with air, note that the water levels in both the hoses have risen due to the internal pressure. In the following picture (figure 23) the slurry had risen above the uppermost position of the outlet pipe and traveled further downstream to be emptied out. This did not happen instantly, it took approximately six seconds for the slurry to travel the distance shown in the pictures, which was the result of the highly viscous slurry substitute. But the conclusion of the experiment was that the prototype functions correctly, and the lag of the system should not be a problem since the feed rate and flow through time were already very long for the system, a fast response from input to output was not considered necessary.

Figure 22 – Prototype test

Figure 23 – Prototype test

A failure mode and effect analysis was also performed, the FMEA table can be found in the supporting documents (chapter 6.4). The eight concepts that were kept after the first screening were analyzed in the failure mode and effect analysis. The different functions that were covered was: feed organic waste into the reactor, empty depleted slurry without leaking gas, extract biogas, raise pressure, maintain mass equilibrium, open reactor for maintenance. All of these and their failure modes, potential failure effects, potential causes and current process controls should all be self-explanatory for the reader.

To evaluate the concepts after the FMEA the average RPN was first calculated, the best averages were in order: Inside reactor, Well Reactor, Well Reactor with Gas Holder, Triple Chamber and Automatic. The second evaluation was to summarize the four highest RPN values of each concept, the concepts that had the lowest sums were (listed in order): Inside reactor, Automatic, Well reactor, Well reactor with gas holder and Triple chamber. The average CRIT values were also calculated, the best were (listed in order): Inside reactor, Automatic with compressor, Automatic, Well reactor, Well reactor with gas holder. The concept that had the lowest risks was the Inside reactor, since it scored best in all the different evaluations. The Well Reactor, Well Reactor with Gas Holder, Automatic and Triple Chamber are the other concepts that are also considered to have low risk priority. While the Automatic with compressor values, especially when the SUM and average RPN were considered had considerably worse R.P.N values.

Assessment of the production feasibility was done by scrutinizing the concepts and analyzing the geometry of the parts. None of the concepts possessed any parts that required any novel geometry or complex production methods. Most of the parts except the biogas reactor could already be found in today's society. The biogas reactor also had quite simple geometry but depending on what material that would be chosen it would be produced in different ways. If a metal would be chosen as the material for the reactor it would have to be shaped and welded to be constructed. Which was considered to be a highly feasible but expensive production method. The other apparent alternative was to use the FOV textile that on one hand also needed to have its seams welded, but since the fabric is flexible it would require less shaping, this production method alternative was also deemed feasible.

Estimating the manufacturing costs of the concepts was done in this phase of the project but was limited to only approximating the relative cost between the concepts. Since some of the concepts clearly had big differences in manufacturing costs it was easy to make a rough relative ranking based on the concepts and estimating the prices that their components would produce. For instance the first concept, Indoor Reactor would probably be the cheapest since it had a simple reactor design with inlets, outlets and solutions that are modest and have low complexity. The large costs of this system would be the reactor and the actual installation of the gas system (depicted in red in figure 24).

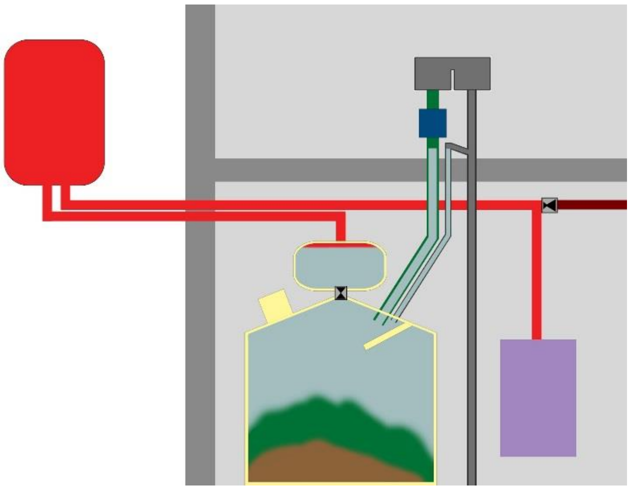


Figure 24

In the other end of the spectrum there was concepts like the Triple Chamber where the reactor and some parts of the inlets, outlets and gas system was placed in the ground. This would inherently lead to an increased installation cost for the biogas system, especially if no old well that could be utilized already existed in the household. Somewhere in the middle of the cost spectrum we would have concept 12, the Automatic with Compressor. The compressor would add both cost and complexity to the system which would raise the price of the concept relatively to the Inside Reactor concept for instance. These logically deducted relative costs were used as a base for the concept selection matrix whose results are presented in the next part.

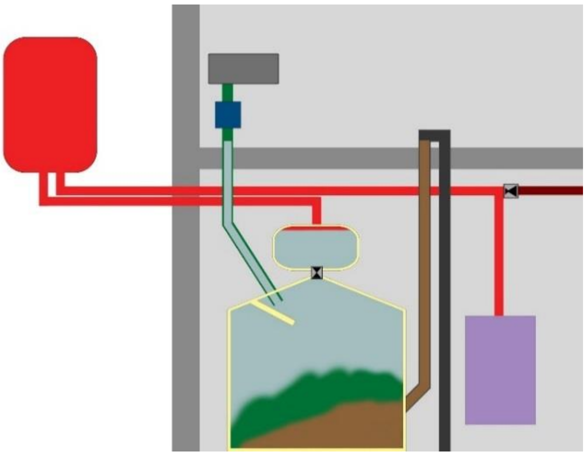


Figure 25 – Concept 13: Automatic

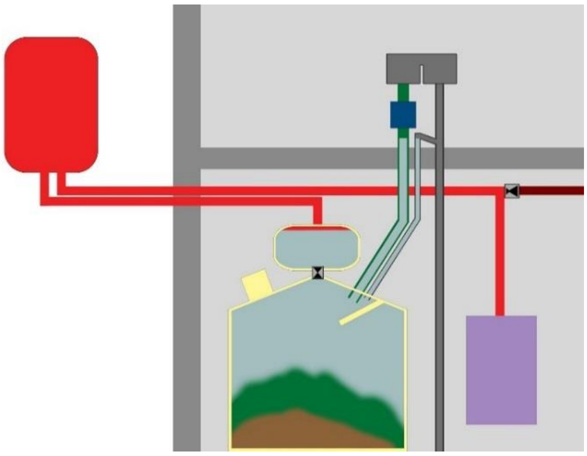


Figure 26 – Concept 1: Indoor Reactor

Concept selection

The concept selection was mainly decided by utilizing the weighted selection matrix that was first introduced in the method chapter, the results of the weighted matrix can be seen in the supporting documents (chapter 6.2). The two top contenders for the final concept that emerged from the weighted selection matrix was the Automatic concept (figure 25 and 27) and the Inside Reactor concept (figure 26 and 28). The Automatic concept scored 424 points and the Inside reactor scored 412 points in the weighted matrix, compared to the third best that had 384 points. The rest of this subchapter will focus on comparing these two concept and their results in the selection matrix. Later the results from the entire selection matrix will be briefly reflected upon. The Inside Reactor concept and the Automatic had similar results in a lot of the criteria of the selection matrix, the criteria that actually did not match were: the robustness, maintenance amount, the ease of emptying the slurry, the space required of the basement and the ease of use. The differences will be discussed below so as to explain the results in the matrix. The largest advantage that the Automatic concept had over the Inside Reactor concept was its ease of use; the feeding process was identical between the cases but the difference was apparent when comparing the maintenance needs between the concepts. Concept 13

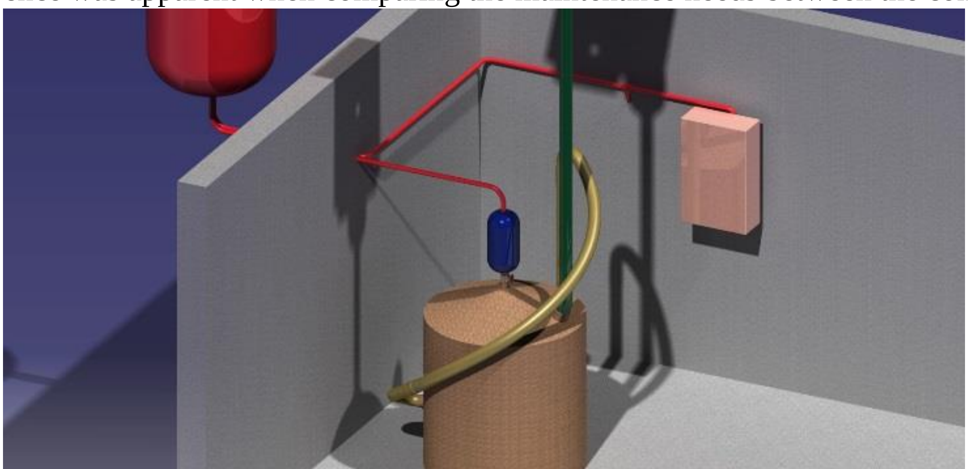


Figure 27 – Concept 13: Automatic - CAD

will probably only need to be serviced after quite a large operating cycle, an estimation would be every three years. While concept 1 would have to be periodically emptied since the slurry would be accumulated and stored in the reactor, this means that the operating cycles will be much shorter for the Inside Reactor concept. Depending on the feeding rate, household size and most importantly the reactor size the interval that the Inside Reactor concept could go before it needed to be emptied was approximated to be anywhere from 4 to 18 months. The difficulty of the process of emptying the reactors was also considered, clearly the Inside Reactor concept was worse since the Automatic concept did this process automatically without any user effort. Also since concept 13 did not have the need to store as much substrate as concept 1 needed to, its reactor could be dimensioned a lot smaller; when emptying the reactors this would greatly affect the amount of time needed. Furthermore the need for periodical emptying also lead to the need for knowing when to empty the reactor, thus far in the development the only solution for this problem was to empty it periodically following a schedule. This schedule would have to be approximated and could for instance be calibrated by measuring the households food waste generation rate over a small time period. For instance by keeping count of the waste generated over a week would determine the approximate time until the next emptying, this task could be made easier through an smartphone app or a homepage for instance.

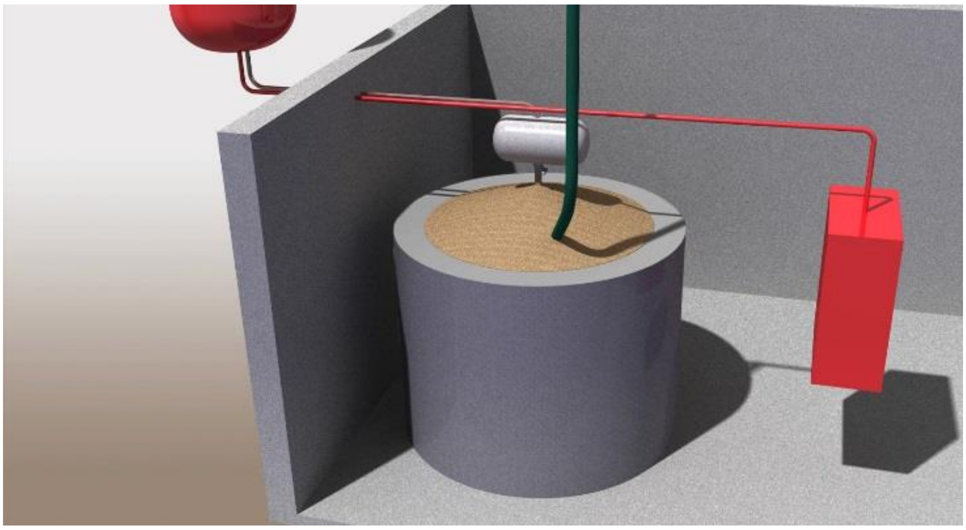


Figure 28

Another method for calibrating the households emptying schedule would be to run the reactor for a low time period and then opening it up to measure the actual amount of slurry that had been accumulated. This would probably be more accurate but would require more effort. However as previously mentioned this need for calculating an emptying schedule does not exist with the Automatic concept, since it is self-emptying the only reason the empty it would be to perform periodical maintenance.

The largest advantage that the Inside reactor concept had over the Automatic was that it was the more robust solution. As long as the organic substrate could make its way into the reactor it would function and had a very low chance of clogging up to an extent that would jeopardize the operation of the system; concept 13 was more prone to clogging in comparison and clogging of the slurry output would have more dire consequences than the clogging that could occur in the Inside reactor concept. This was especially obvious when comparing the FMEA results between the different concepts, where the risk priority number of the failure mode of clogging for concept 13 was 250 the corresponding failure mode for concept 1 had a RPN of only 90.

The Automatic concept scored highest in the weighted matrix which had a lot to do with its high usability. It also had reasonable scores in the FMEA. Where the worst part was the risk that the slurry emptying mechanism could clog up. But since there exists a large number of similar designs, and the possibility to actually incorporate a peek-glass or a maybe even a mechanism to un-clog the slurry without completely emptying the reactor could be implemented. It was deemed that the tradeoff of having a less troublesome operation outweighs the more robust operation that the Inside Reactor concept could potentially deliver.
Considering all of these differences and the fact that the Automatic concept was rated the highest, concept 13 was chosen for further development.

3.3 SYSTEM-LEVEL DESIGN RESULTS

Clearly the homes for which the biogas reactor was developed for does not have common dimensions or geometry. Therefore options for the installation would have to be available for some of the need that will differ between households. The biggest variance between different households was assumed to be connecting the delivered solution to the different parts of the household, for instance the organic waste feeding tube might need to come down in different angles or lengths. In order to adjust the system to different households a variety of lengths and dimensions of the tubes and bends should be available.

The pathing of the slurry outlet could also be made in a lot of different configurations, for instance it could circle around the reactor with a low elevation angle, to make the ascent of the slurry easy at the same time as it would take up little space. Other households might find it less obscuring to extend the slurry outlet in a specific axis of the room, in this case a straight slurry outlet with a slope would be preferred.

There were also a need for different sized reactors, depending on the number of people in the household and the amount of organic waste they produce. The limiting factor for the size of the reactor, as previously discussed in chapter 3 when concept 12 was introduced, was the flow through time in relation to efficiency based on the temperature in the reactor. As previously mentioned this would have to be prototyped and tested in order to get good results.

In this stage of the project the concept was pretty far developed, but the final concept had a few things that needed to be further matured. The first step to completing the development of the concept was to finalize the architecture.

As discussed in chapter 3.1.4 polymer and steel are two materials that was found in use in biogas reactors. However integrating these kind of reactors into a household environment had a couple of downsides, one was that the size of the reactor or the placement could become limited; the optimal reactor size might be too big for the door which it needs to pass through. And another concern was that for instance steel, even with stainless qualities were susceptible to corrosion in the intended environment. Both of these issues are solved if the novel textile developed at FOV was chosen (Rajendran et al., 2013), it had the needed sustainability for the low pH environment and could easily be brought in through any door opening or transported in an efficient manner since it is flexible.

However the biogas reactor was only a part of a larger gas system and a lot of the parts that was to be used in the complete system would preferably be bought off-the-shelf. The parts that were deemed favorable to buy off-the-shelf were: the gas pipes, shut-off valve, buffer tank, hose clamps, gas holder, sealant and of course the waste disposal unit and its peripherals. Furthermore pipes for input and output of the organic waste and slurry respectively could be made up partially of off-the-shelf sewage pipes; however some of the geometry that was preferable for the Automatic concepts connection pipes are not standard geometries. Therefore a combination of using both off-the-shelf products and custom designed ones was deemed the most cost effective option. The flexible fabric that makes up the biogas reactor would need some kind of support and protection, therefore the choice to design a shell and lid was made. The development and construction of these parts are presented in the detail design phase. Furthermore the substrate loading slide was to be constructed in full detail, the function of it would be to hinder that the biogas would make its way up through the input pipe. And the last part to be designed was a support for the slurry output pipe.

Since the concepts have gone from several to one concept, some of the specifications that were in the original target specifications list had ad this point become redundant or changed. One example was the case of the capacity of the reactor where the value range changed from [1,0 / 2,5] to [1,0 / 0,3] m^2, inverting the relation between the ideal and the marginal value, to optimize for a smaller volume instead of a larger. This was due to the fact that the target specifications were not objective enough, it fit the majority of the concepts but not all of them.

Metric No.	Need No.	Metric	Importance	Units	Marginal Value	Ideal Value
1	1	Should not be destroyed by corrosion over a specific time	5	years	10	100
2	1	All fluid and mass containers in the system that needs to, should withstand the control pressure	5	mbar	150	450
3	2	Maceration demands few actions	5	# of actions	5	2
4	2	Feeding time	5	s	360	10
5	3	The reactor capacity	4	m^3	1	0,3
6	3	The maximum amount of biogas that is allowed to escape when the slurry is emptied	4+1	Nm^3	0,05	0
7	5	System manufacturing cost	3	SEK	50000	10000
8	7	Floor area that the system occupies	2	m^2	4	2

Table 3 – Final Specifications

The product and its intended use was almost entirely utilitarian, and therefore some of the industrial design needs that could be associated with products that wants to instill pride of ownership or other non-functionalistic properties was not prioritized to a large extent for this project. In other words the focus for this project was to optimize for performance and utility at a low cost. But the shell discussed previously was one of the few parts where industrial design was more prominent. The shell and lid was shaped to resemble a pressure vessel tube, this can be observed in figure 30. There were two reasons for this decision where the first one was the utilitarian use this design mediates and that being associated with a pressure vessel would not be a bad image considering safety. The second reason was the fact that it also slightly increase the rigidity of the lid in comparison to a flat top.

3.4 DETAIL DESIGN RESULTS

The results for the detail design phase consist of defining the part geometries, material selection and manufacturing cost estimation. The part geometries were all designed in Catia, the system with detailed parts are depicted in figure 29 and 30. Figure 29 represents the final concept of the project in a sectional view cut halfway through the reactor, the peripherals needed to make up a complete example system are also present. Depictions of all the individual parts that are to be fabricated (not bought off-the-shelf) are available in the supporting documents 6.8, they can further be found in figure 30. These are also listed below:

- Biogas reactor
- Shell plates
- Shell lid
- Input pipe
- Input pipe slide
- Slurry output pipe

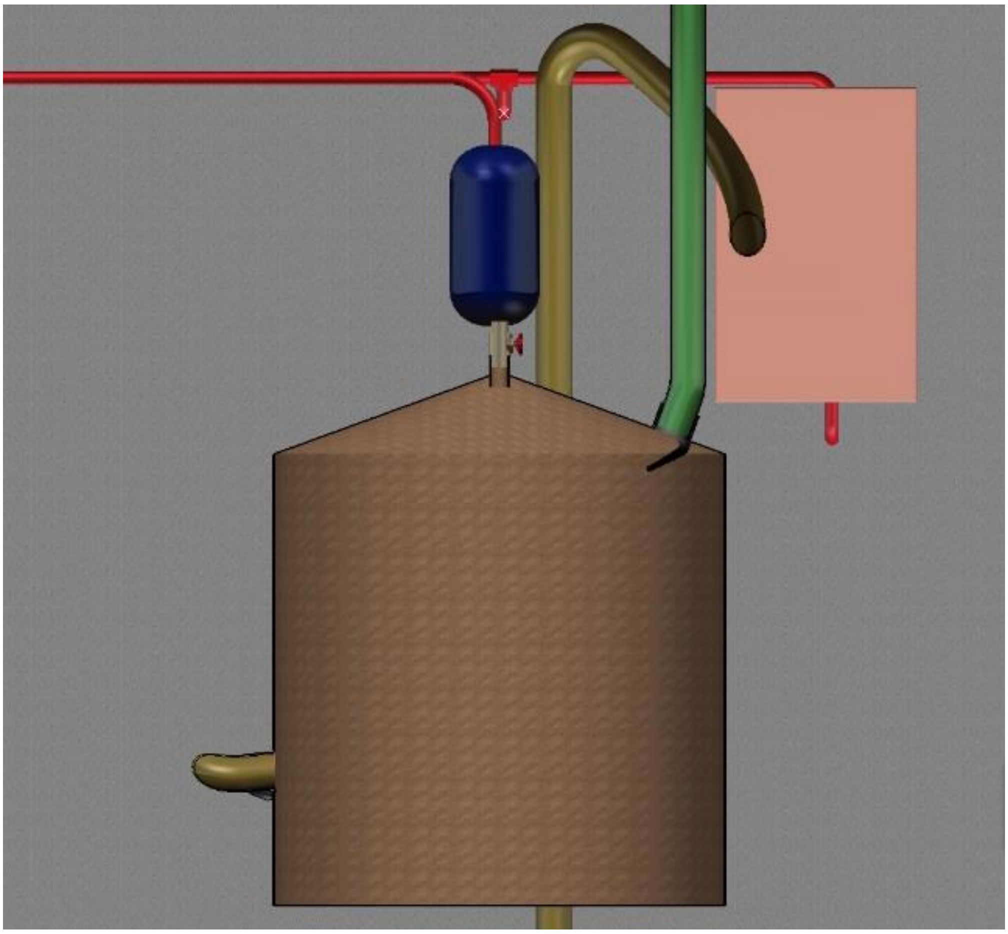


Figure 29 – Sectional view of the final concept

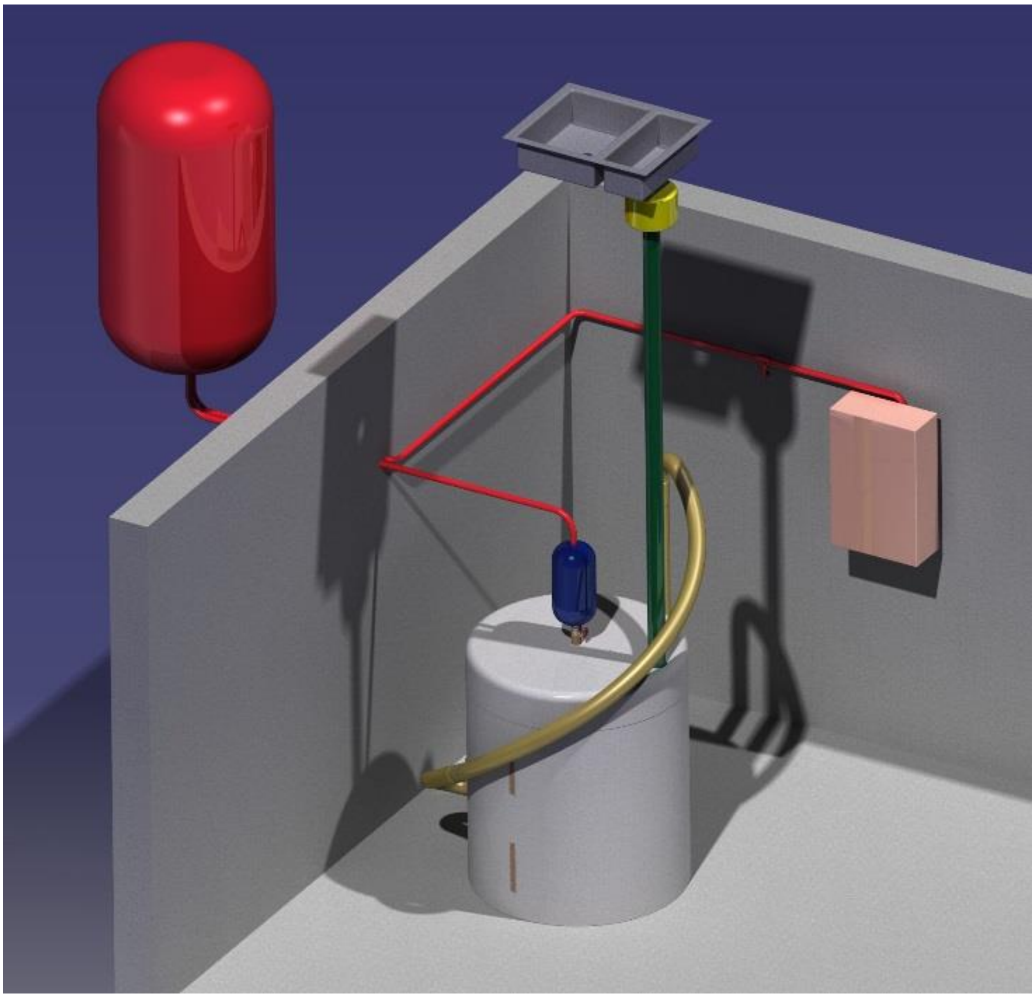


Figure 30 – Render in an isometric view of the final concept

This far in the concept it was already clear what material to use for the reactor chamber, since no comparable alternative existed for the FOV fabric. The material for the reactor chamber had to be resistant towards the hydrogen sulfide environment that would be present, the material also had to be able to withstand the increased pressures in the chamber. The novel textile developed at FOV had been developed specifically to be used as a biogas reactor material and would have no problem resisting this environment, furthermore it would enable easier transport of the reactor into the household (as discussed previously in chapter 3.3).

The slurry output piping, the organic waste input pipes and the organic waste slide had the same demands for their material. It had to be able to withstand a moderately acidic environment but the demands on mechanical properties were relatively low, which matches with material group of polymers extremely well. CES was used to find a suitable material, where a lower limit for yield strength was set at 25 MPa and the Young's modulus was set at 2.0 GPa, furthermore only polymers that could sustain in an acidic environment were included. This generated a trade-off curve presented in figure 32; the three main materials that the curve generated was polypropylene, poly vinyl chloride (PVC) and poly carbonate. PVC was in the middle of the curve and therefore had a seemingly well balanced price per performance, this in combination with that PVC was usually found in similar applications and could easily be bought off-the-shelf (as mentioned in chapter 2.1.4 and 2.3.2) led to the decision to use PVC as the material for the piping and the organic waste slide. Furthermore it was decided that the same material would be used for the shelf of the slurry output pipe, for simplicity and the fact that the mechanical properties of the material would be sufficient.

The two shell plates and the lid for the reactor share common traits, they have the same environmental demands, they have similar strength requirements and they have very thin profiles i.e. sheet designs. Materials which were suitable for producing sheet designs were sorted out in CES, these were plotted on a graph with the inverted Young's modulus on the y-axis and the price on the x-axis. This produced the trade-off curve on the bottom left side of the figure 31. Low carbon steel, low alloy steel, stainless steel, nickel and nickel based super alloys were all present on the trade-off curve; they all had similar Young's modulus but differ in price. In order for the shell and lid to retain its original finish in a presumably damp basement environment it would either had to be coated or made of a material that had moderate corrosion resistance. The latter was chosen for this application and therefore a stainless steel was to be used for these three parts.

Estimating the cost to manufacture the system was the next step in the detail design phase and it would prove to be hard since some variables were unknown. But the price for the parts that were to be bought off-the-shelves were easy to acquire, they include:

Ball vent, buffer tank, gas piping, gas holder, organic waste input pipe, waste disposal unit, slurry outlet console, clamps for the pipe/textile interface, sealant. The cost for these are all present in table 6 in the supporting documents.

The cost of the reactor chamber was estimated by the limited data from the article Experimental and economical evaluation of a novel biogas digester (Rajendran et al., 2013). In the article the cost of the different reactors span from 200 to 300 USD depending on their size, but the geometry of these reactors were less complex and therefore demanded fewer welds. Therefore the chosen estimated cost would be set from 1700 to 5000 SEK. The reactor shell (this included the two shell plates and the lid) was approximated from 300 SEK to 1500 SEK.

When summed up this approximation sets the total cost in the range of 10650 to 23550 SEK which does not exceed the cost of the final specifications previously presented.

4 DISCUSSION

The goal of this thesis was to integrate a biogas reactor into a household environment, specifically targeted for the Nordic market. The largest challenges with the task was to adhere to the safety issues while producing a valid concept at the same time as making it economically feasible; or in another perspective analyzing the problems and restrictions of the project and making the correct trade-offs.

In an effort to comply with the strict regulations when dealing with explosive gases, especially in an indoor environment, the gas holder was moved to the outside of the house to minimize the risk of gas leaking into the basement. An argument could be made that it would be even safer to have the whole reactor outside, but this trade-off was chosen to not restrict the efficiency that the lowered temperature would introduce.

Since this system partly caters to people wanting to have more sustainable waste management system in their household's, using a water lock solution was preferred over having a more simple gas valve. The reason behind this was that the water lock solution would guarantee that when maintenance was needed the reactor could be opened up without affecting the environment in a negative way, by releasing the biogas into the atmosphere.

Another hindrance for producing a successful product was to make it appealing enough to use so that the customer would want to make the extra effort both in everyday use and the investment cost. As evident by the survey conducted in the pre-study phase the demands put on a product of kind were high from the intended user, with ease of use being one of the highest rated attributes. Which at the end of the project was line with the selected automatic concept where all functions except feeding the organic waste into the waste disposal unit and periodical maintenance was automatized.

One of the key elements that increased the viability of the concept was the availability of the novel textile that could be used for the biogas reactor. This ensured that the reactor size was not be limited by the size of the door to the basement at the same time as it enabled superior environmental resistance in comparison to feasible metal alloy alternatives. Furthermore the textile technology would be very beneficial when distributing the product since the reactor could be folded up and tightly packaged, which was a large benefit in comparison to a non-flexible reactor material.

The textile material could also be seen as an enabler for making the product into a platform solution. Since the reactor could easily be scaled to different sizes it would be possible to develop several size options as well as having different connection options available. In other words it would be possible to develop the concept into a platform solution that would suit different household needs in terms of size and biodegradable waste production.

Even though all of the above challenges had been met, there were still some concerns inherent to the biogas technology and thus also the final concept. The expected energy produced was not likely going to be enough as a sole source, depending on the intended application. In the case of heating a household the energy produced would not likely be enough and therefore the system included an external gas source to compensate. The limiting factors for determining if the biogas reactor would be sufficient was the expected biogas yield in comparison with the energy needed to heat the household, where the biogas attained was limited from the amount of organic waste produced. The fact that most households needed an external gas source probably lead to the need for more than a purely economic incentive for the decision of investing into a household biogas digestion system. Since the time for the system to repay the investment cost would probably be over a decade. Fortunately there were other incentives to invest in a biogas digestion system such as the increase in sustainability that comes with better waste management. This effect could be seen from several factors of the concept, both the obvious that the organic waste would turn into useful biogas. But another effect is that the organic waste does not have to be transported by a truck to a biogas plant also increases the systems sustainability. Furthermore the ease of getting rid of the household's organic waste from the kitchen was increased since the thrash does not have to be emptied, the waste would more easily be disposed of down the drain. Also if the organic waste would otherwise be stored in paper bags, which costs up resources, are prone to leakage and can smell, this would all be avoided with the final concept of this thesis.

This project included a diverse set of challenges, for instance restrictions inherent to the technology as well as the need to take safety precautions and the limitations on simulating system operation such as slurry flow through and limited time for testing the concept prototypes. Considering all these challenges the process of this project had systematically produced a feasible concept that added a lot of value to the customer looking for a more sustainable household waste management system. But as mentioned previously, if more development was put into the concept, especially in the phase that had been left out in the scope of this project, testing and refinement, it would increase the certainty and quality of the product even further.

5 FURTHER RECOMMENDATIONS

As mentioned in the discussion there were some concerns about the economic incentive of the product. In the Pre-study of the project the annual cost savings for the case study was approximately 7% (2144 SEK), in comparison to the approximated manufacturing cost of the product (10650 to 23550 SEK) the payback time would probably be over a decade long. In order to achieve a shorter payback time it would be possible to integrate the technology in another environment, aimed at another market segment. This market segment would be apartment buildings or complexes, which would enable a larger scale production between the household and municipal biogas plant sizes. This would make the cost of the system more attractive since it could easily be scaled up in size, depending on the building size. When integrating a biogas production system into an apartment building there also exists some other possible benefits, for instance the building in itself could be labeled as a sustainable solution which could act as a selling point for the customers. The fact that there would be more sources that feeds the organic waste would also be considered beneficial since this would ensure a more consistent load rate. A better consistency in the load rate will make the system more robust which would benefit the biogas production. Furthermore the views that the tenants have of recycling and sustainable living could very well be enhanced, firstly since the solution would have the two positive effects of reducing the energy bill and the ease of getting rid of the waste, but also that the whole building would be doing it as a community. This could possibly act as a catalyst for improving the view of sustainable living. Another benefit for designing the biogas system more integrated into an apartment building would be that the space needed can be thoroughly planned out ahead and the solution would not be obstructing or taking up space in the basement needed for other reasons.

One simplification that could possibly be made to the system would be to remove the gas holder that was placed on the outside of the household. This would however only be safe to do if it was certain that the produced amount of biogas would never exceed the biogas consumption of the household. Since the gas holder acts as a buffer for the system, without the buffer the pressure would immediately rise if the production rate exceeded the consumption rate which could potentially be hazardous for the environment and the people in the household.

The phase testing and refinement that were included in Ulrich and Eppingers' suggested method was left out since the resources for conducting them was not available as explained in chapter 2. Especially some of the functions that would had to be tested under extended periods of time. So in order to further the concept presented it would have to go through testing and refinement to determine proper dimensions for the inlet and outlet piping. And as a result of the pipes being dimensioned the bearings could then be dimensioned to support the piping's weight. The size of the reactor could be decided by testing to determine the flow through rate and then dimension the reactor so that it matches. This also affects the dimensioning of the supporting shell, both the lid and the two shell plates.

In the future it would be possible that there will exist more options for a household to utilize self-produced biogas. Perhaps a household size upgrading unit for refining the biogas could be installed to use the biogas produced as propellant for vehicles. This possibility would be a strong argument for investing into the technology, as the utility of having a private vehicular fuel refilling station could be a high priority for some households.

6 SUPPORTING DOCUMENTS

6.1 SCREENING MATRIX

The screening matrix is a powerful tool for evaluating concepts in order to find one or several of them to keep (Ulrich and Eppinger, 2012, pp. 150-153). The matrix is shown in table 4 and the selection criteria's are listed in the leftmost column. The selection criteria's are evaluated for each concept and are rated with either a negative, neutral or positive score (-, 0, +). When all criteria's have been filled out for each concept the positive, neutral and negative scores are summarized for each concept. From these three sums a net score is calculated then the concepts are ranked according to the net score.

Selection criterias	Indoor reactor	Well reactor	Well reactor with gas holder	Well reactor with integral gas holder	Outdoor reactor with pump	Triple chamber	Indoor reactor with pump	Well reactor with pump	Well reactor with gas holder and pump	Well reactor with integral gas holder and pump	Triple with pump	Automatic with compressor	Automatic	Well with compressor	Well automatic
It is robust and wont break or leak	+	+	+	0	-	+	-	-	-	-	-	-	+	-	+
The biogas digester is easy to use at an every day basis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
It is easy to maintain	+	0	0	0	+	0	+	0	0	0	0	+	+	-	-
The digester is effective at producing biogas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
The investment cost is low	+	0	0	0	-	0	-	-	-	-	-	0	+	-	0
It is easy to empty the slurry	+	+	+	0	+	+	+	+	+	0	+	+	+	+	+
It does not take up much space indoors	-	0	0	0	-	0	-	-	-	-	-	-	-	0	0
It does not leak gas when it is emptied	+	+	0	0	0	+	+	+	0	+	+	+	+	+	+
Sum +'s	5	3	2	0	2	3	3	2	1	1	2	3	5	2	3
Sum 0's	2	5	6	8	3	5	2	3	4	4	3	3	2	3	4
Sum -'s	1	0	0	0	3	0	3	3	3	3	3	2	1	3	1
Net score	**4**	**3**	**2**	**0**	**-1**	**3**	**0**	**-1**	**-2**	**-2**	**-1**	**1**	**4**	**-1**	**2**
Rank	1	3	5	8	10	3	8	10	14	14	10	7	1	10	5
Continue?	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**	**No**	**No**	**No**	**No**	**Yes**	**Yes**	**No**	**Yes**

Table 4 – Screening Matrix

6.2 WEIGHTED MATRIX

The weighted selection matrix is used to evaluate concepts down to a final one, it can be seen as a more thorough alternative to the screening matrix (Ulrich and Eppinger, 2012, pp. 154-157). The matrix is shown in figure (xxx) and the selection criteria's can be seen in the leftmost column; the next column contains the weights for all the respective criteria. All of the criteria's will be rated for each of the concepts, this rating is multiplied with the percentage from the weight in the second column to produce a score for each criteria and concept combination. These score are summarized for all of the concepts and a rating is taken from these sums shown in row x of figure xxx.

		Indoor reactor		Well reactor		Well reactor with gas holder		Well reactor with integral gas h		Triple chamber		Auto with compressor		Auto		Auto well	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Robust	10	4	40	3	30	3	30	2	20	3	30	2	20	2	20	1	10
Won't leak	7,5	3	22,5	3	22,5	3	22,5	2	15	3	22,5	2	15	3	22,5	3	22,5
Won't break	7,5	3	22,5	3	22,5	3	22,5	2	15	3	22,5	2	15	3	22,5	3	22,5
Small amount	8	4	32	3	24	3	24	3	24	3	24	4	32	5	40	5	40
Maintenance is	8	5	40	4	32	3	24	2	16	4	32	4	32	5	40	3	24
Investment co	11	5	55	2	22	3	33	3	33	3	33	4	44	5	55	3	33
It is easy to em	5	4	20	5	25	3	15	2	10	5	25	5	25	5	25	5	25
It does not tak	4	2	8	3	12	3	12	3	12	3	12	1	4	1	4	3	12
It does not leak	16	5	80	5	80	4	64	3	48	5	80	3	48	5	80	5	80
Ease of use	23	4	92	4	92	3	69	3	69	4	92	5	115	5	115	5	115
The sum	100		412		362		316		262		373		350		424		
	Rank		2		5		7		8		4		6		1		

Table 5 – Weighted Matrix

6.3 CATIA v5

Catia is a computer aided design (CAD) software from the French company Dassault Systèmes. The software allows the user to model 3D objects and assemblies with a plethora of different tools. There are many different CAD software's exists but Catia was chosen since the student already possessed knowledge and experience from the software.

6.4 FMEA

Failure mode and effect analysis is a tool that is used to evaluate the risk of different functions in concepts (Carlson 2012). This is done by listing the different functions of the concept and then all of these functions potential failure modes. For each of the failure modes that were listed the potential effects needs to be listed, these effects are rated from 1 to 10 and this rating is called the severity rating. The higher the severity of the potential effect the higher the severity rating becomes. Potential causes of the failure mode needs to be stated next and its corresponding occurrence rating, the occurrence rating will also be set from 1 to 10. The next column will contain the current process control for the failure mode, or in other words in what way the failure made will be detected. The process control will be rated from 1 to 10 and this rating is called the occurrence rating. When these three ratings have been decided the risk priority number (RPN) can be calculated by multiplying the three numbers. Furthermore the CRIT value can also be calculated by multiplying the severity rating with the occurrence, this represents the estimated criticality of the failure mode.

6.5 CES EduPack

Is an interactive material selection software from the company Granta. The software provides tools for finding and selection a material from a large variety of construction materials of different material groups.

6.6 COST ESTIMATION TABLE

Part	Min Cost	Max Cost
Reactor chamber	1700	5000
Ball vent	300	300
Buffer tank	400	600
Gas piping	2000	5000
Gas holder	3000	5000
OW inlet pipes	500	1000
Slurry outlet pipes	1000	1500
OW inlet slide	100	250
Slurry outlet support	100	250
Slurry outlet console	50	150
Reactor shell	300	1500
Waste disposal unit	1200	3000
Fabric clamps	160	200
Fabric / pipe sealant	50	150
Sum	10650	23550

Table 4 – Cost Estimation Table

6.7 SURVEY

Interview Template:

Project background:

I’m working on a thesis where I’m developing a physical interface between a biogas digester and a household. A biogas digester is used to produce biogas by using organic waste. And in this case it is going to be used in a household and be fed with food waste. The biogas digester produces both biogas and a by-product, a kind of slurry that is rich in certain nutrients and can advantageously be used as a fertilizer. So in order for it to work the biogas digester must also be emptied from this slurry in due time.

Initial questions:

Is gas used in your household?

Follow up question if yes:

What do you use the gas for? What kind of gas is it? Do you use a biogas digester to produce your own biogas?

Which of these hypothetical criteria would you rank as the most important for you, if your household were to produce its own biogas? (You can choose several)

- To care for the environment
- The economic incentive
- To become more self-sustained
- Other

Would you consider to have a biogas digester inside of your household?

How much organic waste does your household produce per day?

How many persons live in your household?

Does your household have the possibility to use the slurry as a fertilizer?

Survey questions:

How I want you to rate the following factors from one to five where a five is very important for you and one is not important at all.

- The biogas digester is easy to use at an everyday basis
- The biogas digester is very efficient in its biogas production
- The system is easy to maintain
- The investment cost is small and it has a short repayment period

- It is robust and won't leak or break
- It is compact
- It is easy to empty the slurry

	5	4	3	2	1	Mean	Rank
Everyday use	16	3	1	0	0	4.75	2
Efficiency	10	8	2	0	0	4.40	4
Easy to maintain	12	5	3	0	0	4.45	3
Cost	11	5	2	2	0	4.25	5
Robustness	17	3	0	0	0	4.85	1
Compact	8	5	5	2	0	3.95	7
Slurry emptying	8	4	8	0	0	4.00	6

Table 5 – Survey data

6.7 CES

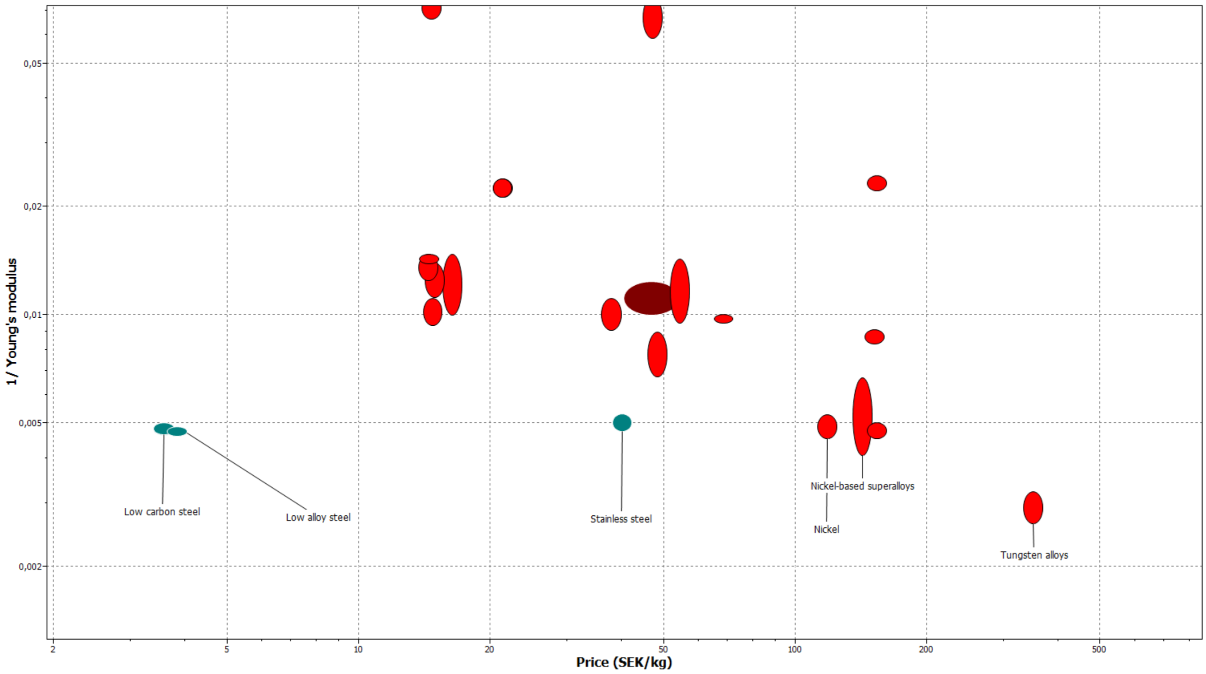


Figure 31- Trade-off curve for metals

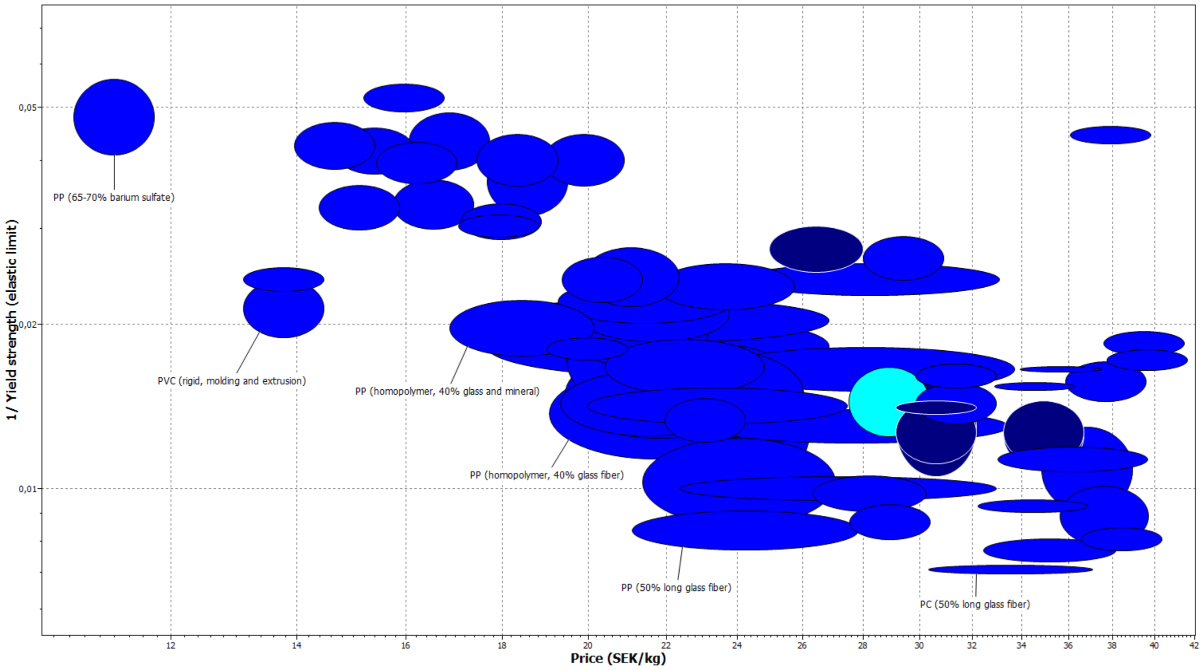
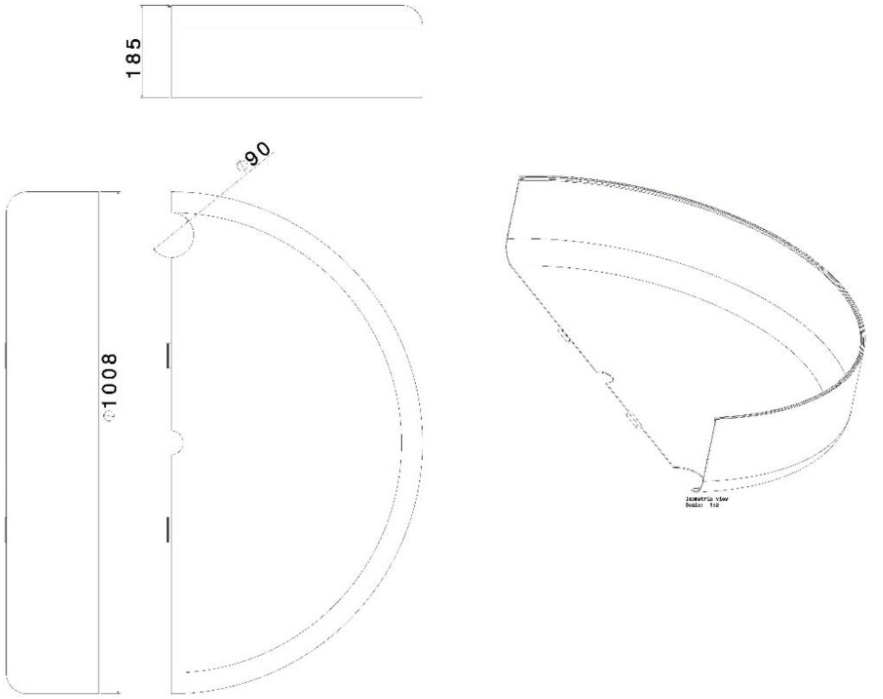
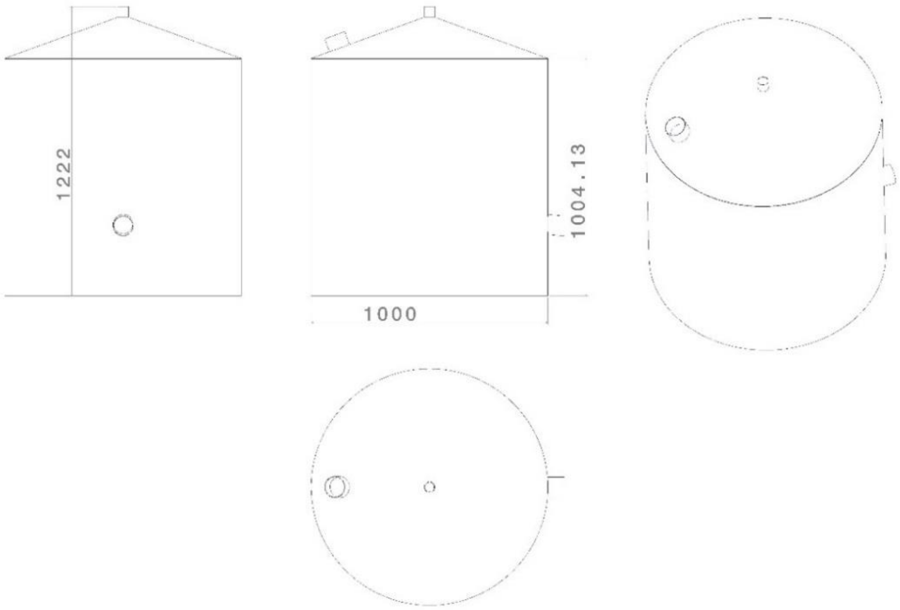


Figure 32 – Trade-off curve for polymers

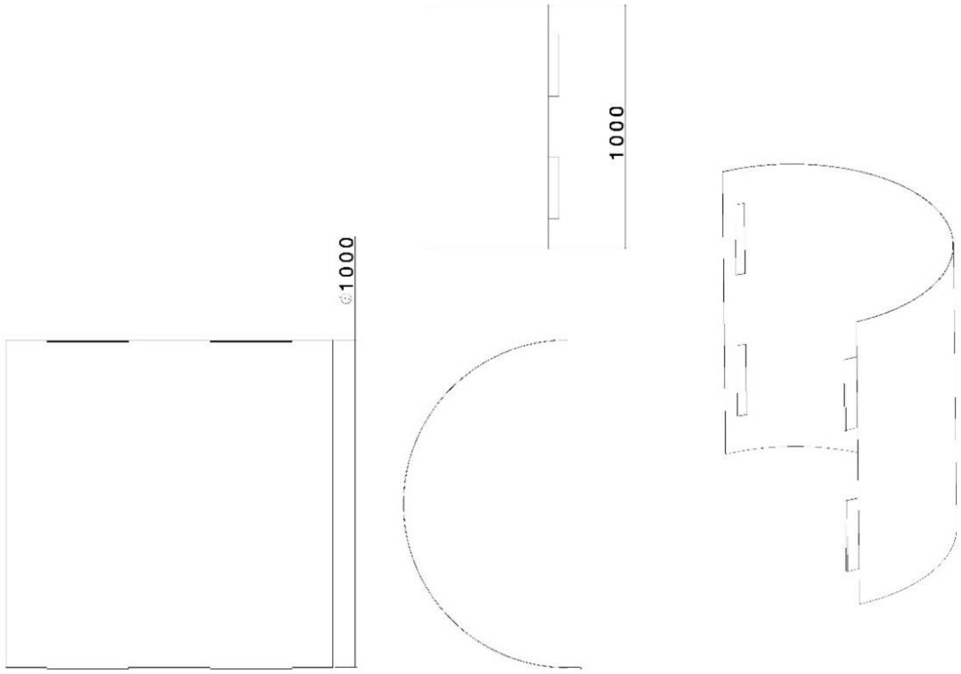
6.8 DRAWINGS



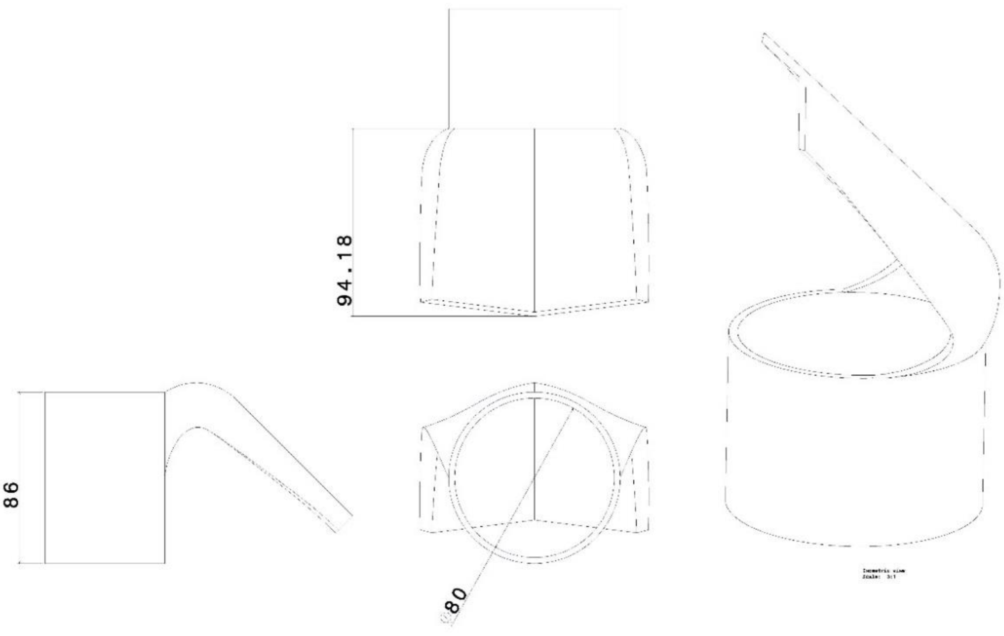
Drawing 1 - Lid



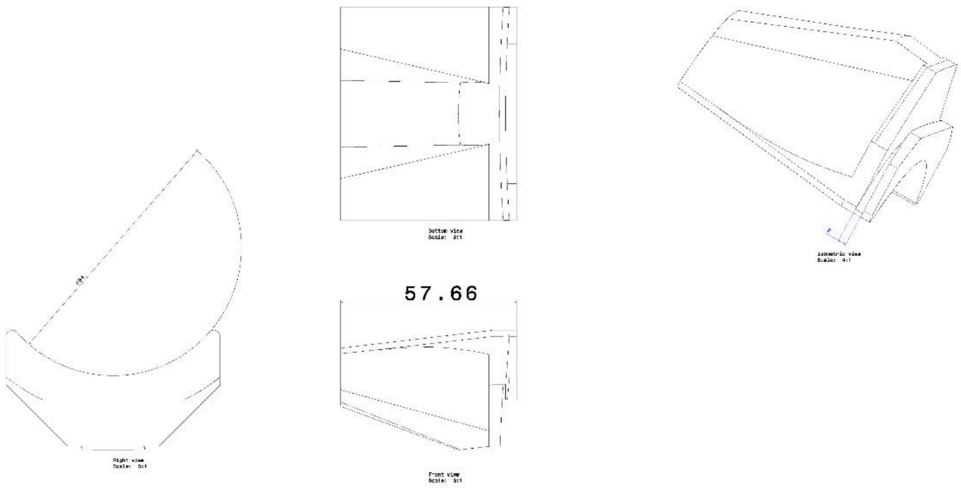
Drawing 2 – Biogas Reactor



Drawing 3 – Shell Plates



Drawing 4 – Feed Slide



Drawing 5 - Slurry Output Support

7 REFERENCES

Ulrich, K. & Eppinger, S. (2012). *Product Design and Development*, 5th edition. New York: MacGraw-Hill.

McQuarrie, E. (2012). *The Market Research Toolbox*, 3rd edition. Los Angeles: SAGE Publications, Inc.

Svenskt Gastekniskt Center. (2015). [online] Available at: http://eks.standout.se/userfiles/file/BiogasSydost/BioMethaneRegions/BasicDataonBiogas2012-komprimerad.pdf [Accessed 3 Sep. 2015].

Vogelsang, H. (2012). *Introducing screw for biogas plants*. US201214356707 2012-11-09.

Efrati, M., Teller, Y., Lanzer, E., Miller, Y., Eilon, T. & Zak, S. (2014*). Lightweight assemblable appliance and respective method for production of biogas and fertilizer*. WO2014203047 A1, 2014-12-24.

Wanjihija, D. (2014). *Biogas production from a flexible digester*. WO2014077419 A8, 2014-09-25.

Down the sink (2015). *How to pick a disposer that suits you*. http://www.downthesink.com/ [2015-09-02]

Roberge, P. (2008). *Corrosion Engineering*. New York: MacGraw-Hill.

Lindstedt, P. and Burenius, J. (2003). *The value model*. Ödesborg: Nimba.

Wickenberg, J., Stamlin, R., Persson, M., Börjesson, S. (2011). *Challenges for increasing component commonality in platforms*.

Wheelwright, S. and Clark, K. (1992). *Revolutionizing product development*. New York: Free Press.

Carlson, C. (2012). *Effective FMEA*s. Hoboken, N.J.: John Wiley & Sons.

Chen, Y., Yang, G., Sweeney, S. and Feng, Y. (2010). Household biogas use in rural China: A study of opportunities and constraints. Renewable and Sustainable Energy Reviews, 14(1), pp.545-549.

Ulrich, K. and Robertson, D. (1998). *Planning for Product Platforms*.

Rajendran, K., Aslanzadeh, S., Johansson, F. and Taherzadeh, M. (2013). Experimental and economical evaluation of a novel biogas digester. Energy Conversion and Management, 74, pp.183-191.

Taherzadeh, M. and Rajendran, K. (2015-05-05). *Post midterm presentation discussion*.

Fredriksson, J. and Lippens, R. (2015-04-13). *Customer visit*.

White, F. (2008). *Fluid mechanics*. Boston: McGraw-Hill.

Öresundskraft. (2015). *Gaspriser - Öresundskraft*. [Online] Oresundskraft.se. Available at: http://www.oresundskraft.se/privat/produkter-tjaenster/gas/gaspriser/ [Accessed 3 Sep. 2015]