Before this graduation project, I was thinking about the limitations of sustainable product design [Appendix I], and I realized that if the oil does run out in 50 years (Fig. 1), we are severely underestimating the consequences for the human race. If this happens, we suddenly become dependent on product design with extremely high sustainability levels, because energy and transport have become very costly. This is how I came to the idea of trying to design a 100% sustainable product.

During the project I had to turn to many people for help. I would like to take this opportunity to thank everyone who was involved in the project.

First of all I would like to thank my Graduation Commission for the pleasant cooperation in a fun and interesting project and most of all, allowing me to pursue this somewhat crazy idea: Prof. Dr. Ir. Han Brezet, for his vision, immediate support and his wide interests, Ir. Stefan van de Geer, for his 1:1 approach and endless design discussions, where we tried to solve some design problems or more, which I enjoyed very much, and Ir. Satish Beella, for his critical view and pushing my limits.

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Last but not least I would like to thank everyone I’ve forgotten to mention.

Thank you,

Arno Scheepens
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Since the start of the industrial revolution approx. 200 years ago the importance of the environment has grown from almost zero to a higher level, as more and more people show interest and acknowledge the importance of the environment to ensure a future for upcoming generations as well as their own. The need for change towards a sustainable future is accentuated by rising energy prices, social inequality and speculative theories like global warming. Until now, different approaches for sustainable product development are being used, e.g. Ecodesign, Sustainable Product Service Development [1], etc. These approaches, in short, take current products and their functions and try to make them less harmful to the environment. Most products are not designed with these issues in mind and since up to 80% of the environmental effects of typical consumer products are determined during the design phase, this makes real improvements difficult [Reference to SPSD paper]. A design process I want to follow is where initially no compromises can be made in the area of sustainability, designing a product which is not harmful to the environment and society. It might be possible to conceive a theory for the most sustainable way to produce consumer goods, beginning with the use of local renewable resources and restricting the off-take to a local market, eliminating resource depletion, social inequality and transport, whereas relatively more jobs are created, because the product probably will require more labour because of the required sustainability level. Cost price of the product is not a primary concern, maybe current pricing is not sustainable because of the neglect of environmental effects, but the internalization of the added value chain might redeem some of the higher price. This new approach of Localized Product Development (LPD) might give some answers, but also raises questions.

To investigate the Localized Product Development method the following assignment has been formulated: The Design of a human-powered transportation product (complex consumer product), using local naturally renewable materials for production and integrating functionality, ergonomics, aesthetics, manufacturability and closing the cycle to study the feasibility of the LPD approach.

The accent will be on the development of a complex consumer product produced with local natural materials. This assignment is a pilot project for the sustainable islands project by the TU Delft and fits within the development plans of the three northern provinces: Energy Valley. Starting point is the design of a bicycle because it serves as the best showcase illustrating the possibilities of LPD in The Netherlands, but since this is very complex, in the first four weeks a general feasibility study is performed defining the system parameters and borders, based on the local natural materials and their properties and the technical needs and functionalities. If needed, a lower level in complexity of human powered transportation products will be developed.

Results

The results of this project will be a Prototype, Final report, 3D model, a Poster presentation and the final presentation at the end colloquium.
LPD relieves the environment of many burdens, but also restricts the possibilities during and after production. The problem is we don’t know whether LPD really works: Is there a need for such products, can they be produced this way and does it fulfil a need in the market?

There are issues to be addressed consequently to reach an optimal sustainability level:
- Technical feasibility
  The assignment has to be technically feasible or no product at all can be conceived.
- Environmental feasibility
  The materials, production energy and land used for the product should bring forth no environmental burden.
- Economical feasibility
  The product should be affordable, but shouldn’t compete with low-cost imported goods.
- Social feasibility
  The product has to provide for the needs and wishes of the target group, Frisians.

Especially economically there are no real indications this approach would work. A good perspective would be provided by the design of a complex consumer product (bicycle) produced with local natural materials. The choice for a bicycle also has other reasons: It is a well known, human powered, complex consumer product and part of the Dutch culture, allowing people to connect easily to the product and avoiding the negative image associated with sustainable products (Tree huggers).

The goal of the design is showing the consumer what is possible with natural materials in a high quality product, as an incentive to stimulate thinking about another paradigm. This serves several sub goals.

The development of an oil independent economy and its responsive clustering leads to growing interest and development for sustainable products and services, increasing the amount of R&D thus speeding up the development towards a sustainable society.

It also creates awareness among the consumers, since many companies say they produce “sustainable” products and there is a danger of a rebound effect: For example the energy saving light bulbs being left on all the time, “because they are energy saving light bulbs”, actually leading to an increased energy consumption. If people know more about the sustainability concept, they can make more accurate decisions, inherently leading to increased sustainable development.

But also another social effect is at hand, being the fact that people are increasingly fed up with green marketing and, as a Dutch politician said recently: “de klimaatwaanzin”, NL or “climate madness”. Thereby does sustainability still have a “tree hugger” image with some social groups which has to be turned around to a “cool” image in order to speed up the development towards a sustainable society.

The development of a regional economy has many sustainability benefits, though is contrary with current economy policy: Making everything available to everyone. Here it has to be said that even though this is the goal of current economics, this goal is hardly reached. Only the West and some other developed countries have this luxury, but the larger part of the world has no or very little benefits from this system.

The design has to communicate these issues by encouraging consumers to find out why this product was designed this way.
In this section I will discuss the design method used in the project. The method used for the design process itself is based on the Sustainable Product Service Development method [1]. This method is chosen as foundation because it first evaluates the general functionality which a product, service or product-service system has to provide for.

The SPSD method is intended for medium - large businesses in large linear industrial networks. The LPD method however is based on a different (future) paradigm, which the Rebicycle is supposed to support as a showcase for paradigm change.

Therefore I chose to combine my version of the SPSD method with the standard Industrial Design method taught at Industrial Design at the TU Delft. I feel that the SPSD method is going in the right direction, but could be taken even further, at least on a product design level.

In the SPSD method two major improvements are introduced: Rethinking the product functionality and closing the cycle. This has been proven to lead to significant ecological improvements, but in order to achieve 100% sustainability I believe it is necessary to add more restrictions to this method.

First of all the restriction to local naturally renewable materials is added. This should decrease the ecological impact significantly, presumably completely (100%). This and the restriction to a local market would also remove the need for transport: distribution.

Secondly, the use of naturally renewable materials means that the cycle shouldn’t be closed towards the materials, but towards nature itself. The used natural materials are expected to be unsuitable for re/upcycling which should be obsolete anyway, because nature is taking care of the recycling, free and without effort. (Fig. 2)

**Fig. 2: Combined SPSD and LPD Approach**
The SPSD method serves as a good starting point for the design process of the project. The main adaptation to the SPSD Method is the introduction of the restriction to local naturally renewable materials, which lead to several adjustments. (Fig. 2,3) The result of these adjustments is a method which has the potential of being the most sustainable product design method currently available, with the potential of leading to 100% sustainable products if these are at all possible.
The adjustments to the SPSD method combined with the standard industrial design approach has lead to the LPD design process (Fig. 4). This process is the result of the Localized Product Development Approach, formulated for the assignment.

**Analysis Phase**
In this phase the feasibility of the LPD approach is investigated by exploring local naturally renewable material possibilities for functionalities required from a regular city bicycle, generating a feeling for the feasibility of the entire project. The feasibility of 100% sustainability for such a product is investigated in the Life Cycle Analysis and the Economical and Social analyses investigate potential effects to the paradigm.

**Idea Phase**
In this phase of the project the ideas are generated after the general functionality is analyzed and selected. The ideas are generated for design sub-problem areas, whereafter the ideas are combined and selected using the A.I.D.A. method, resulting in a concept direction.

**Concept phase**
In this phase the concept direction is detailed into a design proposal according to the programme of demands expanded with three additional iterative analyses: Ergonomics, Strength and Stiffness, and a 3D model. The result of this phase is the design proposal.

**Materialization Phase**
In this phase the design proposal is built in a 1:1 prototype which is used to perform user tests and verify assumptions made about production possibilities of the methods and materials proposed for the design.

**Conclusion**
This phase concludes the process. The process, product and designer are evaluated, resulting in recommendations for the continuation of the project.

**Evaluation**
If I’m correct this approach could lead to one of the highest sustainability level approaches for sustainable product design. The goal is set to achieve a 100% sustainable design by trying to manufacture a bicycle from 100% local naturally renewable material. From here the project starts with the feasibility Analysis up to the final design, The Rebicycle.
For this project it is essential to have an overview of the technical feasibility. Is it possible to design a high quality bicycle with only local natural renewable materials? The bicycle as we know it nowadays is made this way because of the availability of industrial materials like steel, plastics, vulcanized rubber, etc.. Steel for example is a highly durable, strong material with excellent properties as well as rubber which for example is highly wear resistant. I want to minimize/eliminate the use of materials like steel in this project as much as possible, first because it is not a naturally renewable resource (or at least not in a time frame which is relevant to mankind), but also because it takes high amounts of energy to recycle the material as well as to incorporate the raw material in products. Rubber originally was a renewable natural resource, but because of its many applications demand rose to a level where nature couldn’t provide and synthetic rubber came in its place. Furthermore sulphur is added to improve its properties, especially wear resistance. For this project it is questionable whether I can use rubber at all, since it is not a local natural resource of Friesland. Preferably, I want to use native materials, because from a sustainability point of view this is the safest approach because these resources were naturally there and importing other species would increase the number of factors possibly responsible for higher order negative effects on the long term (e.g. elimination of native species because of wild growth of imported species). On the other hand, my designer’s freedom is enhanced significantly when I would allow imported species that grow naturally in Friesland, or even in a greenhouse. Then there are also (waste) materials present in Friesland, like scrap metal, paper, glass, rubber etc. which are already being collected separately for recycling. Though the use of these materials decreases the level of sustainability of the project, e.g. because of transport, if it turns out to be possible to infinitely recycle the materials or even upcycle the material (Cradle2Cradle) it might be possible (sustainable) to use these materials as well.

I take the current city bicycle design as a starting point because of several reasons:

1) It is the most successful bicycle design in The Netherlands.
2) It is a simple design, whilst providing the required functionalities.
3) It has a distinct level of comfort which is generally accepted.
4) It has a distinct image which is socially accepted.

Analysis Method (Fig. 5)

Technical Feasibility

Is it feasible to design a human powered transportation product made out of local naturally renewable materials? To answer this question different sub-questions have to be investigated:

- What is required (properties and function) from the materials in such products?
- Which local naturally renewable materials are available and what are their properties? Also recyclable materials are taken into account since they are nowadays available locally because of many years of transport of products, leading to local wastes like steel, glass, paper etc. However the accent will be on the natural materials because they are likely to remain available unlike petroleum based materials like plastics and rubber. Though steel and glass aren’t petroleum based they do require a high amount of energy for production and
recycling, for which fossil fuels are used. This sub-question is investigated in the materials analysis.

- Which combination of (natural) materials is optimal? This sub-question is investigated in the functionality analysis. The Materials, Parts and Functionality Analyses are performed simultaneously because of the highly iterative content. They are however treated separately in this report for clarity and overview.

**Environmental Feasibility**

What is the degree of sustainability of the technically feasible materials and their accompanying production processes? What is the influence of using local naturally renewable materials? These questions are investigated in the Life Cycle Analysis.

**Economical Feasibility**

What are the chances for this product made with local naturally renewable materials in the current economical system? This question is investigated in the market analysis combined with a strategic analysis and future development scenarios.

**Social feasibility**

Will the consumer accept such a product and, even more importantly, will they prefer such a product over the currently accepted products? This question is investigated in the social feasibility analysis.
To acquire a structured view of the feasibility of the project I will use the approach of deconstructing the current city bicycle into its basic parts with their respective functions and materials, which eventually will be mapped out to the available local natural materials in the province of Friesland.

The inclusion of the functions of the parts is essential because these describe the required functionality for the currently accepted bicycle. When mapped, exchange of functions might become possible, perhaps circumventing some of the problems encountered by replacing industrial materials with local natural materials.

When completed this approach should provide a clear insight into which problems are the most pressing ones revealing clear bottlenecks of which can be estimated whether they are permanent or solvable, helped by cross linking parts, materials and functions.

The full Parts Analysis can be found in [Appendix A]

I have divided the current city bicycle parts into four main categories:

**Structural parts**
These parts provide the necessary strength and stiffness for the product.
- The structural parts have to provide sufficient strength and stiffness to provide for efficiency and safety.

**Movement parts**
These parts enable the force transfer from the user into forward motion and steering. Wear resistance and strength are important properties for these parts.
- Efficiency and wear resistance are important properties for these parts.

**User contact parts**
These are the parts where the user connects to the product. These parts have to provide grip and comfort.
- These parts have to customizable to the specific size of the consumer

**Joints**
These parts (or materials, geometries, etc.) are used to assemble the parts into the final product.
These parts provide the necessary strength to support the user and stiffness for efficiency and control for the user as well as a safe feeling. These parts are mostly made of hollow steel tubes connected by welding in a framework. Here it is very important to know which material they are made of, their cross-sectional area and the type of load when replacing the materials of these parts. Typically, the tensile strength for metals is higher than its compressive strength, since plastic deformation occurs beyond the material’s yield strength which results in strengthening of the metal. This will not hold as much for compressive loading. In natural materials the mechanism of strengthening of the material has not been observed (by me).

These parts include the frame, fork, saddle pin, handlebars and the steering pin.

**Conclusion**

Bicycle frames (and forks) can very well be manufactured with natural materials, sometimes even enhancing user comfort whilst still providing required stiffness and strength. From what I know now the most promising material for the frame is wood, because of its strength, stiffness, alleged shock absorption qualities, easy processing and high fatigue strength. For (connection) reinforcement and weather proofing a natural epoxy resin from the Vernonia Galamensis plant could be used in combination with natural fibre mats a high quality lightweight frame with high durability can be realised. The downside of this construction is the possibly unnatural hardener which has to be used to acquire the required properties of the epoxy adhesive, but since this is only a small weight percentage of the epoxy and very small percentage of the entire Rebicycle, it might turn out that the relative contribution can be considered insignificant. A thorough Life Cycle Analysis should be able to make an assessment of its contribution.

**Insights structural parts**

- All structural parts together should provide maximum torsion stiffness because of efficiency and user perception.
- Vertical and horizontal stiffness is less important, it could even provide shock and (micro) vibration absorbance (www.waldmeister-bikes.de), though for control, it remains very important to achieve a very stiff fork or the bike becomes wobbly.
- Bending strength should be significantly beneath yield strength because of safety of user: In case of bending the material should not fail soon afterwards [2].
- Double triangle structure has been proven as best way to construct bicycle frame because this provides most ideal force distribution [2].
- Hollow parts provide better strength/weight ratio then solid parts (Statics)
- Dynamic loads are hard to compute for a bicycle, generally a factor of 1.6 is used as the “bump factor” over the computed static loads. [3]
- Different parts of the frame are loaded differently: tension, compression and/or torsion
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Chain drive (Fig. 11), axles, wheels (Fig. 12) and controls (Fig. 13) have high structural demands as well as wear resistance. The parts with high structural demands are for example the axles, rims, bearings, chain, front fork etc. especially because they deal with highly dynamic repetitive loads. Important material characteristics are high impact resistance, high hardness, high young’s modulus, high wear resistance, low friction coefficient and high fatigue and yield strength. On the other hand there are the air inflated tyres which are used for surface contact, the drive chain and the braking parts. These are very important for the comfort and safety of the cyclist because they provide grip, shock absorbance, stopping ability and control. Important properties are high wear resistance, low Young’s modulus, high yield strength, high water and UV resistivity and high friction coefficient.

These parts include the axles, bearings, brakes, cranks, drive chain, gear wheels, hubs, rims, spokes, and the tyres.

Conclusion

The most difficult parts are the bearings and brakes because of their high strength, hardness and wear resistance requirements. Here it might be necessary to use small quantities of steel in the design of the Rebicycle which will have to be reused to minimize environmental impact.

The cranks and the gear wheels can be made with natural materials, here the connections and types of loads are important for material choice.

The rims, hubs and spokes have many examples that have been made with natural materials, e.g. wood, therefore I assume it is possible for these parts. Depending on the environmental impact of PUR, the airless tyres are a good solution. They require a simple rim and consist of only one part, contradictory to air filled tyres, which consist of more than 6 parts: Outer tyre, inner tyre, outer tyre inlays, rim protection, valve tube, inner valve etc. Therefore even though there might be a significant impact on the environment, the choice for PUR airless tyres might be justified.

This material might also be necessary to achieve the requirements for the drive chain as well as the saddle and handles, because of its durability, wear resistance and weather resistance.

Insights movement parts

- For the drive chain a leather belt was used because of its high friction coefficient. This would simplify many parts of the chain drive, though under wet conditions this would not function properly.
- Some bearings might be redundant, e.g. head tube bearings. The steering might be a little less supple, but this might not be a real problem.
- Airless tyres have already been developed which give opportunities to replacing the rubber with natural materials. They are now made with PUR foams
- Spokes in wheels are loaded in tension, not compression
User Contact Parts

These parts are usually made with different forms of plastics: Solid, foam, foil, etc. They provide some form of vibration dampening, insulation, protection, and grip. They also provide for anatomical variation because they are flexible. Here specific properties of the materials are used to increase the comfort level of the user. These properties include low Young’s modulus, low thermal conductivity, high impact resistance, high friction coefficient, high water and UV resistivity and low hardness.

These parts include the handles (Fig. 14), pedals (Fig. 15) and the saddle (Fig. 16).

Conclusion

For this feasibility study these parts are of lesser importance, because there are many alternatives in design and materials. Generally it can be said that these parts will not be the bottleneck.

The biggest problems I foresee are weather and wear resistance, and that the natural resources for these materials do not occur naturally in Friesland.

General design problem with the user contact parts (except for the pedals) is that they have to be adjustable to provide for a comfortable and optimal riding experience. This aspect increases the amount of parts, thus making the bicycle more expensive and complicated to manufacture.

One solution might be the individual customization to rider height and reach, which is possible because of the close relationship between Rebicycle and their customers as a part of the Product Service System. An example would be an extended seat tube in different stock sizes to be fitted on customer demand, giving the customer a high customized feel.

Here also the potential is increased because of the natural epoxy material. It can bond a variety of materials to each other, for example steel to wood.

Insights user contact parts

- The parts are relatively simple and can be replaced quite easily with natural materials. Even an improvement of comfort is possible with natural materials.
- Wood has a high fatigue strength and flexibility and thereby might reduce the number of parts significantly by integrating their functions.
Typical joints are welding and nuts and bolts. Clamping is also used for placement of moving parts. The connective material or method is highly dependent on the type of connection, the material and the requirements due to the type of loading. Current city bicycle frames are predominantly welded and the moving parts are connected to the frame with nuts and bolts. This is only possible due to the use of metals. With natural materials the obvious replacement for welded connections is an adhesive since there are many examples of biological adhesives, e.g. starch glue and even experimental bacterial adhesive which can be extremely strong.

Because of the dynamic loading of almost all connections in a bicycle a high strength adhesive (Fig. 18) is needed, which is also weather resistant. This is needed so the material fails earlier than the connection thus the material becomes the limit, similar to welds which are considered stronger than the welded material. The best adhesives are epoxies which are known for high strength and durability (Figure 19). Production needs to be accurate but is easy because when the two components are mixed an exothermic reaction takes place. PUR adhesives are also commonly used for connecting wood, but if the wood is loaded dynamically the adhesive tends to detach from the material, therefore PUR adhesives are considered unsuitable.

Normally the epoxy adhesive resins are derived from oil and then combined with a form of amine as a hardener. The discovery of the Vernonia Galamensis plant might lead to a natural resource for epoxidised fatty acids, because its seeds contain triglycerides with three chains of single epoxidised fatty acids. The hardener might be more difficult to replace. In order to make the glued connections as strong as possible the area over which the glue is used has to be maximized. For wooden connections a very good way is the use of finger joints. Another way to connect the different parts is with pegs in tight fittings securing them in place. On itself this method for connections is not that strong (only as strong as the smallest cross-section or surface) but they might be used as an addition to glued connections. Clamping with natural materials could be done by laminating the connection with fibre mats or even rope winded around the connective area. This is an ancient technique which is very easy and cheap, but not very reliable for dynamically loaded connections.

Conclusion
Because the type of connection method and material is highly dependant on the material and shape to be connected, the conclusion remains general for now. Because the majority of joints in a bicycle are permanent, the way to go seems to be an adhesive. Preferably an adhesive is used which is stronger than the material it connects, enabling the designer to design on the strength of the material instead of the joint material.

Insights connections
- The type of connection is highly dependent on the material, geometry and type of load.
- Epoxy adhesive is the best option for adhesives. It is strong, durable, weather resistant, translucent, selfcuring and it is possible to produce from natural resources present in Friesland.
- Geometric shapes can increase surface for adhesive effectively
- Pegs and holes can easily be used for fixing components in place
- If extra reinforcement is required, laminated textile can be applied, which also improves stiffness
Parts Analysis Conclusion

The Parts Analysis has shown that most parts of a standard bicycle can be replaced with natural materials. Especially the structural parts can be made from natural materials quite straightforwardly (Fig. 20).

The most difficult parts are the movement parts, particularly because of their high strength and wear-resistance requirements. These are for example the bearings, brakes, drive chain and tyres. (Fig. 22,23,24,25)

The joints are also quite difficult to manufacture from natural materials (Fig. 21), however it seems to be possible in the future to produce a high strength adhesive from naturally renewable materials.

The user contact parts (Fig. 26) are highly dependant on the required comfort in the entire product. It is assumed to be quite possible to manufacture these with local naturally renewable materials.
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Natural Materials

There are many different natural materials with specific properties around the world, however the project requires the use of local resources to eliminate transport costs and ecocosts from the process. Friesland has a moderate climate with abundant water and nutrients to produce natural resources which enables the production of a relatively wide variety of resources. In areas where natural vegetation isn’t abundant, the possibilities are much more limited.

So the choice of materials is limited significantly: Which local naturally renewable materials are suitable for application in a bicycle? In order to answer this question the following sub-questions have to be answered:

- Which natural material resources occur naturally in Friesland?
- Which local waste materials can be utilized?
- Which industrial materials might have to be used?
- Which materials are suitable for use in the design of a bicycle?
- Which novel materials have to be developed?

From the Province of Friesland a list of flora naturally occurring in Friesland was acquired. This list was combined with a list of natural materials used in industry from Wikipedia, because the list from Friesland was too elaborate to study completely, and many of the plants were off course completely useless when designing a bicycle.

Some material requirements cannot be fulfilled at this moment, for which other materials available locally as waste materials can be utilized, so transport costs and ecocosts can remain minimal. Material production energy however is likely not to be excludable, since high amounts of energy are required, e.g. steel has a melting point of approx. 1400 °C. This is one of the reasons why these industrial materials should be avoided as much as possible.

Which materials are suitable for use in the design of a bicycle?

The materials analyzed provide a list of materials which are probably suitable for designing a bicycle. These materials were placed in a suitability matrix determining the materials most suitable according to the formulated suitability criteria from the assignment:

Suitability criteria

Durability

This factor entails the longevity of the material in its proposed functions and environment. This includes wear resistance, weather resistance, fatigue strength and robustness. [Appendix A:Parts Analysis]
Local naturally renewable
This factor shows the degree to which the material naturally exists/grows in Friesland. There are three levels to this factor: The first level is the native species, which grow without climate control. The second level is the species that grow in greenhouses and the third level is the species that are very difficult to grow in Friesland. [Assignment]

Variety in production methods
Some raw materials have a high variety in production methods used in the production process, either because the raw material is very versatile and/or the material has been around for a time frame which has allowed the development of a variety of methods. [Appendix B: Materials Analysis]

Wastes usability
From raw material retrieval, material processing, manufacturing and end of life, waste is a by product of (almost?) every consumer product. Some wastes compared to other wastes are better suited for (re)processing/using than others. [Appendix B: Natural Materials Analysis]

Properties suitability
Material properties are suited for a limited number of functionalities within the system of a bicycle. This factor weighs the difference in material suitability for the same (general) functionalities. [Appendix A: Parts Analysis]

Diversity in application
This factor is closely related to the latter factor but some materials have properties which make them suitable for several functionalities required in the system of a bicycle thereby decreasing the number of raw materials needed to produce the product. [Appendix A: Parts Analysis]

Growth ability
This factor could also be described as a cost factor because it denotes the rate of renewability, which might almost have a linear correlation with costs. The higher the rate of renewability, the fewer land is needed to grow the same amount of material, thereby decreasing costs. [Appendix B: Materials Analysis]

(Chemical) additives needed
Some processes and/or materials that I’ve come up with still might require some kind of additive, catalyst etc. to really make the material suitable for its application and achieve a preferred level of quality. This complicates the process, sometimes decreases the level of sustainability, e.g. in case of petroleum derived chemicals, but I’ve allowed some additives for now since they are either inert to the process or consist of such small amounts that compared to the entire product they for now might be considered negligible. [Appendix B: Materials Analysis]

- Which novel materials have to be developed?

The conclusion from the parts analysis is that at the moment a 100% use of local naturally renewable resources is not possible. However, the choice for industrial materials has to be based on the possibilities for the material for production with naturally renewable resources. From the suitability analysis the selected materials provide a direction for R&D: Natural PUR, Natural Epoxy Resin and Natural Curing agent for both Epoxy Resin and PUR. The research can not only deliver materials for the bicycle, but also patents and licensing opportunities. The most difficult parts, the bearings and brakes, still require the use of steel, simply because the unique properties of steel provide excellently for the required function. These functions have to be addressed because they provide for important general requirements of the bicycle. Efficiency and safety. However, in the future it might be possible to make these parts with local naturally renewable materials only.

Based on the materials research a number of materials have been selected that are either local naturally renewable or possess specific material qualities for a bicycle: (Fig.27)

Natural Materials Analysis Conclusion
According to the formulated suitability criteria the choice was made that the following selection of materials is suitable for designing the Rebicycle:

- Epoxy
- Flax/Hemp
- PUR
- Varnish
- Wood
- Glass
- Steel

These materials will be considered input for the functionality analysis.

Conclusion
Promising Materials

- Bamboo
- Cork
- Epoxy
- Hemp/Flax
- Leather
- Polyurethane
- Natural Rubber
- Starch
- Varnish
- Wood
- Wool
- Glass
- Paper
- Recycled Rubber
- Steel
In order to converge the knowledge I acquired during the reconnaissance part of the analysis phase I reviewed the natural materials on their suitability for this project. Only the materials I found promising enough or that have specifically useful properties are taken into consideration. Also recyclable materials present in Friesland are taken into account. The result of this suitability analysis is the matrix below. I used eight criteria which I found to be important to judge the suitability of the materials for this project which are weighed intuitively on a scale of 0 – 1, multiplied by each other to reveal the relative suitability of each material. I chose to multiply the criteria weights because this way a low score is weighed more then with addition. The order in which the factors are placed is random for now, since the general outcome of the approach, for now, is more important.

**Selected natural material:**

<table>
<thead>
<tr>
<th>Material</th>
<th>Durability</th>
<th>Local naturally renewable</th>
<th>Variety in production methods</th>
<th>Wastes usability</th>
<th>Properties suitability</th>
<th>Diversity in application</th>
<th>Growth ability (Chemical) additives needed /100</th>
<th>Suitability index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bamboo</td>
<td>0,5</td>
<td>0,5</td>
<td>0,3</td>
<td>0,8</td>
<td>0,9</td>
<td>0,2</td>
<td>0,1</td>
<td>0,001</td>
</tr>
<tr>
<td>Cork</td>
<td>0,7</td>
<td>0,1</td>
<td>0,7</td>
<td>0,8</td>
<td>0,9</td>
<td>0,5</td>
<td>0,1</td>
<td>0,002</td>
</tr>
<tr>
<td>Epoxy (vernonia)</td>
<td>1</td>
<td>0,5</td>
<td>0,9</td>
<td>0,3</td>
<td>0,9</td>
<td>0,8</td>
<td>0,8</td>
<td>0,054</td>
</tr>
<tr>
<td>Flax</td>
<td>0,5</td>
<td>1</td>
<td>0,5</td>
<td>0,6</td>
<td>0,5</td>
<td>0,6</td>
<td>1</td>
<td>0,045</td>
</tr>
<tr>
<td>Hemp</td>
<td>0,5</td>
<td>1</td>
<td>0,5</td>
<td>0,6</td>
<td>0,5</td>
<td>0,3</td>
<td>0,9</td>
<td>0,020</td>
</tr>
<tr>
<td>Leather</td>
<td>0,9</td>
<td>1</td>
<td>0,3</td>
<td>0,3</td>
<td>0,8</td>
<td>0,3</td>
<td>0,2</td>
<td>0,003</td>
</tr>
<tr>
<td>PUR</td>
<td>1</td>
<td>0,7</td>
<td>0,8</td>
<td>0,3</td>
<td>0,8</td>
<td>0,9</td>
<td>1</td>
<td>0,060</td>
</tr>
<tr>
<td>Rubber (natural)</td>
<td>0,7</td>
<td>0,1</td>
<td>0,8</td>
<td>0,3</td>
<td>0,3</td>
<td>0,5</td>
<td>0,3</td>
<td>0,001</td>
</tr>
<tr>
<td>Starch glue</td>
<td>0,1</td>
<td>1</td>
<td>0,7</td>
<td>0,3</td>
<td>0,2</td>
<td>0,4</td>
<td>0,7</td>
<td>0,001</td>
</tr>
<tr>
<td>Varnish</td>
<td>1</td>
<td>0,9</td>
<td>0,7</td>
<td>0,3</td>
<td>0,7</td>
<td>0,3</td>
<td>0,4</td>
<td>0,013</td>
</tr>
<tr>
<td>Wood</td>
<td>0,5</td>
<td>1</td>
<td>0,9</td>
<td>0,9</td>
<td>0,8</td>
<td>0,9</td>
<td>0,5</td>
<td>0,146</td>
</tr>
<tr>
<td>Wool</td>
<td>0,9</td>
<td>1</td>
<td>0,6</td>
<td>0,9</td>
<td>0,1</td>
<td>0,2</td>
<td>0,4</td>
<td>0,004</td>
</tr>
</tbody>
</table>

**Selected industrial material:**

<table>
<thead>
<tr>
<th>Material</th>
<th>Durability</th>
<th>Recyclability</th>
<th>Variety in production methods</th>
<th>Wastes usability</th>
<th>Properties suitability</th>
<th>Diversity in application</th>
<th>Availability</th>
<th>(Chemical) additives needed /100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>1</td>
<td>1</td>
<td>0,6</td>
<td>0,9</td>
<td>0,3</td>
<td>0,3</td>
<td>0,9</td>
<td>0,8</td>
</tr>
<tr>
<td>Paper</td>
<td>0,3</td>
<td>0,7</td>
<td>0,5</td>
<td>0,7</td>
<td>0,3</td>
<td>0,1</td>
<td>0,9</td>
<td>0,5</td>
</tr>
<tr>
<td>Recycled rubber</td>
<td>0,7</td>
<td>0,3</td>
<td>0,4</td>
<td>0,1</td>
<td>0,9</td>
<td>0,3</td>
<td>0,7</td>
<td>0,3</td>
</tr>
<tr>
<td>Steel</td>
<td>0,8</td>
<td>0,9</td>
<td>0,8</td>
<td>0,9</td>
<td>0,9</td>
<td>0,5</td>
<td>0,9</td>
<td>0,5</td>
</tr>
</tbody>
</table>
Because the materials are different than the regular materials like steel, they perhaps can also provide for different functions in the system. If so, it also might be possible to integrate some of the parts of the regular city bicycle into single parts from natural materials providing for the same function. To explore this I made a functionality analysis of the parts connecting them to the materials selected in the natural materials review. The main goal of this analysis is to explore the possibilities of reducing the number of parts needed, thereby reducing the cost of the product. Secondary goal is making sure every part of the city bicycle is covered by a material option.

Method

The parts analyzed in the Parts Analysis provide a list of basic parts needed to produce a city bicycle. The parts are linked to their main functionality, whereafter they are linked to new parts made from local naturally renewable materials if possible (Fig. 28). From the materials analysis I have the following choices for materials:

- Epoxy
- Flax/Hemp
- PUR
- Varnish
- Wood
- Glass
- Steel

Most parts of a city bicycle have more than one functionality, but in order to maintain overview, I limited the basic parts to their main functionality.

Parts with suspension functionality can be simplified and intergrated when using wood instead of steel. Laminated wood from for example Taxus Baccata is very flexible and strong, which could replace many parts in the saddle and handle bar construction, providing better vibration dampening and shock absorption.

Also the use of foamed natural PUR tyres greatly simplifies a number of parts from a regular bicycle by merging the outer tyre, inner tyre, gasket and rim protection into one single part. Thereby should it be possible to produce PUR from natural resources.

Epoxy is for now a very unsustainable product, but due to its many functionalities cannot be excluded. It can be used for joining parts, wear and weather resistance. It should be possible though to produce Epoxy from for example Vernonia Galamensis.

This material can also be used to produce other parts like the saddle cover, handles and even the drive belt. With the selected materials it is considered possible to produce all the necessary basic parts of a bicycle, therefore the general conclusion of the feasibility analysis is that the design of a bicycle with natural materials is feasible, however for certain parts it might be necessary to use steel. The percentage of steel material is still expected to be very low, and there are still possibilities for replacing steel parts with other parts.

Generally it can be said that five materials, Wood, Flax, PUR, Epoxy and Steel, would be enough to provide for the manufacturing of a city bicycle.

---

**Introduction**

Because the materials are different than the regular materials like steel, they perhaps can also provide for different functions in the system. If so, it also might be possible to integrate some of the parts of the regular city bicycle into single parts from natural materials providing for the same function. To explore this I made a functionality analysis of the parts connecting them to the materials selected in the natural materials review. The main goal of this analysis is to explore the possibilities of reducing the number of parts needed, thereby reducing the cost of the product. Secondary goal is making sure every part of the city bicycle is covered by a material option.

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**Conclusion**

Parts with suspension functionality can be simplified and intergrated when using wood instead of steel. Laminated wood from for example Taxus Baccata is very flexible and strong, which could replace many parts in the saddle and handle bar construction, providing better vibration dampening and shock absorption.

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Generally it can be said that five materials, Wood, Flax, PUR, Epoxy and Steel, would be enough to provide for the manufacturing of a city bicycle.
Material Functionality Analysis

Graduation Arno Scheepens

Movement parts
- Handle bar
- Steering pin
- Axles
- Fork
- Spokes
- Hubs
- Rims
- Cranks
- Crankshaft
- Front gear wheel
- Rear gear wheel
- Bearings
- Inner tyres
- Outer tyres
- Brakes
- Drive chain
- Connections
- Welding
- Nuts & Bolts
- Tight fitting

Structural parts
- Top Tube
- Head Tube
- Down Tube
- Seat Tube
- Seat Stay
- Chain Stay
- Housing
- Saddle pin
- Saddle frame
- Saddle spring
- Pedals
- Saddle shape
- Saddle filling
- Steering handles
- Saddle cover
- Grip
- Weather resistance

User contact
- Saddle shape
- Saddle filling
- Saddle cover
- Steering handles

City Bicycle

Strength/Stiffness

Similar parts
- Top Tube
- Head Tube
- Down Tube
- Seat Tube
- Seat Stay
- Chain Stay
- Housing
- Saddle pin
- Saddle frame
- Saddle spring
- Pedals
- Saddle shape
- Saddle filling
- Saddle cover
- Steering handles

Strength/Stiffness

Custom seating part

Wood, Epoxy, Natural Fibre

Natural PUR & natural fibres

Steel

Epoxy & Geometry (e.g. finger joints)

Natural PUR

Fig. 28: Functionality Analysis

23
Now that the materials have been selected, it is time to take a closer look. In this Chapter I will analyze the selected materials more in-depth to make sure nothing severely inhibiting has been overlooked.

**Wood**

The next issue with this material is the species of wood to be used as material for the Rebicycle. In general it can be said that hardwood has better properties for the use in a bicycle than softwood, however are two important problems:
- Hardwood generally has relatively high weight
- High costs due to slow growth rate

Therefore an investigation into different wood species that grow naturally in Friesland is needed.

**Method**

Three variables are thus very important for selecting the wood species: Strength & Stiffness, weight and costs. I combined mean mechanical property data from the CES database with the list of occurring flora in Friesland [5], thereby limiting the available wood species to 17. These are listed to the right. The data is arranged from top to bottom starting with the species having the highest E-modulus/density ratio which yields the stiffest wood species per unit of weight, which turns out to be the Picea Abies tree, also known as the Norway Spruce (Fijnspar, NL). This species also has the highest Yield Strength/density ratio, and shares the lowest cost per Kg. This leads to the choice of Picea Abies wood as the material to use for the frame fork and similar parts.

It remains questionable whether the data provided by CES is accurate, but an alternative wood species is selected easily.

There are two main problems with wood. Its manufacturability and its weather resistance.

The possibilities for mass production of wood in products are limited. But there are methods of shaping wood. One I found very promising is the shaping of thin sheets of wood with steam and simple moulds. The wood is cured at a certain temperature and its moisture content is raised so the wood becomes malleable to a certain extent. When finished, the wood maintains its strength and form. This technique would allow me to manufacture a hollow frame at relatively low costs. Another technique which has been developed recently is the Plato method [6]. The process cures the wood in two steps: The first step is carried out at a temperature of 150-180 °C with steam, and the second step is carried out at 150-190 °C in dry conditions. This procedure changes wood from normal spruce (Class IV) to hardwood (Class I), improving durability massively. This is partly the answer to weather resistance as well. Of course, the layer of epoxy and/or varnish will protect the wood, but in case of damage, I want the wood to be as durable as possible.

After a consult with Plato International B.V., I have to conclude that the Plato technology is not suitable for dynamically loaded applications. The process chemically alters the material, leaving it very brittle. Therefore for structural parts I cannot use Plato wood, however it would remain suitable for fenders and chain protection. The other solution is the Accoya method, where anhydride is used to enhance wood durability. This is probably worse for the environment, on the other hand, if the life cycle of wood is shortened because its durability hasn’t been improved, the ecoburden is estimated to be many times higher.

Therefore the choice is the Accoya method to enhance wood durability.
### Results

The matrix below is ranked starting with the wood species having the highest E/Density ratio. According to the used sources softwood has the same price regardless the species. This cannot be entirely true, however it can be assumed that the softwood species grow at approx. the same rate. The highest ranked species appears to be spruce medium density, which also has the highest Strength/Density ratio.

<table>
<thead>
<tr>
<th>Species of wood that grow in the Netherlands</th>
<th>Latin Name</th>
<th>Dutch Name</th>
<th>native</th>
<th>Cost/growth rate EUR/kg</th>
<th>Density Mg/m3</th>
<th>Elastic moduli E GPa</th>
<th>Yield strength MPa</th>
<th>E/density ratio</th>
<th>Strength/density ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce medium density</td>
<td>Picea Abies</td>
<td>Fijnspar</td>
<td>no</td>
<td>1.1</td>
<td>0.51</td>
<td>16</td>
<td>48</td>
<td>31</td>
<td>94</td>
</tr>
<tr>
<td>Fir</td>
<td>Abies procera</td>
<td>Spar/ grenen</td>
<td>no</td>
<td>1.1</td>
<td>0.44</td>
<td>13</td>
<td>40</td>
<td>29</td>
<td>90</td>
</tr>
<tr>
<td>Spruce</td>
<td>Picea Rubens</td>
<td>Zilverspar</td>
<td>no</td>
<td>1.1</td>
<td>0.45</td>
<td>12</td>
<td>40</td>
<td>26</td>
<td>88</td>
</tr>
<tr>
<td>Oak</td>
<td>Quercus spp.</td>
<td>Eik</td>
<td>no</td>
<td>9.2</td>
<td>0.92</td>
<td>23</td>
<td>48</td>
<td>25</td>
<td>52</td>
</tr>
<tr>
<td>Douglas Fir</td>
<td>Pseudotsuga menziesii</td>
<td>Douglas spar</td>
<td>no</td>
<td>1.1</td>
<td>0.54</td>
<td>13</td>
<td>48</td>
<td>24</td>
<td>88</td>
</tr>
<tr>
<td>Birch</td>
<td>Betula Verrucosa</td>
<td>Berk</td>
<td>yes</td>
<td>1.1</td>
<td>0.69</td>
<td>16</td>
<td>53</td>
<td>23</td>
<td>76</td>
</tr>
<tr>
<td>Larch</td>
<td>Larix</td>
<td>Lork/Lariks</td>
<td>no</td>
<td>1.1</td>
<td>0.58</td>
<td>13</td>
<td>53</td>
<td>22</td>
<td>91</td>
</tr>
<tr>
<td>Oak medium density</td>
<td>Quercus falcata</td>
<td>Eik medium dichtheid</td>
<td>yes</td>
<td>2.5</td>
<td>0.77</td>
<td>17</td>
<td>61</td>
<td>22</td>
<td>79</td>
</tr>
<tr>
<td>Willow</td>
<td>Salix Alba</td>
<td>Wilg</td>
<td>yes</td>
<td>2.5</td>
<td>0.35</td>
<td>8</td>
<td>27</td>
<td>22</td>
<td>77</td>
</tr>
<tr>
<td>Ash</td>
<td>Fraxinus nigra</td>
<td>Es</td>
<td>yes</td>
<td>2.5</td>
<td>0.55</td>
<td>12</td>
<td>43</td>
<td>21</td>
<td>78</td>
</tr>
<tr>
<td>Pine</td>
<td>Pinus spp.</td>
<td>Den</td>
<td>no</td>
<td>1.1</td>
<td>0.49</td>
<td>10</td>
<td>41</td>
<td>20</td>
<td>83</td>
</tr>
<tr>
<td>Maple</td>
<td>Acer saccharum</td>
<td>Esdoorn</td>
<td>no</td>
<td>1.8</td>
<td>0.71</td>
<td>14</td>
<td>56</td>
<td>19</td>
<td>78</td>
</tr>
<tr>
<td>Cherry</td>
<td>Prunus avium</td>
<td>Kers</td>
<td>yes</td>
<td>9.2</td>
<td>0.61</td>
<td>11</td>
<td>50</td>
<td>18</td>
<td>81</td>
</tr>
<tr>
<td>Walnut</td>
<td>Juglans regia</td>
<td>Okkernoot</td>
<td>yes</td>
<td>9.2</td>
<td>0.69</td>
<td>13</td>
<td>62</td>
<td>18</td>
<td>89</td>
</tr>
<tr>
<td>Beech</td>
<td>Fagus grandifolia</td>
<td>Beuk</td>
<td>yes</td>
<td>2.5</td>
<td>0.83</td>
<td>13</td>
<td>54</td>
<td>15</td>
<td>65</td>
</tr>
<tr>
<td>Elm</td>
<td>Ulmus thomasii</td>
<td>Iep</td>
<td>yes</td>
<td>2.5</td>
<td>0.71</td>
<td>11</td>
<td>53</td>
<td>15</td>
<td>74</td>
</tr>
<tr>
<td>Yew</td>
<td>Taxus baccata</td>
<td>Taxus</td>
<td>yes</td>
<td>9.2</td>
<td>0.7</td>
<td>7</td>
<td>40</td>
<td>10</td>
<td>57</td>
</tr>
</tbody>
</table>

### Conclusion

Hardwoods aren’t as well suited in a lightweight design. The highest scoring hardwod is Oak, having a high E/Density ratio, but scoring badly on the Strength/Density ratio. Moreover the price is 9 times higher than the best scoring wood species.

The best wood species for the Rebicycle is Picea Abies: Norway Spruce (Vurenhou,NL). It has the highest Stiffness and Strength/Density ratio. Other wood species like Fir are close runner ups, and if higher stiffness is required somewhere, Oak might be used because it has the highest stiffness of the species analyzed.
Selected Materials

Flax/Hemp

Of the four species of fibre plants that will grow in Friesland the two most promising are Hemp and Flax.

Hemp has slightly better properties than Flax:
- Hemp has an E-modulus of 3 – 10 GPa and Flax 2.9 – 8.5 GPa
- Hemp has a yield strength of 200 – 400 MPa and Flax 150 – 338 MPa
- Hemp produces longer fibres (up to 4 metres) than Flax

But, Hemp is much more vulnerable to a species of fungus which kills large amounts of crops in wet circumstances. Flax has been grown in the Netherlands for a long time, presumably it is better resistant against the Frisian climate, not needing toxic detergents.

Also the planting to harvest time is a little shorter for Flax than for Hemp: 100 days and 120 days respectively.

Then again Flax can only be harvested from the same piece of land every 6 – 7 years.

For now I conclude that either crop can be used for the production of fibres usable for the Rebicycle. Ropes will be yielded easier from hemp, but a higher quality of fabric can be made with Flax.

However, Flax harvests also yield linseed oil which can be used for the production of natural PUR, therefore the preliminary choice is Flax.

In comparison: Carbon fibre can achieve E moduli between 370 – 390 GPa and yield strengths between 1800 – 4300 MPa so for example it’s a factor 50 stiffer and a factor 10 stronger than natural fibres.

Nevertheless, because the natural fibres can be oriented and thereby reinforcing structures in specific areas and directions, the application of natural fibres can be beneficial as connective material, reinforcement, added stiffness and because of its matrix material can provide weather resistance.


Fig. 29: Flax Textile
Recycled steel can be a high grade material for which the use in a bicycle might be justified by its properties on strength, durability, safety and wear resistance. Especially the bearings, brakes and braking cables, might have to be made from steel, because of the specific requirements for those parts.

However, the recycling of steel requires high amounts of energy for transport and melting, because the material has a high density and a melting point of around 1400 °C. This means large, heavy equipment to render the process economically feasible.

Therefore I want to minimize the use of steel in the Rebicycle. The use of recycled steel is a lesser problem since the Rebicycle is supposed to return to the company at the end of life stage. However, the amount of energy needed for melting, cleaning and reproducing the parts is high, as well as the amount of equipment needed.

To maintain the required level of quality it might be impossible to exclude steel as a material, but its volume could be minimized. Nevertheless, the goal of exclusion of steel is likely to have a positive contribution on the sustainability of the Rebicycle, given that this will not affect consumer opinion negatively.
A natural source for the epoxy adhesive has been found in the Middle African plant Vernonia Galamensis. This plant doesn’t grow naturally in Friesland, however it has been proven possible to grow the crop in a greenhouse in the U.S. in the midatlantic region at a temperature of around 20-25 °C with artificial lighting which is considered not a problem because of the amount of energy and heat that can be produced from the wastes.

An epoxy adhesive consists of two components: resin and hardener/curing agent. The resin can be made directly from Vernonia oil because the oil naturally contains epoxidised fatty acids. E.g. Linseed oil needs to receive a treatment of formic acid and hydrogen peroxide. Bio synthesis of the Vernonia fatty acids is possible [8].

A common form of curing agent is ethylenediamine, a chemical which is derived quite easily from its raw materials: ethylenedichloride and ammonia. The resulting substance is ethylenediamine with the by-products of sodium chloride (salt) and water. Ethylenediamine is liquid at room temperature and has a light ammonia-like odour, therefore if there is a leak it is detected easily. This is necessary because the vapour is lightly toxic and flammable. However because it is expected to be used in small quantities the negative effects of using this substance are considered insignificant, however in the design it has to be taken into account.

In the Rebicycle company it is questionable whether the amount of ethylenediamine is high enough to justify the investment for the equipment to manufacture the material in-house. If not, it will have to be bought. The price of ethylenediamine is around 100 USD per liter.

Biosynthesis from biowaste through fermentation yields a feasible way for production of ethylene. The barrier is the economical feasibility, oil prices would have to rise with a factor 5 in order to render biosynthesis economically interesting [9]. This means however that there are ways to produce organic chemicals like ethylenediamine from biowaste without the need for petroleum.
The process for the production of an epoxy adhesive is simple: put the two components together, mix them and apply. The exothermic reaction cures the mixture. Depending on the curing agent the properties of the adhesive can be influenced.

The production of Vernonia oil and its fatty acids derived from the oil can be performed in-house, but the production of ethylenediamine (or other curing agent) is too complex and economically infeasible because of the small quantities to produce in-house.

The application of the epoxy adhesive and the mixing of components prior to that is very important, because of the potential environmental and health risks, mainly because of the vapours released from the ethylenediamine itself and during the mixing and curing of the components.
Still the problem remains of the oil derived MDI needed for the production of PUR (Fig. 39), but in the future this might be solved by a recent development in PUR manufacturing techniques:

“In a different approach towards polyurethanes fatty acid derivatives were carbonated in supercritical carbon dioxide.[10,11] The resulting cyclic carbonates can be converted to polyurethanes with primary amines avoiding the use of isocyanates (usually phosgene is used for isocyanate synthesis). Recently, such an approach was applied to carbonated soybean oil that was reacted with ethylene diamine, hexamethylenediamine and tris(2-aminoethyl)amine to obtain polyurethane networks with Tg values of approximately 34 °C, 18 °C and 43 °C, respectively.[12]”

This process indicates that there are possibilities to circumvent the use of the fossil oil based MDI’s for the production of PUR and possibly TPU. For now these processes are not available for use in products, but in the future these materials might well be applied in the Rebicycle. Important is the preparation and flexibility of machinery for these processes and materials.

After a consult with Professor Picken of the ChemTech faculty at the TU Delft, I have to change the set up of materials.

The source for natural PUR has shifted from Linseed to Vernonia, because the Linseed oil has to be epoxidised in preparation for the PUR manufacturing process which is not needed for Vernonia because it contains a naturally epoxidised oil (Fig. 35). By circumventing the epoxidisation the use of formic acid and hydrogen peroxide is avoided (Fig. 37). Also the natural PUR derived from Linseed oil has glass temperature values of around 77 °C, which probably yields a too inelastic plastic for the purpose of the tyres, saddle and handles. This property can for example be influenced by the amount of catalyst, the amount of crosslinkers and the choice for filler material. But since the soya oil fatty acids (oleic acids, Fig. 35, 1) largely resemble the Vernonia oil fatty acids (vernolic acid, Fig. 35, 9) the outcome is expected to be closer to the PUR derived from carbonated soya oil with glass temperatures around 34, 18, and 43 °C. Adding a filler to this material has a high probability of being capable to exactly produce a material with the required properties: the glass temperature of natural rubber is around -60 °C. One choice for filler material could very well be recycled cork.

Deriving supercritical CO2 is not as complicated as it sounds. Supercritical CO2 is CO2 under specific conditions where a homogeneous state is achieved. For CO2 this is at around 40 bar and 46 °C, which can be achieved with a simple compressor and abundant heat from the energy production process. (Fig. 38)
This means that I will need a larger greenhouse, but on the other hand I will not need hydrogen peroxide and formic acid used in the epoxidisation process of Linseed oil and since my preliminary LCA indicates that I will have more energy and heat than I need for the process, this is the better solution.

This means that I no longer need oil flax, and I only have to derive one oil: epoxidised Vernonia Galamensis oil (Fig. 40). I can use this oil for epoxy adhesives as well as natural PUR, probably using the same hardener for both e.g. in the form of ethylenediamine, hexamethylenediamine and tris(2-aminoethyl)amine, which are simple substances that should be easy to derive from nature.

When designing a 100% sustainable product it is also necessary to evaluate the design according to existing methods to obtain the effectiveness of the new approach: the use of local naturally renewable materials. The chosen method is the Life Cycle Analysis (LCA) combined with the ecocosts 2008 database. A Life Cycle Analysis is the evaluation of all Life Cycle Inventory analyses (LCI). A LCI is the mass and energy balance, or the sum of all inputs and outputs. [14,15]

The ecocosts 2008 database uses consumers’ estimates and expert judgement to assess the environmental impact to what it would be worth to the consumer, leaving dimensionless units behind and using a tangible unit, the euro.

Goal
This LCA is meant to explore the impact of the proposed materials in this feasibility analysis. I've made preliminary decisions on which parts of a bicycle can be replaced with natural materials and for which parts it is probably (yet) impossible. Some of these parts have a longer life-cycle than the product itself. But most of all it is necessary to have an idea of the impact made by the use of natural materials, especially the end-of-life point, the deletion of transport and the energy production from waste materials.

Scope
Within this LCA the scope is on the Rebicycle, its materials, the production and end-of-life. Normally the end-of-life is not considered in LCA, it handles with input/output only. For this project however it is very important to include this product stage, because the project uses the natural cycle to reach a sustainable product.

Functional unit
In order to make a comparison a functional unit is needed with which the amount of ecocosts are estimated. For this LCA a functional unit is chosen of 10.000 Rebicycles. This is the estimated series production numbers for the Rebicycle company.

Life Cycle Inventory
Because of limited time in this project I discussed with an expert in the area of life cycle analyses, dr.ir. J.G. Vogtländer, how to best approach the Rebicycle life cycle analysis. We concluded that I have to summarize the ecocosts for the natural materials used excluding the energy and transport inputs and outputs, because we expect that the waste materials would deliver more energy than needed for the process itself, redistributing energy to the grid, instead of using energy from the grid. I could use the Simapro software, which combines in this case the Ecoinvent unit processes and Idemat 2008 database with ecocosts 2007. The resulting ecocosts have no meaning on themselves, at least not in this project, but they serve as a comparative mean to gain insights into what is better. I would prefer a system that determines what is good instead of better (or less bad), but if the sum of ecocosts is negative in total, I for now have to assume that that is good.

So I made life cycle inventories of the materials proposed in the feasibility analysis and for each step in their respective processes I excluded the energy inputs and outputs. I also excluded transport because all material production is to be done locally.


The technical details of the Life Cycle Analysis can be found in [Appendix C]
Method

The Ecoinvent database in SimaPro uses unit processes and combines them into general processes. In order to exclude energy and transport ecocosts, the origin of those ecocosts have to be found at the basis of each process. A LCI is made for each of the selected materials from the suitability index matrix. These LCI’s are then combined in the Life Cycle Analysis. The energy inputs are removed from all steps in the process. This is justified by the assumption that the natural wastes produce more energy than needed in these processes. Since these wastes are derived directly from nature, the only ecocosts that remain are dust and emissions from burning. However it still remains debatable whether these are actual ecocosts since their origin is 100% natural, therefore the emissions have to be equal to the input, only in another form and/or state.

For now the ecocosts of emissions from the burning of natural wastes are not included, because I feel that whenever nature’s cycle is utilized, harm can’t be done to the environment, at least not significantly. The transport ecocosts are also removed from all steps in the process. This is justified because the natural resources are grown in the direct vicinity of the production company. Hereby all transport ecocosts are removed, from land occupation for roads to the steel and fuel necessary for the transport means. The result of the ecocost analysis are ecocosts of the material, land occupation of the material, equipment, labour and machinery for processing the material with a separate total of energy and transport requirements. Hereby only the energy amounts are important to complete the equation and estimate the degree of sustainability of the project. Of course the real problem of LCA persists because not every input and output is known for each process, and some inputs and outputs are weighed with estimations from experts in their specific field and industry while other inputs and outputs are left out. Therefore no absolute result can be yielded, but a comparison can be made. In this phase I want to make the comparison between the use of natural materials the way they are utilized nowadays and the use of natural materials produced locally combined with energy production from their wastes.

This comparison will provide insights in the degree of improvement in ecocosts for the idea of local production and closing the cycle. It will not provide any insights into the relative improvement on regular bicycles, for which a separate Life Cycle Analysis is needed.

Ecocosts/value ratio

This LCA will eventually lead to an estimation of the ecocosts/value ratio. This is the primary indicator of the ecocosts 2008 method. Basically this indicator reveals the degree of sustainability in relation to its consumer-perceived value. The lower the indicator, the higher the degree of sustainability. In principle, this theory is based on the idea that people on average spend the amount of money they earn during their lifetime, e.g. Europeans a bit less, Americans a bit more. If consumers spend more on low ecocost/value rated products, this could mean a huge improvement.

In order to estimate the quantity of ecocosts, the amount of materials used have to be estimated. I made the following assumptions for the required amounts of material per bicycle:

- 10 kg. Softwood
- 3 kg. PUR
- 1 kg. Steel
- 0,5 kg. Epoxy
- 0,5 kg. Flax textile

After the design is finished and the exact inputs and outputs are known the life cycle analysis will be expanded to include land usage. This has to be done to obtain insights in the degree of sustainability of the project as a whole: How much land does it take to produce 1 bicycle over what time span?

Then I will have to make a selection between different methods for assessing the impact, or suggest a system of my own:

The amount of land available in Friesland divided by the total of inhabitants yields the average amount of land per person. These can be divided into segments like urban, agricultural, natural, industrial recreational etc., where the Rebicycle land would be placed in the industrial segment. If this yields 1%, that result would be very promising, if it yields 50%, this means the Rebicycle has used half of the industrial land intended for the consumer. I like the logic of this theory, since it focuses on the most important actor in sustainable development: The government and policy-makers, because it yields indicational data for future development in the region. For example if the Rebicycle is succesful and uses 1% of industrial land available in the region, and together with other industrial products only 98% of industrial land is used, the policy makers could then conclude that 2 % of industrial land has to be shifted to another segment of land use.

Off course a lot of research has to be done to validate this theory and in this project I won’t be able to do that, but I can test it to see what results it would yield.

In order to obtain insights on the relative sustainability improvement of the localized product development method (LPD) the final LCA of the Rebicycle has to be compared to the LCA of the current bicycle design.
All LCI’s were put together in order to get an overview of the contribution of each material and especially the effects of removing transport and energy from the process. The ecocosts portrayed are calculated with a functional unit of 10,000 Rebicycles per year.

**Material**

First, the results indicate an overall saving on ecocosts of approximately 75%, due to the removal of transport and energy ecocosts. This possibly is too high a percentage because of assumptions that had to have been made and lack of data. However it can be concluded that there will be a significant reduction in ecocosts when removing transport and energy from the system. Moreover, the ecocost reduction compared to the current city bicycle design can become something in the order of 75% reduction of the 10% which is left after 90% reduction caused by the use of natural materials, instead of steel, rubber, etc. I for now have no insight into the exact percentages, but as expected there will be a huge reduction in ecocosts, especially because here transport and energy can also be excluded. This comparison will be made after the design is finished, because then detailed information is available.

**Energy**

This means that the Rebicycle concept is going in the right direction, though the goal of 100% sustainability is not yet reached. However, in Life Cycle Analysis theory, the produced energy from the process could be interpreted as negative ecocosts, reducing the total of ecocosts generated by the Rebicycle. For now an estimation is made for the amount of energy to be produced from the biological waste. This estimation is based on the expected amount of wood wastes, including the wood in the Rebicycle, as the product is to be returned to the Rebicycle company where eventually it will be incinerated for energy as well.

The largest negative contribution to the ecocosts of the Rebicycle is made by the polyurethane (more than 50%), then steel, epoxy, flax and wood. Especially wood has an ecocost which is close to zero while it is the main material used to produce the Rebicycle. The negative contribution of PUR and epoxy is mainly caused by the curing agent ethylenediamine. This confirms the hypothesis that the use of local naturally renewable materials is more sustainable. Whether it is 100% sustainable remains questionable because of lack of data and comparative means, but the indications are that there is an estimated improvement of 75%, which is considered to be quite good, especially if the comparison is made between the Rebicycle and the current city bicycle design. For now the comparison is only between naturally renewable materials with external energy and local naturally renewable materials with internal energy.

The Life Cycle Analysis of the current city bicycle design will have to be made to obtain insights into the level of sustainability of the entire project, which will be made at the end of the detailing phase because then all materials and their quantities are known.

**Ecocosts/Value Ratio [14]**

“1. it is an indicator for sustainability in LCA (additional to the eco-costs) in cases where the quality of products (with the same functionality) differs
2. it is an indicator which is relevant to corporate strategies and governmental policies: it links the consumer side with the production side
3. it is a parameter in economic allocation of LCA calculations”
The estimation of the ecocosts/value ratio is also promising. At an estimated sales price of 600,- euros, the ecocosts value ratio is approximately $12.187,- /10.000/600,- = 2,03 \times 10^{-6}$ for the Rebicycle. This has no real value, but it can be compared to the ecocosts/value ratio of the current city bicycle design. This will become clear when the LCA is completed at the end of the project, when the amounts of material and energy are known exactly from both the Rebicycle and a regular city bicycle.

It is however quite interesting to take a look at the land use, because these are direct ecocosts. This will be treated in the next section. It will also be possible to derive a business scenario. [Appendix D]
Land Use

Introduction

A very important issue in this project is the degree of sustainability. The attempt of a 100% sustainable product seems not yet entirely possible, however it can be said that the elimination of transport and external energy consumption by the use of local naturally renewable materials is promising. However there exists a problem with this approach, similar to the biofuels problem: Land use.

If more and more products are made from local naturally renewable materials, the amount of fertile land available for growing food diminishes, or doesn’t it?

Method

In order to assess the project’s sustainability level first an estimation of land use is made for the production of 10,000 bicycles per year. This is done by comparing the gathered data from the Life Cycle Analysis and research data gathered in Sweden in Norway Spruce Production. Because by far the largest quantity of material is Norway Spruce, the calculation is restricted to this material only. Also in the first stage of the Rebicycle company this will be the local naturally renewable material most fit to start the experiment with, because this investment will always yield at least some income.

The Life Cycle Analysis provides data on the estimated wood use in a Rebicycle and the amount of waste accompanying the processed raw materials. A Research paper, [16], provides insight into the current Norway Spruce Production and the potential of its increase with added nutrients and ample water (Fig. 41). From this the production of Norway Spruce is predicted, on the basis of comparing the mean temperature. Norway Spruce stops growing beneath a temperature of approx. 8 °C. This is assumed to have a weakening effect on the material itself, because the relative amount of softer
tissue increases with extension of growth the period. For now it is considered too complicated to predict the amount of strength stiffness lost to a different climate zone. It is however expected to have an insignificant effect, below 10%. It is expected that with increasing the amount of material it should be possible to compensate for that loss in the final design.

**Calculation Results**

According to the Life Cycle Analysis estimation 269,000 kg. of wood is needed to produce 10,000 bicycles per year.

If the Norway Spruce production is estimated correctly at 12 m3/ha/year (Fig. 42), that would yield:

12 x 510 = 6120 kg./ha/year.

The amount of land thus needed to produce 10,000 Rebicycles per year is:

269,000/6120 = 44 ha. Error margin here is chosen as 2, therefore the estimation is that between 44 and 88 ha is needed for 10,000 bicycles per year.

Wheter 44-88 ha is an unsustainable amount of land for the production of 10,000 bicycles per year is difficult to say. There are too many variables involved for me to investigate this issue now. However the comparison to a standard agricultural company can yield insights into whether the system could fit within the current economical paradigm:

The mean land use of agricultural companies in the Netherlands in 2007 was approx. 40 ha. The mean turnover of those companies is estimated below € 3 million. This estimation was made from the fact that the 20% largest agricultural companies have a turnover € 4 million for crops and € 5 million for horticulture. The Rebicycle company however aims to yield a turnover of 10,000 x € 600,- = € 6,000,000,-. This is no proof that the approach will work, but it is a positive indication for being able to redeem the added costs relative to conventional industrial processes.


But the main solution I see is to form a boundary with the Rebicycle company between the industrial world and nature. The plantation could (partly) expand the local nature reserves and soften the boundaries between agriculture and nature. Also the Rebicycle company could form a link between several isolated nature reserves. This way the land is used for several functions simultaneously, increasing its sustainability level and economical value (Fig. 43).
Economical Feasibility

Since the start of the industrial revolution around 200 years ago, the linear economic model has led to the belief that there are nothing but advantages from globalization. The linear economic model assumes an unlimited (exponential) growth of production and transport, providing more people with more diverse products. There is however one (potentially fatal?) flaw in this model which is the assumption that nature will sustain the increasing demand in resources and production of wastes. The exponential growth of consumption is caused by an increasing population with increasing wealth due to global economic growth, depleting nature’s resources and approaching the limit of nature’s capacity to restore itself. It is commonly believed that nature is approaching a tipping point which, if reached, will be a point of no return in the sense of irreversible damage to ecosystems and radical climate change of which its form or magnitude is impossible to predict. Because this tipping point is impossible to predict it would be plain stupid to wait and see what happens, because an experiment with nature gone wrong has the potential of destroying mankind’s ability to sustain itself, or worse, destroying the earth’s capacity to sustain life. Critics claim that the climate changes are foremost natural, and only in small part caused by human action. However, this way of reasoning seems to be short term based since it is a given fact that we will run out of fossil fuel supplies at some point, be that in 50, 100 or 500 years. By continuing business as usual we shut our eyes to this problem with a short term goal of profiting while still possible.

One of the solutions proposed as an alternative to the current economical model is the distributed economies model. This model is not linear but networked, which is supposed to be much more resilient in terms change and risk. The network consists of small independent economies interconnected through mainly ICT control systems, eliminating most long distance transport needs. If in a linear model on element stops to function, the whole system collapses, whilst in the distributed economies model only a small part of the system collapses, with the possibility of nearby similar micro systems compensating for the loss of one small part of the system. One example of such a model is the planned wind turbine park network around the North Sea, where local wind turbine parks from Norway, England, The Netherlands etc. are interconnected providing a steady power supply, even in The Netherlands, if at that moment in time there is now wind energy produced in the Dutch wind turbine park.

The current credit crunch may be the best example of the problems of a linear economic model, since the financials (one link in the chain) which made mistakes due to continuing belief in unlimited economic growth and lack of transparency and control has led to a global economic crisis. Therefore I think that we have to start acting now creating new ideas for innovation outside the current economic system. Time is running out for these innovations, even though we still have the luxury of no immediate need for 100% sustainable products because we still have a (decreasingly) functioning industrialized system, since even the most pessimistic predictions for climate change made by scientists around the world have been proven to be too optimistic (e.g. the rate of decline of arctic ice reserves). The idea of using local natural materials only for a local market fits within the distributed economies model. The extent to which the market has to remain local and the resources local naturally renewable has to be evaluated after the design has been made available to the public.
According to DE labs, a research group specializing in Distributed Economies, the system can be described as follows (Fig. 44):

“The general characteristics of DE are:
• To draw from regional/local values, strengths and possibilities.
• To make sustainable development as an integrated part of innovations.
• To realise large-scale benefits through better utilization of SME networks.
• To develop unique high-quality products based on knowledge, design, quality and environment.
• To make the technical development learn from and cooperate with nature.
• To pay increased attention to qualitative aspects of living and consumption patterns.
• To focus on small-scale and flexibly distributed technology systems, rather than centralized bulk-systems.

• To identify new producer/customer relations, i.e. show how SMEs can be local and global actors at the same time.
• To better utilize and develop local resources and values (e.g. natural resources, finances, human capital, knowledge, technology, and so on).”


The Rebicycle would be an example of a business unit in such an economic system. It relies on local resources and depends as much as possible at present on local industries as well as large scale industries. Eventually it is meant to become totally independent from non-local resources and industries.

In return the Rebicycle delivers products, their accompanying services and energy back to the consumer at minimal costs to the environment. A glance at business scenarios is given in [Appendix D].
The Market Analysis is intended to provide insight into the marketplace into where the Rebicycle is to launched. The market segment is defined by the target group, the product(s), a SWOT Analysis and a general Market Analysis.

Target group
- Early adaptors of the sustainability concept
- Dutch government

Product
- Bicycle
- Production facility
- New production techniques (Patents)

Strengths
- Unique product
- Appealing concept
- Strengthen Dutch position on sustainability subject
- Sustainable product design consultancy future

Opportunities
- Funding
- Media attention
- Patents
- The Dutch government has issued that starting from 2010 (motie Koopmans), every purchase by the government should be “sustainable”. This is off course very vague, depending on its definition of sustainability. However, it does imply intent to take sustainable development seriously.

In Friesland the population is approx. 650,000. This is approx. 3.8 % of the Dutch population. This means that approx. 50,000 bicycles are sold every year in Friesland, but this number will be slightly higher since it is to be expected that there are on average more cyclists in Friesland. This means that the market share to be achieved is 20%, which is very high.

But if the time is there that fossil fuels, energy and transport have become a rarity and thus expensive, such a market share is highly feasible.

Weaknesses
- Economic feasibility
- Technical feasibility

Threats
- Development of cheap durable sustainable energy

Every year about 1.32 million new citybicycles are sold in The Netherlands (2006). This number is growing, since in the first half of 2007 it relatively increased by 10% and seen from 2005 to 2006 there was an increase of 7%. The average price of a Dutch bicycle is around €600. Total €770,000,000.

BOVAG expects electric bicycle sales to be around 150,000 at an average price of €1800. (!)

594,000 secondhand bicycles are sold every year (2006). “It is a very conservative market, but there are numerous possibilities for innovation. “

594,000 secondhand bicycles are sold every year (2006). “It is a very conservative market, but there are numerous possibilities for innovation. “

I also investigated three possible scenarios for the Rebicycle company as a whole, which can be found in [Appendix D]
A direct consequence of globalization has been the increased social inequality in the world. Though it is claimed that globalization has achieved the opposite through increased average global welfare, still 1 Billion people survive on less than a dollar per day. Average welfare might have been elevated, but only under the condition that the welfare of the West increased with at least the same pace [23]. In short it can be said that capitalism pursues globalization in which lies a sustainability paradox: “Producing more products for more people made by less people.”

The amount of consumers keeps rising, therefore product demand keeps increasing, competition forces prices down, automation replaces workers, all resulting in a fragile situation where more consumers are being supplied by less workers.

The scale of industry has grown disproportionally, centralizing industry away from the consumers, inherently increasing home-work transportation needs and thus the load on the entire transportation system. These kind of developments only were possible to a certain extent at the expense of nature and its resources. The point where nature can’t provide for the growing needs of humanity has been reached or will be reached in the relatively near future.

The Rebicycle concept also provides a possible solution for this trend. By employing locals for the relatively labour intensive production process, transport is minimized, the local economy is stimulated. Because of these effects the consumer is likely to be proud of such a product, which inherently increases the product life cycle time, because the consumer is likely to be more careful when using the product. I feel this is the main social benefit of a product like the Rebicycle, because it evokes an opposite behaviour from over- or hyper-consumerism. Thereby the goal of developing a showcase product would be achieved in part.

**Regional dependency**

If the project is performed in 2nd or 3rd world countries or areas, these social effects are likely to be the same, or even stronger. This would be due to the social inequality between the Western world and the rest where western consumers pay too little money for products produced in the developing world compared to the western region, because wages are lower. From a sustainability point of view this is completely wrong, because these products generate much more ecocosts due to transport, fossil fuels, and poor social and ecological laws, while the product costs less. The winners in the equation are the multinationals, who essentially shift costs to the developing world in order to decrease costs. These companies use the different tax and law systems to optimize their profit without concern for the environment and workers, or, in general, responsibility. These developments make it hard for western consumers to make the right choice, because the ecologically worst products are the cheapest (in general) and the price difference is paid for by the environment, but perhaps even more important, by the workers in developing countries which work and live mostly in poverty, especially compared to the western consumers which buy the product they have made.

For now it is concluded that a showcase product like the Rebicycle probably will improve awareness amongst consumers, helping them make the right choices in the future, but without radical changes to the paradigm, e.g. higher import taxes etc. the advantages of globalization should be removed for all products that can be produced locally as well.
The Rebicycle Project

After analyzing the parts, materials and functionalities, the conclusion is that it is not possible to produce a high quality bicycle with local naturally renewable materials only. A very high percentage is however highly feasible. By replacing steel with wood as the material for the frame, wheels and other structural parts a large percentage of the product can be made with local naturally renewable materials.

With a non local naturally renewable resource, Vernonia Galamensis, the possibilities for producing natural PUR and epoxy adhesives is great. The downsides of this resource are the need for a greenhouse and a chemical curing agent for both PUR and Epoxy adhesives.

The greenhouse is expected to be justifiable because the break even point of ecocosts for building and maintaining the greenhouse and ecocosts for transport of the resource from its natural habitat is expected to be reached quickly. The waste from wood processing as well as other biowaste is expected to yield enough heat and energy to sustain the entire process of manufacturing.

Therefore the only real compromise is the need for a curing agent for PUR and epoxy adhesives. Is there no other alternative for the need of this material? From the analysis the need for PUR is created by the invention of the airless tyres. The tyres reduce the number of parts significantly, are more durable than rubber tyres and are manufactured with high simplicity. Naturally epoxidised fatty acids from Vernonia Galamensis combined with a ring opener catalyst, supercritical CO2 and ethylenediamine as a curing agent can yield a high quality PUR. For now, this process is under development and not suitable yet for implementation, however the tyres already exist for current city bicycles, therefore the design can be prepared for the development of natural PUR. The Rebicycle company could conduct R&D for natural PUR with the application for tyres, drive belts, handles and saddle covers, but numerous other applications could be researched as well.

The use of wood for the majority of parts requires a reliable connective material and/or method. The use of an epoxy adhesive is likely able to be used for all connections needed to assemble a bicycle. Because this simplifies the entire process by using one resource for all connections, epoxy is the choice for now. The high strength and durability make epoxy adhesives extremely suitable for its application in a bicycle, mainly made from wood.

Although a chemical is needed for both processes, the same chemical can be used as well as the same resource which greatly simplifies the entire process. This makes it likely for the product to be more economically feasible. Later in the project I discovered that ethylene, the main component of ethylenediamine, can be best produced from wood wastes. It is still 5 times more economical to use oil for production, but it is possible.

The parts that are the most difficult to produce with local naturally renewable materials are the bearings and the brakes, because of their high material requirements. The dimensions of the parts and their high loads and wear combined with the high necessity for their functions force the project for now to make compromises on local naturally renewable material use.

However, the parts have possibilities for recycling, not only because they are made of steel, but also because the parts are likely to last (much) longer than the entire product, which could mean they could be reused directly, reducing ecocosts significantly. For now the estimation is a possibility of approx. 70% of the materials used for the Rebicycle can be made with local naturally renewable materials.

The Life Cycle Analysis was key in discovering the potential of closing the cycle for the Rebicycle. During this Analysis I found out that wood when rotting produce methane gasses, which are very harmful. Therefore it was chosen to incinerate wood and other biowastes for heat, steam and electricity generation (Fig. 45). Even though this produces carbon emissions, these carbon emissions have been absorbed by the natural materials over the time of their creation.

The economical and social analyses are conducted to place the Rebicycle concept in context. There is not much that can be derived from these analyses directly, but they do point into a certain direction regarding different socio-economical paradigms which might be necessary to achieve a sustainable future.
The Rebicycle Project

Fig. 46: Suggested Product Configuration
Process

The process that was followed during the first parts of the analysis phase has been very useful in determining the feasibility of the project as a whole. I haven’t been able to research all natural material possibilities, but I have been able to find suitable natural materials for most parts.

The compromises that might be necessary to design a high quality product are not in compliance with the assignment of making a 100% sustainable product, but the social function of the design is not compromised, because it still is made predominantly with natural materials. The potential for the design to achieve a considerable ecocost savings is still very high, and the goal setting of 100% sustainability has lead the project to the development of feasible new biomaterials that fulfil specific functions, instead of biomaterials having a decorative marketing function. The project still has the potential of delivering a showcase.

Product

The product as it is shown to the left (Fig. 46) is a rough idea of what the Rebicycle could look like. There are many possibilities for using Local Naturally Renewable Materials.

It will be a challenge integrating all required functions into a successful complete design, however I’m pretty confident at this stage that the product as proposed is feasible.

The Programme of Demands & Wishes is not yet completely at the stage of judging the different ideas that will be generated in the next phase. For that some additional analyses will have to be performed.

All in all I feel the product is going in the right direction.

Personal

According to the plan I was supposed to work on the Feasibility Analysis for 4 weeks. This has been doubled due to the fact that I realized that replacing the industrial materials with Local Naturally Renewable Materials wasn’t the only bottleneck. The concept needed to be supported by Analyses in different fields. This has delayed the start of the idea phase, but on the other hand there have been a lot of design decisions in the Feasibility Analyses, greatly determining the course of the idea phase and its scope.
From the Analysis phase a preliminary Programme of Demands & Wishes is derived. These demands are derived specifically for the design of the Rebicycle. However in the first stages of the idea phase, which follows the Analysis phase, it is important to have a general description of the bicycle functionality. These general requirements have been formulated according to the Parts Analysis mostly.

It is important to evaluate the first ideas according to the general functionality, because I follow the SPSD method. This method greatly resembles the standard industrial product design method, only at the beginning the product functionality is examined thoroughly in order to be sure not to make an inappropriate redesign. I compare different concepts for human powered transportation that could comply with the general functionality to the design criteria in order to determine which types are most suitable.

The general functionality is described as facilitating human powered transport over a distance of maximally 20 km. in urban as well as rural areas.

**General requirements**

- The design has to be produced with Local Naturally Renewable Materials. [Assignment]
- The design has to be safe [Parts Analysis]
- The design has to be comfortable [Parts Analysis]
- The design has to be efficient [Parts Analysis]
- The design has to be durable [Parts Analysis]
- The design has to be an eye catcher [Social Analysis]
- The design has to be customizable [Parts Analysis]

These General Requirements form the basis for the Programme of Demands & Wishes

### The Rebicycle has to be made of naturally renewable materials, grown locally.

1. Only naturally renewable materials are allowed, except for the bearings, brakes, tyres and drive chain
2. The materials have to be grown locally
3. Other materials have to be either fully recyclable or biodegradable

### The Rebicycle has to be safe.

1. The product has to be strong enough to support P90 of the Dutch population
2. The frame and fork have to be stiff enough:
   - The frame has to have a torsion stiffness of at least 50 Nm/°
   - The fork has to have a stiffness of 40 Nm/° or a maximum elongation of 3 mm. measured from the rear axle to the front axle
   - The bracket stiffness has to be at least 30 Nm/° and a maximum deflection of 4 mm. is allowed
3. The weight of the bicycle has to be between 10 and 20 kg. Some of the lightest bicycles produced nowadays weigh around 10 kg. and 20 kg. is an estimated value for the maximum weight for a bicycle.
4. The tyres, handles, pedals and saddle need sufficient grip
5. The brakes have to be reliable in dry and wet conditions
6. The rider position should provide overview in city traffic
The Rebicycle has to be comfortable.

1. The product has to be adjustable to individual size and weight.
2. The product has to be suitable for short to medium distances within cities and between villages and cities. The average distance travelled with city bicycles in the Netherlands is approx. 2.5 km. per day but Friesland is hardly a urban region, and the few cities are widely spread. Therefore the product has to be suitable for distances, 1-5 km., and medium distances, 5-20 km. This is also in compliance with urban residents using the product for within the city as well as recreational in the countryside.
3. The user has to have a comfortable riding position, providing enough support and suspension.
4. The radius of the bicycle has to be small enough to comfortably manoeuvre in urban areas. This can be derived directly from the current city bicycle design. This is one of the main complaints with reclining bicycle users, manoeuvrability in urban areas is uncomfortable.
5. The product has to have minimized friction and rolling resistance

The Rebicycle production has to be efficient.

1. The amount of parts has to be kept as low as possible
2. The production methods have to be based on wastes and by products of essential processes
3. Easy assembly and disassembly shortens labour time and costs
4. The production methods should require the least amount of equipment possible
5. The product has to be produced in series of around 10,000/year. At an average price of € 600 this should yield a turnover of € 6,000,000, which for now seems a reasonable figure to start with.

The Rebicycle has to be durable.

1. The moving parts have to be wear resistant
2. The product has to be weather resistant
3. Fatigue strength has to be sufficient
4. The product has to be robust

The Rebicycle has to fit Frisian life-style.

1. The product has to be simple
2. The product has to be “cool”

The Rebicycle has to be an eye-catcher

1. The product has to look different
2. The product has to be recognizable

The Rebicycle has to be customizable

1. Saddle height and suspension have to be adjustable
2. Handle bar height has to be adjustable
The Feasibility Analyses have defined the boundaries for the idea generation summarized in the programme of demands. The generated ideas should, in compliance with the Programme of Demands, provide solutions for the design to be made. A human powered transportation product is a complex product interdependent on several subsystems. These subsystems together are the design problem. Seen as a whole this is a too complex system for efficient idea generation. Therefore the design is divided into six design problem areas:

Construction
Actuating
Wheels
Brakes
Suspension
Bearings

However, before the ideas are generated I feel it is important to determine which kind of product is suitable for the required general functionality, according to the SPSD method. This is very important because I need to be sure whether the design should be a product, a bicycle as analyzed or another human powered transportation concept. Or maybe even a service? The result of the project can’t be a service, because facilitating human powered transportation can’t be done with a service only. A service would only be possible if the entire functionality of the product becomes obsolete because of that service, meaning that there no longer would be a demand for human powered transportation, e.g videoconferencing or taxi’s.

As indicated the design method is based on the SPSD method which is turned into the LPD method predominantly by the restriction to the use of local naturally renewable materials only. One very important element of the LPD method is the general functionality which is examined for 6 basic human powered transportation concepts. Thereafter the design process returns to a regular industrial design process:

1. The three chosen basic concepts are used in combination with the ideas generated after the general functionality is examined.
2. The ideas are generated for 6 defined design subproblem areas. The high-potential ideas are then combined into complete product ideas.
3. These idea combinations are thereafter filtered and the best (parts of the) idea combination are put together to form the concept direction which is the end result of the idea phase. (Fig. 47)
Idea Phase Process

General functionality

Selection by criteria & functionality

Subproblems Idea Generation

Morphological Chart & A.I.D.A.

Combined Idea Generation

Combined Idea Selection

Monocycle

Step

Draisine

Bicycle

Tricycle

Reclining Bicycle

Construction

Actuating

Wheels

Brakes

Suspension

Bearings

Combined Ideas

Concept direction

Fig. 47: Idea Phase Process
Because of the required General Functionality, it is concluded that facilitating human powered transport cannot be provided for with a service, thus a product is needed. However, a product service system is a good possibility for maintaining a close producer-consumer relationship and, more importantly, a stimulus towards the consumer for returning the used Rebicycle to the production company, aiding closing the cycle.

In this project the focus is on the design of the product, and a bicycle is analyzed as an example. This however doesn’t mean that a bicycle is the right basic concept to continue with. Therefore six different human powered transportation concepts are compared in order to choose the right direction for the idea phase.

A **Step** (Fig. 48) can be made with natural materials quite easily, except for the bearings. It is reasonably controllable and operates at low speeds.

The standing position as well as the leg movements are not very suitable for distances longer than a few km. Because it is a construction with limited possibilities the production will not be highly efficient because of material use.

It can be a very durable product, though the natural materials are bound to need servicing more often. It doesn’t quite fit the life-style of the Frisians, since they often travel longer distances.

It can be eyecatching, but it’s nothing new. Because the steering is the only thing to vary for customizing, the step is well customizable, even though construction support is limited.

A **Monocycle** (Fig. 49) is very easy to construct from natural materials, the type of load greatly resembles the natural forces on trees. There is no stability, therefore accelerating, steering and stopping is difficult.

Comfort level is decreased by lack of stability and support.

The production can be highly efficient.

The product is likely to be able to endure for a reasonable time period.

Constantly balancing on one wheel is not considered to be very Frisian.

It will draw attention.
Only the height of the saddle needs to be adjustable, therefore easily customizable.

The Draisine (Fig. 50) was one of the first human powered transportation products. They are easily made with natural materials. It is relatively safe to use a draisine.

Leg motion and riding position are uncomfortable, energy usage is highly inefficient. The production and material usage can be quite efficient. Few moving parts make its durability potential higher. Because it is not suitable for longer distances, it doesn’t fit the life style. It is something different. It can be customized quite easily.

The Bicycle (Fig. 51) can be made with natural materials for the largest part. Rider position and overview make it safe to use. Efficiency and ergonomics make the concept fairly comfortable. Material usage is highly efficient.

Cycling fits Frisian life-style. Even with natural materials it can be quite durable. The materials make it interesting, the bicycle is too well known on itself. A bicycle is reasonably customizable though different frame sizes are required commonly. The construction of a Reclining Bicycle (Fig. 52) is less efficient, therefore harder to construct with natural materials. Lack of overview compromises safety, especially in the city. Rider position and efficiency make it a comfortable ride.

The reclined position improves efficiency. Even with natural materials it can be quite durable. Because of the longer distances it fits life-style well. It remains an eye-catching concept. It can be customized quite easily.

The construction of a Tricycle (Fig. 53) is not optimal, therefore more difficult to build with natural materials. Lack of overview compromises safety, especially in the city.

Rider position and efficiency make it a comfortable ride. The reclined position improves efficiency, however the third wheel decreases efficiency (rolling resistance). Even with natural materials it can be quite durable. Because of the longer distances it fits life-style well. It remains an eye-catching concept. It can be customized quite easily.

Conclusion

Because the general product functionality is described as facilitating human powered transportation over a distance of max. 20 km in urban and rural areas, it is concluded that the step, monocycle and draisine are inadequate concepts. These concepts lack safety, power efficiency and most of all comfort. The remaining three concepts seem to be suitable to provide for the general functionality. The idea generation will commence with ideas for the six different problem areas defined for the next phase of which the primary problem area is Construction. The ideas generated in this area are based on these three concepts: the Bicycle, Reclining Bicycle and Tricycle.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Draisine</th>
<th>Bicycle</th>
<th>Reclining Bicycle</th>
<th>Tricycle</th>
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<tr>
<td>Natural Materials</td>
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<td>Fit life style</td>
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<td>Eye catcher</td>
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<td>Customizable</td>
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The generated ideas and their selection is seen in the Morphological Chart (Fig. 54). The detailed considerations for selecting these ideas is described in [Appendix E]

For each sub problem area the most feasible solutions have been selected on the basis of the general requirements, especially the four most important criteria.

However, not all possible solutions to these subproblems have been treated because of time pressure on the project. Moreover, the selected solutions aren’t necessarily the right solutions, so if in the concept phase one of the selected solutions isn’t adequate the other options will have to be reviewed, and even new other solutions might have to be conceived.

Though there are limits to the approach in this phase, highly feasible solutions were generated and selected very efficiently, and these leave sufficient possibilities for combining these into complete solutions.

The three possibilities for the frame are selected in order to cover a wide range of concepts within the feasibility of the project. The exception was the combination of idea 3 & 5 which were combined in order to comply with the general requirements.

For the drive system an existing solution was selected, the drive belt, together with a variant of the chain because of its expected high efficiency. The direct drive was selected because of its high efficiency and easy production due to few simple parts.

The solid wheel was selected because of the possibilities for natural materials and easy production, but also the flexible wheel was selected, because the implementation of new developments (tweed, michelin) with natural materials could simplify many parts and increase comfort. Even though this wheel can only be used as a front wheel with limited combinations of other solutions.

The solutions are depicted to the right in the morphological chart starting with the most viable solution to the left. These solutions would generate far too many combinations to evaluate in this project, therefore the A.I.D.A. method is selected to combine these solutions into combinations.

This method is pretty dated and hardly used in modern industrial design practice. In this project however I’ve come up with this method after a discussion with my mentor. The reason for selecting this method is that for each subproblem areas the most feasible and/or promising ideas have been selected, however many of these solutions have configuration possibilities which could render the individual solutions impossible.

One example would be the use of a flexible wheel with calliper brakes: the rim wouldn’t be located at the same position continuously, causing the brakes to be ineffective at some rim positions. This would be unacceptable.
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<tr>
<td><strong>A) Construction</strong></td>
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<td><strong>B) Actuating</strong></td>
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<td><strong>C) Wheels</strong></td>
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<td><strong>D) Braking</strong></td>
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<td><strong>E) Suspension</strong></td>
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<tr>
<td><strong>F) Bearings</strong></td>
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Fig. 54: Morphological Chart
Analysis of interconnected decision areas is a method where the individual solutions are combined with other solutions where the impossibilities are left out. For this project this method is highly suitable because there are many conflicting ideas (Fig. 55):

- A1-B3: A normal frame combined with the ergonomics render direct drive impossible.
- A2-B3: For a reclining frame direct drive is principally possible, however to achieve the required speed the driven wheel has to be as large as possible, which will obstruct the view of the cyclist.
- A3-B1: With a tricycle the use of a drive belt is obsolete, because direct drive is far more affordable and the cyclists’ sight isn’t obstructed.
- A3-B2: With a tricycle the use of a drive chain is obsolete, because direct drive is far more affordable and the cyclists’ sight isn’t obstructed.
- C1-E3: A solid wheel can’t be flexible.
- C2-B1: A flexible wheel can’t be driven because the forces on the hub will cause the wheel to collapse.
- C2-B2: A flexible wheel can’t be driven because the forces on the hub will make the wheel collapse.
- C2-B3: A flexible wheel can’t be driven because the forces on the hub will make the wheel collapse.
- C2-D1: Because the wheel is flexible the rim isn’t located at the same position for the calliper brakes to use them as braking surface.

With these combinations ruled out 15 idea combinations are left with a high feasibility for this project (Fig. 56). One exception is kept in mind during the formulation of these combinations: The flexible wheel. This is an exception because it cannot be used as a driven wheel, however a combination of solid and flexible wheels is in some cases possible, if the calliper brake is not used on the front wheel. It is probably more attractive to use one type of wheel, but the flexible wheel might reduce the impacts on the head tube and top bar of the frame, for which it might even become necessary to use this type of wheel.

The idea combinations are evaluated according to the programme of demands which is derived from the general requirements. The programme of demands is adapted for this stage of the idea phase, because this stage greatly determines the looks and aesthetics of the design. Therefore the Programme of Demands is reformulated according to the Target Group Analysis combined with two important requirements from the Programme of Demands.
Analysis of Interconnected Decision Areas

Fig. 55: A.I.D.A.
The selection for these idea combinations is done according to the demands specified for this stage in the idea phase of the project. Because this stage of the idea phase for a large part determines the appearance and form of the Rebicycle, the social feasibility analysis is performed. In order to get a feel for the social feasibility of the project the target group is analyzed. The project is a reaction to trends like eco-design, green marketing etc. which seem to catch on with the general public. Take for example biologically grown foods, hybrid cars, recycling and general waste and pollution prevention. Some of these products and/or services cost more than “normal” products and/or services, e.g. biologically grown foods. It remains questionable whether it remains cheaper when for example medical costs are incorporated which are believed to be higher for consumers that consume “normal” foods. This set aside, a trend has been observed of increasing interest from consumers for sustainable development. The three northern provinces of The Netherlands, including Friesland, are the most progressive in sustainable development of all 12 provinces in The Netherlands, probably because these are more rural provinces having more interaction between people and nature, resulting in a higher appreciation for the environment and its importance. Therefore Frisian are thought to be more susceptible to products that have as a main goal to provide for a need whilst, instead of harming the environment, cooperating with the environment which could be explained as 100% sustainable. Because of the rural as well as urban surroundings in which most Frisians live, the product has to be suitable for urban as well as rural areas in order to be suitable for most Frisians.

Though Frisians may be more susceptible to these kind of products than the average Dutch person, still the bicycle market as a whole is very conservative. The reclining bicycle for example, despite its advantages hasn’t been a great success even though The Netherlands is a cyclist country excellently suited for long range cycling due to the lack of steep slopes and wide array of bicycle lanes. Therefore, on the one hand, the Rebicycle will have to look pretty similar to the current products on the market in order to be sold, but on the other hand, the idea of a 100% sustainable product attempt has to be communicated as much as possible to generate awareness among the public of the possibilities of sustainable product design. This is crucial to widen the criteria of consumer judgement which they use to select between the vast array of products available. Therefore the product has to be distinguishable from regular city bicycles.

There is also a psychological effect not to be underestimated. The feeling of owning and using a product which is good in every sense, not just quality and comfort but also not harming the environment, providing jobs in the consumers’ direct surroundings and the direct relationship between consumer and producer are likely to provide a positive consumer experience. This experience might well prove to be crucial in the transition to a sustainable society, because it might be so that in the future consumers become increasingly aware of secondary or higher order consequences for buying these kind of products. Indirectly these products may reduce energy costs, traffic jams and pollution, not just in some rainforest on the other side of the world, but in the direct surroundings of the consumers themselves.

Another aspect of the target group is the image of sustainability as a whole. Though interest for the concept is ever increasing, sustainability is still associated with a fuzzy tree hugger image, which doesn’t add to popularity.
This image should not be reflected by the Rebicycle, instead the design should radiate a “cool” and robust image. The trend nowadays for “cool” bicycle designs has three faces:

(Fig. 56) The “oma-fiets” as a classic is considered “cool” because of its simplicity and is popular among school kids and students

(Fig. 57) The “beach cruiser” is considered “cool” as a part of the “pimp my ride” culture

(Fig. 58) Minimal bike designs with integrated functions and a clean design are also popular

In order to fit Frisian lifestyle it is concluded that the Rebicycle has to fit the following demands:
- The product has to be suitable for rural as well as urban areas.
- Appearance
  - The product has to be recognizable as a bicycle.
  - The product has to be distinguishable from regular bicycles.
  - The product has to be a crossover between an “oma-fiets” and a beach cruiser and have integrated functions showing the least amount of parts resulting in a clean design.

Furthermore, the Rebicycle has to meet other important demands which improve customer acceptance for the natural materials used in the Rebicycle:
- Utilize specific material properties (comfort)
  Consumers are more easily persuaded into purchasing the product if the specific material properties fulfill functions that the “old” materials weren’t able to do.
- Efficient material use and production (price)
  Eventually price is very important for persuading the customer. The use of local naturally renewable resources result in a direct correlation between the amount of material used and the cost price of the final product.

From the appearance requirements formulated according to the target group analysis the following semantics have been distilled:

Elegance
Elegant design is achieved by using organic shapes that provide functionality as simple and straightforward as possible. E.g. the curved top bar in the “oma-fiets”/“Dutch bike” design determines greatly the appearance of the entire design, whilst providing a functionality, resulting in an elegant design.

- The Rebicycle has to look elegant, therefore functional curved shapes are required

Robust
Robustness communicates reliability to the consumer. The three popular bicycle designs have a robust appearance due to their straight forward design without many accessories. Large wheels with wide tyres also contribute.

- The Rebicycle has to look robust, therefore oversized dimensions should be applied in some parts of the Rebicycle

Conclusion
Off course the chosen directions should also meet the general requirements as well, but as these are used for selecting the sub-problem solutions the general requirements should be met as with the A.I.D.A method the impossible combinations were eliminated. Therefore the idea combinations are judged by the following demands:
Suitable for rural and urban areas, recognizable as a bicycle, crossover between three trends, utilize specific material properties and efficient material use and production.
The solution combinations provided by the A.I.D.A. method were subjected to the adapted programme of demands. These solution combinations can be seen below (Fig. 59). The detailed selection process can be found in [Appendix F].

- Suitable for rural and urban areas
- Recognizable as a bicycle
- Clearly distinguishable from a regular bicycle
- Crossover between three trends
- Utilize specific material properties
- Efficient material use and production
The concept direction will have to consist of the highest ranked ideas made from the solution combinations. First the low ranked ideas are excluded which are the tricycle ideas. The main reason for discarding these ideas are the low rider positions and the high material use for the construction. The appearance doesn’t connect to the desired crossover. Increased comfort due to aerodynamics is partly rendered obsolete due to 1/3 increase in rolling resistance because of the third tyre.

Secondly the reclining bicycles are excluded. The main reasons for excluding these types are the low resemblance with current bicycles and their larger length which results in a large turning radius and the need for larger storage space. Also the lower rider position results in decreased safety within the city and more material is required to produce a product with approx. the same functionality. These are more suitable for long range cyclists in rural areas, not suitable for the combination of city and rural use.

Thirdly the two ideas with the medium height rider position are discarded. Though they provide for within the city as well as in rural areas, the majority of city bicycle riders will not even consider these types of bicycles. For example Flevobike which produces an industrial material version of idea combination A2 B1 C1,2 D1,2 E1 only have high-end users as clients, whereas the Rebicycle is intended for the majority of cyclists which are regular city bicycle clients. These don’t want to be associated with the latter group of consumers.

The highest ranked idea from the solution combinations was idea A1 B2 C1 D2 E1 (Fig. 60), mainly because of the shape of the bicycle. The shape resembles a regular bicycle, though remains clearly distinguishable. Material use is minimal and the properties of wood are utilized well except for the steering suspension. Wheel suspension is now discarded because of production efficiency which is lower for two different wheels than for one. Wheel suspension also creates the need for brakes like the rim brakes used in the highest ranking idea, which are likely to be less reliable than calliper/cantilever brakes because the latter is a proven system frequently seen on regular bicycles.

The concept direction has to be the most feasible and reliable direction for further development, since there are many detailing problems to be expected in the concept detailing phase. Therefore the concept direction has to be distilled from the 6 highest ranking ideas focussed into idea A1 B2 C1 D2 E1. This is done by converging the best solution of every problem area defined in the beginning of the idea phase into the general idea combination A1 B2 C1 D2 E1. This solution combination is not optimal in several aspects:

The brakes are likely to be unreliable. Therefore the brake system should be cantilever/calliper. The drive chain is also likely to be unreliable. Though it is possible to produce with natural materials, the gear wheels are likely to be much more complicated and the endurance of the natural materials is questionnable. Therefore the choice lies with the proven technology of drive belts, which for now is less sustainable, but given the possibilities for producing natural PUR is a wise compromise. Steering suspension should also be incorporated into the concept direction, be it of less importance than the previously mentioned adjustments because the handlebar is loaded far less than the saddle.
The concept direction is composed of the previously selected idea with the selected solutions to the different problem areas. These solutions are (Fig. 61):

**Construction**
- Double triangle laminated wooden frame for maximum strength/weight ratio and incorporation of irregularities of the natural material.

**Actuating**
- The drive belt combined with wooden gear wheels for proven functionality, efficient forces transfer and easy production of gear wheels.

**Wheels**
- Rigid wooden wheels with a laminated rim and spokes for incorporation of irregularities of the natural material and structural consistency of the rim position for braking purposes.
- PUR foam tyres for long life, never-go-flat tyres which only consists of one part. Slightly higher rolling resistance is considered a reasonable compromise since the regular user is not probable to inflate his airfilled tyres to specification on a regular basis.

**Brakes**
- Steel Calliper/Cantilever brake system for reliability and safety and proven functionality.

**Suspension**
- Saddle and handlebar suspension for user comfort and diminishing of parts during assembly.

**Bearings**
- Standard steel roller ball bearings for optimal force transfer efficiency.
Now that the direction of the concept (Fig. 62) is selected, the concept will have to be designed into detail. The concept is detailed on three levels:

- Ergonomics, which is crucial for user comfort and efficiency.
- Strength and stiffness, which is crucial for safety, efficiency and comfort as well.
- 3D model, which is crucial for incorporating the results of the ergonomics and strength & stiffness analyses.

The process (Fig. 63) has been highly iterative on the three levels, though a certain order was identified. First the ergonomics analysis was performed. This was done to identify the restrictive dimensions which form the boundaries for the dimensions of the design. After these boundaries for the design were identified, they were transferred to a thread model in Solidworks. This was necessary because the restrictive dimensions were plentiful and interdependent. In Solidworks these dimensions are easily placed, whereas incorporating these dimensions correctly in sketches is considered nearly impossible.

This thread model was thereafter transferred to MatrixFrame software. Main goal of the strength & stiffness analysis is to determine the required cross-section dimensions of the members of the frame, seat tube and fork.

The computed cross-section consequently was modelled into the thread model containing the restrictive dimensions, creating a rough 3D model of the concept. The 3D model revealed problems, from where the process becomes highly iterative. One of the main problems that occurred was the integration of different parts of the concept, whilst maintaining strength and stiffness, e.g. placing the bearings into the frame and getting the drive system cleared and aligned.

Thus changes were made to the thread model, which were incorporated into the MatrixFrame software and thereafter into a rough 3D model in Solidworks. These iterations occurred several times, finally resulting in a detailed 3D model of the design proposal.

The results of the ergonomics and strength & stiffness analyses are explained in the following section.
One of the most important aspects of a bicycle leading to comfort, safety and efficiency is the ergonomics of the design. There are a number of body dimensions that are restrictive which have been taken from an ergonomics research paper: [24] Johan Molenbroek: Children’s bicycle design as well as [25] www.ergonomiesite.be which describe many rules of thumb. The current bicycle design requires a range of frame sizes to provide comfort for all users. From a sustainability point of view this is undesirable because for example many different moulds are needed. Multiple production lines increase cost per product. Therefore it is desirable to design a one size fits all bicycle, but this is a very ambitious goal because in the extremes there is a high variation in body dimensions due to the fact that ergonomic measurements are mean numbers. This renders the design for all nearly impossible. It is decided to investigate the dimensions variation for the Dutch adults (20-60 years) between the P5 for women and the P95 for men percentiles, covering approx. 90% of the Dutch population. The Frisian population is expected to be slightly taller than the average Dutch population, but this is left out of consideration since larger dimensions are not considered to be restrictive, the P5 female dimensions restrict the frame dimensions. Solidworks was thereafter used to put these dimensions into the context of the bicycle design according to the design solutions and sketches made in the idea phase. This yielded a 2D thread model view of the selected restrictive dimensions found in the research paper [24] as well as in the parts analysis. These dimensions are shown in the table to the right.

The result (Fig. 64) showed possibilities for the P90 range of the Dutch population. This is however still a thread model, thus no final conclusion can be drawn. Dr. Ir. Johan Molenbroek, an ergonomics expert at the Faculty of Industrial Design, was consulted on how to approach testing the design on ergonomics. It was decided to transfer the thread model to ADAPS software which contains an ergonomic measures database. This allowed the integration of the P5 female percentile and the P95 male percentile simultaneously in the same thread model.

Conclusion
According to the result of the ADAPS analysis it is concluded that the thread model (Fig.64) is suitable for customization to fit 90% percent of the Dutch Adults between 20 and 60 years.
Buttock - Knee depth: This dimension determines the minimum distance between the back of the saddle and the handlebars. Inner leg length/crotch height: This dimension determines the range of the distance between the saddle and the crank axle. Inner leg length/crotch height x 1,06: This dimension is a rule of thumb found on www.ergonomiesite.be which determines the saddle - ground distance. Shoulder height: This dimension determines the maximum height difference between the saddle and the handlebars. Shoulder width: This dimension determines the minimum handlebar width. Hand width: This dimension determines the minimum handle length. Foot width: This dimension determines the minimum pedal width. User weight: The weight of three users is a measure used in children’s bicycle design. From the parts analysis however it is known that in bicycle design a rule of thumb is that the dynamic loading of a bicycle can be computed by multiplying the static loads with a bump factor of 1.6. This is used in the strength & stiffness analysis. The knee height is tested in ADAPS for clearance of the knee and the handlebar. The grip circumference is simply taken from the existing handlebar dimensions. The step in height of the frame is also left out because the heigh of the crank axle is taken from existing city bicycles which is around 250 mm. In the design a height of 255 mm is used to incorporate tyre deformation. Crank length is also taken from the standard which is 170 mm. Tread is standard taken as 120-140 mm. This is necessary for good force transfer from the hips for which the saddle set-back should be adjustable in a range of approx. 100 mm.

All these dimensions should be possible with the frame as suggested in the thread model (fig.). The next step is to investigate whether the dimensions of the frame itself needed for sufficient Strength and Stiffness can be compliant with the thread model. Therefore the Strength and Stiffness Analysis is performed. 

<table>
<thead>
<tr>
<th>Body Dimension</th>
<th>Restrictive Percentile</th>
<th>Dimension</th>
<th>Extreme dimension</th>
<th>Bicycle dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buttock-knee depth</td>
<td>&gt; P95</td>
<td>&gt; 689</td>
<td>&gt; 560</td>
<td>Saddle - handlebars</td>
</tr>
<tr>
<td>Inner leg length</td>
<td>&lt; P5</td>
<td>&lt; 696</td>
<td>&lt; 914</td>
<td>Saddle - lower pedal</td>
</tr>
<tr>
<td>Inner leg length x 1,06</td>
<td>&lt; P5</td>
<td>&lt; 737,8</td>
<td>&lt; 968,8</td>
<td>Saddle - ground</td>
</tr>
<tr>
<td>Shoulder height</td>
<td>&lt; P5</td>
<td>&lt; 523</td>
<td>&lt; 673</td>
<td>Maximum height difference saddle - handlebars</td>
</tr>
<tr>
<td>Shoulder width</td>
<td>&gt; P95</td>
<td>&gt; 674</td>
<td>&gt; 381</td>
<td>Minimum handlebar width</td>
</tr>
<tr>
<td>Hand width</td>
<td>&gt; P95</td>
<td>&gt; 99</td>
<td>&gt; 73</td>
<td>Minimum width handles</td>
</tr>
<tr>
<td>Foot width</td>
<td>&gt; P95</td>
<td>&gt; 111</td>
<td>&gt; 84</td>
<td>Minimum width pedals</td>
</tr>
</tbody>
</table>

Adapted restrictive dimensions

<table>
<thead>
<tr>
<th>Weight of three users (3x P95)</th>
<th>&gt; 1.6 x P95</th>
<th>&gt; 168</th>
<th>&gt; 78.4</th>
<th>Carrying weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee height</td>
<td>&gt; P95</td>
<td>...</td>
<td>...</td>
<td>Upper pedal - handlebars</td>
</tr>
<tr>
<td>Shoulder height</td>
<td>&lt; P95</td>
<td>...</td>
<td>...</td>
<td>Maximum circumference handlebars</td>
</tr>
<tr>
<td>Step height</td>
<td>&lt; P5</td>
<td>...</td>
<td>...</td>
<td>Maximum step-in height of the frame</td>
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</tbody>
</table>

Restrictive Dimensions

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<td>Maximum step-in height of the frame</td>
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Strength is not perceived directly by the consumer, only product failure is directly perceived. The Rebicycle is mainly made from wood, which probably will surprise most consumers as a suitable material in this application. It is crucial in providing for consumer safety for obvious reasons. Therefore in the calculations of the frame it has been considered that the maximum stress in the material should be below the fatigue strength of the material, which is found to be approx. 22MPa for Picea Abies Medium Density [Appendix B, Materials Analysis].

Stiffness on the other hand is directly perceived by the consumer and if the stiffness is too low, the consumer perceives the product as “wobbly” and unsafe. Furthermore the deformations in the product absorb energy which might be used for propulsion.

It is however not desirable to have a bicycle with absolute stiffness, because then the shocks from the road are transferred too directly to the consumer, resulting in a very uncomfortable ride. High stiffness levels are required for professional cyclists, not for the majority of cyclists: city and recreational cyclists which are the target group of the Rebicycle project. Therefore in the calculations it is set as goal to achieve a frame which meets the demands formulated in [Appendix A: Parts Analysis] where the fork displacement is 3mm. at most and the bracket deformation is 4 mm. at the most. whereas the seat stay is supposed to flex within a reasonable range.

Method
To compute these deformations and stresses I had to turn to software, because if done by hand these calculations would have taken an enormous time investment. I turned to MatrixFrame software, where a simplified thread model of the dimensions of the Solidworks thread model was placed. This software enables the variation of the cross-section of each individual member determining at first the approx. size of the cross-section.

The shape of the cross-section is determined according to the possibilities of wood. The laminated parts should be loaded in bending, to utilize the specific properties of the material. To optimize the torsion stiffness/material use ratio the cross section is chosen to be symmetric. A cylinder is known to have the highest torsion resistance/material use ratio, however production of a cylindrical tube frame from wood is expected to be very difficult because double bending of the material is very complicated. Straight tubes will cause that the frame would have a very similar shape and look to the current city bicycle frames, which I want to avoid, partly because of the design vision where the Rebicycle has to stand out from the regular bicycle but also because of ergonomics where there would be the need for different frame sizes as with the current city bicycle design: the position of the seat tube, top tube and seat tube joint has to be as close as possible to the crankshaft to allow enough user height variation enabling a larger portion of the Dutch adults to fit on the frame. Also straight tubes would cause the material to be loaded in tension and compression instead of bending.

Four different load cases were defined to incorporate extreme use scenarios into the strength and stiffness analysis.

1. Fully loaded on the saddle: a Force of 1680 Newton is simulated on the saddle. (Fig. 65, 69)
2. Full acceleration: a Force of 1680 Newton is simulated on one end of the crank axle. (Fig. 66, 60)
3. Standing on pedals: a force of 840 Newton was simulated on each end of the crank axle. (Fig. 67, 71)
4. Distributed load: this is a simulation of the approx. loading in normal use. (Fig. 68, 72)
The cross-section dimensions should be as large as possible with thin walls to deliver the highest stiffness/weight ratio. Too large a cross-section would result in ergonomic issues and undesirable aesthetics. Eventually for the frame a rectangular cross-section with minimal dimensions of 50 x 50 mm is chosen. This shape is easily laminated from 5 mm. boards into a hollow rectangular shape. The fork, seat stay and chain stay have a cross-section of 25 x 50 mm, because the same height enables the manufacturing of the top tube & seat stay and the down tube & chain stay as single parts. The seat tube cross-section is set to 30 x 35 mm for flexibility.

### Strength

The MatrixFrame analysis can determine the maximum stress and its position occurring in the frame for each load case. This should be below the fatigue strength of the material, which is 22 MPa.

In all four analyses peak stresses occur in the head tube and the seat tube. For all other members the stresses remain below the limit of 22 MPa. Therefore it is concluded that the chosen cross-sections are sufficient in terms of strength, with two exceptions:

**Head tube**

The head tube is however modelled as a circular cross-section with a diameter of 30 mm., which is the cross-section of the steering pin. The strength of the head tube is not taken into account, but since the stress in the steering pin is approx. 50 % higher than the fatigue strength: 33.25 MPa, it is concluded that this part will not be strong enough. However, because the stress is significantly below the yield strength: 43 - 52 MPa, the steering pin will not fail immediately and serves as a good fatigue strength test where the steering pin should fail first.

**Seat tube**

The seat tube experiences stresses of approx. twice the fatigue strength: 46.62 MPa. This is approx. the yield strength of the material. Therefore it is concluded that the seat tube lacks strength and this is where the Flax textile comes in. The yield strength of Flax is between 150 and 300 MPa, which should be enough to cope with the load. The flax should be laminated on top of the outer fibres in the surface which take the peak load. The flax textile is then able to absorb the peak load and distribute this load over the entire length of the part.

### Stiffness

The MatrixFrame software can also predict the deformations as a result of the loads. Two types of deformations were examined: the bracket stiffness and fork stiffness.

The bracket stiffness is measured by the deflection of the bracket in mm. Regular high end frames have a bracket deflection of approx. 4 mm. Therefore the deflections of the bracket in all load cases should remain beneath this 4 mm measure.

The occurring deflection of the bracket as predicted by the software all remain beneath 4 mm. Thus the chosen cross-sections and the frame lay-out provide adequate stiffness properties of the frame.

The fork stiffness is measured by the deflection of the fork and frame which increases the distance between the two wheel axles by approx. 3 mm.

Maximum deflection of the front wheel axle as predicted by the software is 3.89 mm. This is above the allowed deflection and therefore it should be concluded that the fork stiffness is too low. But because the model doesn’t incorporate the head tube it is estimated that this should be less in real-life and the application of flax textile could be incorporated if stiffness proves to be too low.
With the aid of the Ergonomics Analysis and Strength and Stiffness Analysis the Programme of Demands and Wishes can be completed. This is essentially the summary of all Analyses performed which connect directly to the design of a Frisian bicycle.

**Demands**

1. 70 weight % of the Rebicycle has to be made of local naturally renewable materials (Assignment, Parts Analysis, Materials Analysis, Life Cycle Analysis)

2. The material choice is limited to Wood, PUR, Epoxy, Flax and Steel (Functionality Analysis)
   - To minimize investment costs, machinery cost and ecocosts, labour and knowledge investment the number of materials has to be kept minimal.

3. The specific local naturally renewable material properties have to be utilized (Materials Analysis, Functionality Analysis)
   - Because of its high fatigue strength, bending is the best way to load wooden parts
   - Because wood is a natural material, it needs to be laminated to get an homogeneous material
   - PUR is versatile so it should be used for the tyres, drive chain, saddle, handles and brake cable tubes
   - Flax should be used in textile because its high tension strength and low strain can distribute loads evenly
   - Epoxy is besides high strength also weather resistant
   - Steel is strong, highly wear resistant and hard, therefore it should be used for the bearings and the brake cables as well as reinforcements around the brakes and joints if needed
   - Biowaste should be incinerated for energy

4. Sufficient Strength and Stiffness (Parts Analysis, Materials Analysis)
   - Double triangle structure for the frame
   - Frame cross sections have to be minimally 50 mm in height and width and a wall thickness of at least 5 mm.
   - Double frame cross-sections like the fork can be made with half the width, because the material is even more effective
   - Support a static weight of 105 kg, with a “bump factor” of $1.6 = 168 \text{ kg}/1680 \text{ N}$.
   - The frame has to have a torsion stiffness of at least 50 Nm/°
   - The fork has to have a stiffness of 40 Nm/° = a maximum elongation of 3 mm. measured from the rear axle to the front axle
   - The bracket stiffness has to be at least 30 Nm/° = a maximum deflection of 4 mm. is allowed (this can only be tested on the prototype)

5. The natural materials have to be treated to ensure a durability of at least 5 years (Materials Analysis & Market Analysis)
   - Water resistant & UV resistant -> treatment for wood = Accoya
   - PUR foam tyres
   - Steel bearings
   - Superficial damage resistant -> Epoxy/Varnish layer
   - Rim sides need to be coated with Epoxy/sand adhesive to become abrasive.

6. The product has to be suitable for rural as well as...
urban areas, thus a distance of approx. 0-20 km (Target group Analysis).
- Current bicycle lay-out must be used to provide overview in city traffic for safety and a comfortable rider position for use on longer distances, which is in between the city and touring rider position.
- The rider position has to be between city and touring, resulting in a 70° angle for the seat tube and head tube, crankshaft height of 255 mm, crank length of 170 mm and 28 inch wheels for proven performance on Dutch terrain.
- The weight should be between 10 - 20 kg.

7. Customizable to individual size (Ergonomics Analysis, Parts Analysis)
- Saddle – ground distance has to be customizable between 735 and 970 mm.
- Handlebar – ground distance has to be customizable between 735 and 970 mm.
- Seat stay – head tube distance has to be approx. 540 mm.
- Seat stay – handlebar distance has to be larger than 600 mm.
- Crank axle height is standard 250 mm. To incorporate tyre deformation a design height of 255 mm is used.
- Crank length is standard 170 mm.
- Tread has to be between 120 and 140 mm.
- Handlebar width has to be larger than 674 mm.
- Saddle set-back should be adjustable in a range of approx. 100 mm.

8. The design has to stand out from other human powered transportation products (Assignment)
- The natural materials should be visible in combination with the high tech materials.
- It should have a distinguishable look from the current city bicycle design.
- The Rebicycle should be recognizable as a bicycle.

Wishes

1. Prepare the design for the goal of 100% local naturally renewable materials achieving full independence from external resources and fossil fuels (Assignment)
- Incorporate only those non-local naturally renewable materials that have high probability on production from local naturally renewable materials.

2. Design for bio energy generation (Life Cycle Analysis)
- The design should be based on using local naturally renewable material wastes as the main energy source.

3. Minimize waste (Life Cycle Analysis)
- Since the Life Cycle Analysis points in the direction of superfluous waste from (mainly wood) processes, the accent should be on avoiding process steps and wasting processes like milling.

4. Fit Frisian life style (Target group Analysis)
The design has to fit Frisian semantics:
- The design has to look robust, which might be achieved with overdimensioning some parts.
- The design has to be elegant using curves and simplicity.

5. Minimize the use of non local naturally renewable materials (Life Cycle Analysis)
(The use of PUR, Epoxy and steel has to be minimal).
Sustainability Demands

1. 70 weight % of the Rebicycle has to be made of local naturally renewable materials (Assignment, Parts Analysis, Materials Analysis, Life Cycle Analysis)

6. The product has to be suitable for rural as well as urban areas, thus a distance of approx. 0-20 km (Target group Analysis)

Product design Demands

2. The material choice is limited to Wood, PUR, Epoxy, Flax and Steel (Functionality Analysis)

3. The specific local naturally renewable material properties have to be utilized (Materials Analysis, Functionality Analysis)

4. Sufficient Strength and Stiffness (Parts Analysis, Materials Analysis)

5. The natural materials have to be treated to ensure a durability of at least 5 years (Materials Analysis & Market Analysis)

7. Customizable to individual size of P90 percentile of the Dutch population (Ergonomics Analysis, Parts Analysis)

8. The design has to stand out from other human powered transportation products (Assignment)

In order to proceed with detailing the concept direction efficiently, the demands and wishes have been divided into general sustainability demands and wishes and specific product demands and wishes. The specific product demands and wishes will be used to detail the most important parts of the concept. The concept detailing process will be executed on the basis of the product design demands and wishes. The sustainability demands and wishes either should have been met by design decisions in the earlier stages of the project or will be reached through the combination of product design demands and wishes.

Sustainability Wishes

1. Prepare the design for the goal of 100% local naturally renewable materials achieving full independence from external resources and fossil fuels (Assignment)

2. Design for bio energy generation (Life Cycle Analysis)

3. Minimize waste (Life Cycle Analysis)

Product design Wishes

4. Fit Frisian life style (Target group Analysis)

5. Minimize the use of non local naturally renewable materials (Life Cycle Analysis)
In this phase of the project I combine all previously selected design solutions with the programme of demands to make sure the design proposal will be compliant with the programme of demands.

Method

The concept detailing is again divided into the previously defined design sub-problem areas:

Construction, Actuating, Wheels, Brakes, Suspension and Bearings

Brakes, Bearings, and other parts that will be bought from external parties and are described separately.

Though each design sub-problem area is discussed separately, again the process has been highly iterative. Not all iterations are shown in this report, since most iterations were quite complex and executed in my head.

Because there are many interdependent dimensions it is chosen to design the concept in detail with Solidworks. The design of the frame and fork comes first because these parts are considered most defining for the complete design.

Construction

The first problem area discussed is the construction. The frame and fork are the primary parts of the construction. I investigated four ways for constructing a double triangle frame out of wood and Epoxy.

Product Demands

- The material choice is limited to Wood, PUR, Epoxy, Flax and Steel
- I only need these two materials to produce the frame, Epoxy and Steel, except for small steel inserts as later would become apparent.
- The specific local naturally renewable material properties have to be utilized
- Utilizing material properties of wood leads to a bending load on the frame. Wood has excellent bending properties and a nearly unlimited fatigue strength (think of a skate/snowboard). Thus the frame has to contain curves to generate bending loads instead of pure compression or tension. Epoxy is used for its high strength and durability properties.
- Sufficient Strength and Stiffness
- From the Strength and Stiffness Analysis roughly the dimensions for the cross-sections of the frame and fork are known. To approach consistent strength and stiffness in the frame the parts of the frame will have to be laminated. A thinwalled circular cross-section is ideal for strength, stiffness to weight ratios. However the frame has to be loaded in bending, and a circular cross section for curved parts would require double bending of wood, which is only possible for extremely thin wooden sheets. These thin sheets would however lead to an enormous waste and cost generation, thus this option is discarded. (Fig. 73)
The Rebicycle Project

The Fork is one of the most severe and dynamic loading of all parts of the Rebicycle. From the Strength and Stiffness Analysis I know that a steering pin diameter of 30 mm should be enough, though the fork was not calculated for torsion. For the fork itself the same thickness is applied as for the seat and chain stay. To achieve optimum Strength, the fork is chosen to be produced out of ten single sheet layers, whereafter the steering pin is milled out of the protruding layers. (Fig. 83)

The shape of the lower frame part is derived from the crankshaft housing. This part needs to be above the lower frame part, to optimize force absorption and optimal frame stiffness. (Fig. 82)

Construction

It became quite apparent that the best solution would be to horizontally laminate the frame with a hollow rectangular cross-section. This is the next best thing to a circular cross-section, can be constructed hollow, leaves little waste and minimizes parts, while the frame is loaded in bending. (Fig. 81)

The natural materials have to be treated to ensure a durability of at least 5 years.
- For the wood an Accoya treatment is needed. This uses anhydride to acetylate the wood, resulting in 80% less water absorption, making the wood more durable than hardwood, without loss of strength. A Varnish coating should also be applied.
- Customizable to individual size of P90 percentile of the Dutch population
- The dimensions from the ergonomical analysis give the correct dimensions for the design. Integrating them with the strength & stiffness analysis dimensions

Fig. 78: 1st 3D Iteration
Fig. 79: 2nd 3D Iteration
Fig. 80: 3rd 3D Iteration
Fig. 81: Proposed Frame Lay-up
Fig. 82: Desired Lower Frame Part Position
Fig. 83: Fork Assembly
Results

[Image - 829x12 to 872x626]

has been a highly iterative and complex process. The iteration can be summarized as follows: Maintaining strength and stiffness and ergonomics requirements with wood and Epoxy. Later iterations would evolve from integrating other parts and subsystems, like the wheels and drive system.

- The design has to stand out from other human powered transportation products
- By using wood for a frame in this shape would definitely make the design stand out from regular human powered transportation systems. It’s definitely recognizable as a bicycle, and also clearly different.

Product Wishes

- Fit Frisian life style
- Through the thick frame with rectangular cross-section and curved lines I feel I have achieved a robust though elegant appearance.
- Minimize the use of non local naturally renewable materials
- Very few industrial material is used. Only Steel wheel tensioners and Epoxy adhesive.

The result (Fig. 84) is expected to be compliant with all demands, except for the 28 inch wheels. It proved to be impossible to design a bicycle made from wood with 28 inch wheels for P90 of the Dutch population. Therefore the tyre size is chosen to be 26 inch. It is not considered a noticeable disadvantage, though rough terrain will be slightly more difficult.
In this section I will discuss the design of the drive system, and its placement within the frame combined with the rear wheel.

**The Actuating System**

**Product Demands**

- The material choice is limited to Wood, PUR, Epoxy, Flax and Steel
- The gear wheels and flanks are to be made from Oak wood gear wheels flanked with Norway Spruce to guide the drive belt. The fibre orientation is turned 90° during lamination, to provide unidirectional strenght and stiffness.
- The specific local naturally renewable material properties have to be utilized.
  - The hardness of Oak wood is needed for the gear wheels and teeth. Its high strength and stiffness are needed for the crank and pedal axles. *(Fig. 85,86)*
- Sufficient Strength and Stiffness
  - The gear wheels haven’t been calculated for strength and stiffness. I wanted to try to produce them from Oak wood because its a lot stiffer, harder and wear resistant than Norway Spruce. If it turns out that the gear wheels are too weak, they can easily be redesigned in the continuation of the project. They could be redesigned for a broader drive belt, or a simple steel cast toothed ring could be integrated.
  - The natural materials have to be treated to ensure a durability of at least 5 years
  - The design has to stand out from other human powered transportation products

Besides the Accoya treatment a layer of Epoxy is required to improve wear resistance of the gear wheels.

- Customizable to individual size of P90 percentile of the Dutch population

There is very little room for the drive system combined with the cranks. Because the aim for the tread has been set to 130 mm, the thickness of the frame which is 50 mm, the spacing of the gear wheel and the rest of the frame and the fact that the drive belt has to be aligned exactly straight because otherwise the stress on the gear wheel flanks would be too great.

This leads to a crank thickness of 15 mm, which is certainly too small if made in Norway Spruce. Therefore I apply Oak wood cranks, and also Oak wood pedal axles. These too need to have a small dimension, 20 mm in diameter, because of the pedal bearings *(Fig. 85,86)*. If these are too large, the pedals would look awkward and turn the design into a toy. Whether this crank and pedal construction is strong and stiff enough remains to be seen in the prototype.

The cranks have a standard length of 170 mm. The front and rear gear wheels are set to an approximate diameter of 200 and 70 mm respectively. In combination with the drive belt the drive ratio is: 62 teeth/22 teeth = 2.81. This is slightly larger than for a regular city bicycle, because the design is meant for distances up to 20 km.

- Fit Frisian life style
- Minimize the use of non local naturally renewable materials

The big pedals combined with the large bearings give the design a robust feel, though the sleek cranks keep the construction slim supposedly giving it an elegant appearance.

**Product Wishes**

- The design has to stand out from other human powered transportation products

By using wood combined with a drive belt the design will certainly stand out from other similar products. But the setup is very familiar, leaving no uncertainties about its use.
Drive System Results

The drive system (Fig. 88) is likely to be functional, only its strength and stiffness is questionable which will be tested on the prototype. This was due to the fact that the tread of the drive system should not be larger than 130 mm requiring a very slim construction. After testing the prototype a redesign might be necessary, perhaps resorting to industrial materials like steel, if it at all appears to be impossible. Surprisingly the drive belt length was calculated in Solidworks to be approx. 1560,63 mm, which is close enough for the standard T10 linear drive belt with 1560 mm in length. The accuracy needed for the drive system has urged me to consider some kind of tensioning system, which is very difficult when making it with natural materials. Together with my mentor Stefan we came up with an eccentric wheel positioning system. (Fig. 89) It’s basically an eccentric steel ring inserted in the axle hole, giving the structure more strength around the removed fibres, and allowing a 2 mm adjustment of the rear axle to crank axle distance. These parts also make it possible to align the wheel in the frame, and therefore it is also applied to the fork.
The wheels are considered the most dynamically loaded parts of the design. It was however not feasible in this project to analyze all parts with the Matrixfram software, because it cannot analyze curves.

The limits to the design of the wheels are the shape and size of the tyres, the size of the bearings and the required strength.

Because the dimensions of the cross section have to be considerable to provide enough strength and stiffness, it is not considered possible to bend the rim out of one beam. This part is therefore also laminated around a mould. Afterwards a groove could be milled in the rim which is used for keeping the tyre on the rim.

I had a meeting and discussion with the founder/owner of Flevobike, Johan Vrielink, who had conducted a user research on the appearance of bicycle wheels. The outcome was that if I’m not using regular steel spokes, the next best thing is an uneven number of spokes above four is perceived as beautiful.

But because of the presumably needed thickness of these spokes, the number of spokes should be minimized in order not to lose strength in the hub or the necessity to oversize the hub (Fig. 91). Therefore the number of spokes was chosen to be 5.

There was no real need for sketching the wheels because of the preceeding insights, therefore the design was immediately modelled in Solidworks.

I ordered the Greentyres because for the rim the fitting of the tyre is considered essential for safety and comfort. To achieve a perfect fit I had to know exactly what size the 26 inch greentyre commuter would be. Because the tyres are designed to stretch approx. 120 (!) mm, the design of the rim is initially made out of three inner rim layers, after which the tyre is forcefully stretched and placed on the rim. Thereafter the two layers of tyre walls are joined with Epoxy, keeping the tyre on the rim. (Fig. 92) If the tyre walls would be placed before the tyre, the forces needed to place the tyre are likely to destroy the wooden tyre walls. (Fig. 90)
Results

Fig. 92: Wheel Assembly
In this section I will discuss the design of the drive system, and its placement within the frame combined with the rear wheel.

The Actuating System

Product Demands
- The material choice is limited to Wood, PUR, Epoxy, Flax and Steel
- The two materials needed for the suspension parts are wood and Epoxy
- The specific local naturally renewable material properties have to be utilized

This part is the best example of utilizing material properties. The high bending and fatigue strength combined with the lower stiffness than Steel should yield a part with suspension. (Fig. 93)
- Sufficient Strength and Stiffness

From the Strength and Stiffness Analysis I know that if loaded with 168 kg, the stress in the material would exceed its yield strength. Therefore flax textile-Epoxy laminate should be applied to the front of the seat stay because the stress is highest in the outer fibres.
- The natural materials have to be treated to ensure a durability of at least 5 years

Besides the Accoya treatment a layer of Varnish is required for superficial damage resistance.
- Customizable to individual size of P90 percentile of the Dutch population

Because the height of the saddle has to be adjustable over quite a range: 735 - 970 mm, the lower part has to be straight. The straight part can be cut off at the right height for the specific user before being joined permanently to the rest of the frame. In the frame two slots have been integrated for fitting the seat stay. The adjustability requirements leave very little room for the double curve, which is desirable for optimum comfort (Fig. 94). As a result one of the curves has a very small radius, which is questionable in the field of production. If it turns out to be impossible, a simple redesign can be made during the prototyping phase.
- The design has to stand out from other human powered transportation products

By using wood material for suspension this design stands out from current designs. Also its simplicity should be enough for consumers to question its functionality, which also makes it stand out though combined with the frame and saddle the purpose and use are completely recognizable.

Product Wishes
- Fit Frisian lifestyle

This part can hardly be described as robust, since that’s exactly the point. This part is supposed to flex, and thereby looks perhaps a little feasible. In combination with the frame and saddle the overall impression is still considered to be robust.
- Minimize the use of non local naturally renewable materials

The custom made rider height originates from excluding industrial materials for this part. The industrial materials would be necessary for making the part adjustable by the user. The exclusion of industrial materials has been preferred over adjustability, whereas a custom made product is generally perceived as high value.
The result (Fig. 95) is the design portrayed. If the assumptions of comfort and manufacturability have been correct, the part should be compliant with the Programme of Demands and Wishes. Many parts for the regular city bicycle have been simplified into one part whilst maintaining core functionalities.
The Rebicycle Project

Suspension

Since most of the design has been entered into Solidworks, it is possible to try different shapes of the handlebars on the design. First I tried a conventional Dutch city bicycle handlebar shape. This shape comes directly from reaching out to the upright user whilst still leaving enough room for leg movement. (Fig. 101) Seeing this design with the entire product however I concluded that I don’t like this shape in the entire design, even though on its own it has a elegant and robust appearance. Also it is quite difficult to produce this shape efficiently. Thus I tried a more straightforward shape which is much easier to produce. (Fig. 102) This shape is however too far away from the rest of the design. It does have a robust feel to it, but it certainly isn’t elegant. The straight design doesn’t fit the curved frame. (Fig. 103) Thereafter I combined the two previous designs. This shape is however too far away from the rest of the design. It does have a robust feel to it, but it certainly isn’t elegant. The straight design doesn’t fit the curved frame. By now I came to the conclusion that it is better to use a bent wooden rod as handlebars. This is a proven way of producing wooden handlebars, and the shape as proposed fits the overall design of the Rebicycle. Because of the proposed diameter of 30 mm, the design has a robust look and the curves render it elegant. The width is set to a minimum of 700 mm, to provide for P90 of the Dutch population. (Fig. 104)

The negative aspect of this handlebar design is the extra part needed to space the handlebars away from the knees of the user. However, this extra part does allow a better customization, because this way the angle of the handles can be adjusted prior to assembly as well.

Handlebars

Product Demands
- The material choice is limited to Wood, PUR, Epoxy, Flax and Steel
- The two materials needed for the handlebars are Wood and Epoxy only.
- The specific local naturally renewable material properties have to be utilized

This part is pretty much a test whether it is possible to bend a wooden rod in such a curve. If it is possible it is expected that the natural bending of the wood could actually be more comfortable than regular handlebars. Bendywood is not an option because its flexibility is expected to be too high.

- Sufficient Strength and Stiffness
I performed a Strength and Stiffness Analysis in Cosmosworks software (Fig. 100). The simulated load is 50 kg on each handle. Based on these results I concluded that it was worth the try.
- The natural materials have to be treated to ensure a durability of at least 5 years
Besides the Accoya treatment a layer of Varnish is required for superficial damage resistance.
- Customizable to individual size of P90 percentile of the Dutch population
Because the height of the saddle has to be adjustable over quite a range: 735 - 970 mm, this also is true for the handlebars as described in the Ergonomics Analysis. The handles are at least 700 mm apart, also in compliance with the Ergonomics Analysis. The extra part should also be able to provide more customization possibilities because the handlebars can be glued under a specifically requested angle.
- The design has to stand out from other human powered transportation products
By using wood material for suspension this design stands out from current designs. Also its simplicity
should be standing out whilst the shape is completely recognizable.

**Product Wishes**

- *Fit Frisian life style*

  This part can hardly be described as robust, since that’s exactly the point. This part is supposed to flex but only just a little is required, because control must be maintained and its loading is much less than the seat tube.

- *Minimize the use of non local naturally renewable materials*

  The custom made rider height originates from excluding industrial materials for this part. The industrial materials would be necessary for making the part adjustable by the user. The exclusion of industrial materials has been preferred over adjustability, whereas a custom made product is generally perceived as high value.
This is one of the most important parts of the Rebicycle in terms of comfort. The development of bicycle saddles has taken over a hundred years, therefore I will not try to design my own ergonomically shaped saddle in this project. However, the saddle has to be made out of wood and polyurethane padding (which is common padding in current bicycle seat designs) therefore the type of saddle has to be chosen as well as the exact dimensions. Saddle suspension is covered by the flex in the seat tube, however the load on the contact surface between user and saddle has to distributed to achieve a higher comfort level, therefore the padding remains necessary. There are many different types of saddles:

1. Race
   - Ideal user: You ride for fitness and training wearing cycling clothing and maintaining a high pedal rpm and fairly rapid pace. You like to go long, ride centuries and sometimes ride aggressively on and/or off road. You sit in a racey position with your handlebars lower than your seat.
   - Features: Lightweight (sometimes have titanium or hollow seat rails); minimal padding; narrow shape; pretty stiff top.

2. Mountain bike
   - Ideal user: You ride a lot off road on challenging terrain where your body and bike take a beating. You move around on the seat a lot to apply body English on technical sections, for example sliding way off the back of the seat to safely descend a steep slope or perching on the saddle nose to keep the front wheel down on a cliff-like climb.
   - Features: Fairly narrow shape; medium padding to soften blows; lightweight; shaped rear section to ease moving backward; downward sloped nose for moving forward further; sometimes reinforced on the areas that touch down when you crash. A few models designed for aggressive off-road riding, feature extra length for even more fore/aft body position adjustments when jamming.

3. Gel
   - Ideal user: Fairly narrow shape; medium padding to soften blows; lightweight; shaped rear section to ease moving backward; downward sloped nose for moving forward further; sometimes reinforced on the areas that touch down when you crash. A few models designed for aggressive off-road riding, feature extra length for even more fore/aft body position adjustments when jamming.
   - Features: Great cushion through the use of gel, a shock absorbing material that also molds to your shape for a custom fit; medium weight (not light); often slightly wider throughout; flexible top; may feature bumps to support the sit bones; can have high-tech look.

4. Suspension
   - Ideal user: You ride long and hard on and off road and you like the fit and feel of a narrow, lightweight racing seat but you’d like a little more give in the seat. You don’t want to go to more padding or gel because of the additional weight and because you prefer the racey looks of the lightweight seats.
   - Features: Suspension is built into the underside of the seat in various ways, often by adding elastomers (rubber bumpers) between the seat rails and the seat. Otherwise, the seat resembles a standard narrow racing seat with a sleek long top; light weight; high-tech look.

5. Cutaway
   - Ideal user: You’ve tried lots of seats and you can’t find anything that eliminates pain, tingling, numbness and irritation. Especially bothersome is the saddle nose that digs into your groin and genitals causing pain and suffering even on short rides.
   - Features: Material is removed from the saddle top to eliminate pressure points; some have actual cutouts (holes) in the top; various models (i.e.: performance; mt. bike; gel; etc.); high-tech look.

6. Wide/Cushion
   - Ideal user: You ride in an upright position on a bike where the handlebars are as high or higher than the seat, which puts a lot of your weight on the seat. You don’t pedal very fast or ride very aggressively. You don’t wear cycling clothing.

7. Leather
   - Ideal user: You’re a traditionalist who likes natural bike products and wants a classy looking bicycle. You ride long distances at a good pace and you want a seat that will break-in to fit your body over the miles. You don’t mind taking extra steps to maintain your products but you like them to last a long, long time.
   - Features: Beautiful; absorbs body heat keeping you cooler; medium weight; breaks-in to your anatomy over time; susceptible to water damage (carry a plastic cover...
and use it whenever it rains); can be expensive; not widely available; may require break-in before it becomes comfortable.

8. Alternative

Ideal user: You’ve had prostate surgery or have injuries to the groin area that make it very painful to sit on regular bicycle seats and you’ve tried them all. You ride in an upright position with handlebars higher than the seat and you don’t pedal fast or ride aggressively. You just want to ride again for fun and exercise and are willing to experiment to find a seat, any seat that won’t hurt you. Features: Wildest designs of any seat category; often adjustable or articulated (parts of the seat move with the body); ample padding (some are inflatable); can be expensive though not all are; heavy; don’t always attach easily to the bike.

The decisive factor for choosing the saddle type is the rider position, because the amount of weight carried by the saddle varies with the rider position. In an upright position most of the rider’s weight is carried by the saddle in contrast with a race position where the weight is distributed more towards the handlebars.

This is the main reason why the choice for the type of saddle lies with the wide/cushion type, perhaps combined with the all leather type because of the type of user, however the entire product already is made from natural materials, therefore it is not needed to reach out to this type of user. The drawbacks of using leather (maintenance/poor weather resistance and price) lead to the conclusion that the focus should be on the wide/cushion type of saddle cushioned with polyurethane pads for comfort as found in [Appendix B, Parts Analysis]. It is on the other hand well known that leather saddles, after a breaking-in period, are by far the most comfortable saddles, because they take on the shape of the user over time (break-in). The leather is tensioned from the nose of the saddle towards a bridge located behind the sit-bones. This construction is difficult for production from natural materials, but the idea of the self customization fits very well to the overall product idea.

Another factor is decisive for the choice between these two types of saddles. The Rebicycle is designed to fit the P5 smallest and P95 largest people of the Dutch population. For the P5 smallest people the lowest height of the saddle is approx. 740 mm. The design of the seat tube and frame therefore allows a low height of the saddle itself. The construction for a leather saddle is higher than for a cushion type saddle, which for now points into the direction of the latter type of saddle. This construction is estimated to be higher because of the gap needed below the loaded leather part of the saddle whilst the saddle should be movable forth and back to vary the saddle set back, which is a crucial adjustment for precise rider comfort.

Therefore the decision is to design a wide/cushion saddle type with a cover of polyurethane foam padding and polyurethane cover.

Now partially the shape of the saddle is determined, but there is a trend of shapes that leaves the middle of the saddle open to relieve the rider’s sensitive parts.

First the rider position on the Rebicycle is so that these parts aren’t dominantly loaded, but an argument for such saddles would be fertility complaints obtained (hearsay) from conventional saddles.

The solution for this problem supposedly is the gap in the middle of the saddle, however research performed on these saddles prove (for women) that these areas are loaded more than with a regular saddle. Therefore this method is considered a myth, although for some cyclists it might be a good solution due to their specific shape and size.
The type of saddle to be designed for the Rebicycle is the wide/cushion type because of rider position. No center hole will be designed since the presumed positive affects appear to be negative overall (Fig. 105). If the prototype proves the saddle to be uncomfortable, a redesign with a leather saddle construction is the next step. For now its problems: non-weather resistance, high cost and increased saddle frame height leave the choice with the wide/cushion type saddle.

The final step is the determination of the dimensions of the saddle.
It is hard to find the exact dimensions of bicycle saddles, since there are so many different kinds and models. The general shape has been determined, but its exact dimensions are difficult to establish. Therefore the method chosen to design the saddle is to copy an existing wide/cushion saddle roughly and execute the design in foam to test and adjust the exact shape with trial and error.
A photo of the chosen shape saddle is placed in Solidworks to copy the rough dimensions which is then executed in foam, reshaping it until the desired comfort is reached. The base is made with 5 mm wood layered at 90° in each layer to achieve unidirectional strength and stiffness. The relatively thick base is needed for adhesing the saddle to the seat stay, for which a groove is needed at the underside of the saddle base. This resulted in the design of the saddle shown in (Fig. 106).
In this section I will briefly discuss the choice for the braking system. From the idea phase two types of brakes were concluded to have potential for the Rebicycle. There are essentially only two reasons for choosing an existing calliper braking system.

The first and most important reason is the Strength and Stiffness of the braking system combined with the wooden frame to which the system must be attached (Fig. 107). If cantilever brakes are used, the forces on the rim caused by braking actions will be transferred directly into the frame, causing the frame to bend outwards. In a Steel frame this is not a problem, but a wooden frame is considered too flexible to cope with the braking forces which are very high (Fig. 110).

Calliper brakes (Fig. 109) have one pivot point around which the braking arms revolve and exert pressure on the rim. This way the braking forces are almost entirely absorbed by the braking system itself instead of the frame.

Another less measurable reason for choosing steel calliper brakes is the consumer. If a wooden bike is brought to this market, consumers are likely to have doubts especially towards safety (Fig. 108). Therefore it is expected to have a positive impact on consumer safety experience, if the braking system is made of steel instead of wood, which would be the likely local naturally renewable material for constructing most of the brakes.

Most currently available calliper brakes are made for racing rims, which are very narrow. Therefore I went to look for used calliper brakes from older city bicycles, and a friend who works in bicycle repair shop found a pair for me. Of course it is possible to order a new braking system, but that is for now unnecessary.
In this project I concluded that for now it is not feasible to produce bearings with local naturally renewable resources (Fig. 112). Steel is extremely suitable in this application and the amount of steel needed for the bearings comes to 1.25 kg, which is only a small part of the expected total weight. This compromise is considered necessary for efficiency and comfort, which have to be in the same level as the regular city bicycle.

According to the axle diameters the bearings were selected. The wheel axles and steering pin have a diameter of 30 mm, derived from the Strength and Stiffness Analysis. The pedal axles are 20 mm in diameter. For all these parts thinwalled roller ball bearings were selected, because otherwise the parts embodying the bearings would become too large.

For the head tube bearings tapered bearings were selected, because of the high bending moments which were observed inside the head tube in the Strength and Stiffness Analysis.

These bearings were selected from SKF (Fig. 111,113):

- Bearing: 61806
  4 x Roller ball bearing 30 x 42 x 7
- 61804
  4 x Roller ball bearing 20 x 32 x 7
- 61908
  2 x Roller ball bearing 40 x 62 x 12
- 32006 X/Q
  2 x Tapered bearing 30 x 55 x 17

In the prototype open bearings are used, but in the final design closed bearings were chosen. These are necessary for weather and wear resistance, especially if the bearings are to be recycled directly.
From the design of the frame and drive system the required length of the drive belt is known, approx. 1560.63 mm. (Fig. 115) This is surprisingly close to the standard drive belt length of 1560 mm. The type of drive belt hasn’t been carefully examined because there are many drive belt bicycle on the market. The drive belt has been in development for quite some time, resulting in rounded teeth on the drive belt to decrease wear. However, in this project I chose to use a standard T10 linear drive belt, because this type has more rectangular teeth which can be milled more easily. Though not optimal, this drive belt is sure to do the job and is likely to reveal wear problems if these occur on the gear wheels.

The technical description of the T10 drive belt is shown below (Fig. 114). The drive belt should at least be capable of withstanding forces up to 3000 N and more.
All preceding design solutions lead to the design proposal (Fig. 116). This is the final test before proceeding to the prototype. In Solidworks all parts are assembled to create the design proposal where all dimensions are checked before printing the 2D production drawings. This also allowed me to make a final judgement on the aesthetics, where I believe that the design looks robust, because of the slightly thicker frame construction compared to a regular bicycle, and elegant through its dynamic curves, which only look dull if seen exactly from the side, which occurs very rarely. The demands then have been met in theory and need to be tested in the prototype.
Now that the design is proposed, the most important part of the design process has begun. Building a functional prototype serves several purposes. First of all, can the design be made the way it was designed? In every design project there will be matters that weren’t thought of, wrongly assumed, or even impossible. The most effective way of finding out is building a prototype. Secondly, is it a successful design? A prototype is the best way to find out whether consumers like or dislike anything about the design. Thirdly, and most importantly, is it feasible? The calculations and assumptions that were made during the design process should provide indications whether it is feasible to produce a high quality bicycle with local naturally renewable materials.

The prototype building is considered a complex process, because of the limited time available. To make sure that the prototype is finished in time, a prototype building plan is made using Microsoft Office Project 2007 (Fig. 117). This programme allowed me to meticulously plan the course of action for each individual part. The prototype building plan can found in the digital appendix.
Prototype Building Process

Fig. 118: 5 mm Boards waiting for Steam

Fig. 119: Bending after Steaming

Fig. 120: Crank Assembly

Fig. 121: Milling the Hubs

Fig. 122: Crankshaft Housing

Fig. 123: Saddle, Fork Lay-up and Crankshaft Housing

Fig. 124: Blueprinting Woodboards

Fig. 125: Finished Top Tube

Fig. 126: Bent Rim Layers
Prototype Building Process

Fig. 127: Laminating the Fork
Fig. 128: Bending the Down Tube
Fig. 129: Partial Assembly of the Wheel

Fig. 130: Milling the Saddle Slot
Fig. 131: Rear Wheel Assembly
Fig. 132: Lathing the Steering Pin

Fig. 133: Inserting the Tyre Walls
Fig. 134: Lasercutting the Gear Wheels
Fig. 135: Two Wheels
Prototype Building Process

Fig. 136: Laminated Down Tube
Fig. 137: Drive System
Fig. 138: Checking Important Dimensions
Fig. 139: Handlebars cutouts in the Steam Box
Fig. 140: Laminating the handlebars
Fig. 141: Tapered Bearing
Fig. 142: Assembled Frame
Fig. 143: Almost There!
Fig. 144: Finished Prototype
During every prototype build the designer comes across unforeseen problems and false design assumptions. During the prototype building process I encountered four major issues which had to be overcome by improvisation. The lower frame part, fork, handlebars and seat tube.

**The lower frame part** is bent along the underside of the crankshaft housing to better absorb the forces into the frame. This curve was designed to be manufactured from 5 mm. thick boards of wood. However when the first frame layer was attempted to be bent on the mould it became clear that this was impossible without breaking the material. This problem was solved by using 2.5 mm. thick boards which I tried in a little experiment and seemed to work. However another problem arose, which was the mould itself. It was placed underneath the frame part, because I thought I could use the crankshaft housing to press the wooden boards into place. This was a wrong assumption but it was too late to re-make the mould and therefore the wooden board layers are slightly flawed, but structurally sound.

**The fork** is made from ten sheets of 5 mm Norway Spruce, which in itself proved no problem, though the largest lathe in the faculty workshop was barely large enough. After being placed in the frame it became painfully clear that there was one fatal flaw in the design: the fibre direction in the fork causes the wood to split at the arch in the top of the fork. A temporary solution is improvised, which is nothing more than an extra arch glued to the inside of the arch of the fork.

**The handlebars** turned out to be quite impossible as it was designed. The 30 mm radius was far too large to bend a wood species like Norway Spruce into the curves designed for the handlebars. Therefore I went to a wood bending specialist, Van Rijsoort. This design was based on real-life examples of wooden handlebars, but the flaw was in the lack of straight sections of at least approx. 100 mm to be able for a rod bending machine to apply the bends. And this only works for Bendwood, a bendable wood product available on the market. This material is compressed wood, allowing a larger flexibility. However, this material is unsuitable for the use in handlebars, because it tends to bend in use. Therefore, ultimately, I came back to the “old” method of laminating 5 mm. boards on a mould, and used the mold I had already made for the rod design of the handlebars. The result came out pretty much in the shape I designed it, only with a rectangular cross section and a little more exotic curves than expected which give it an streamlined appearance, which is a surprising result.

**The seat tube** design also contains too small a curve for the wood layers to be bent in. The design of the seat tube is considered impossible based on the experiences of the lower frame part. This curve needed to be this small because the saddle height has to be adjustable over a wide range. The beginning of the curve determines the range, and it was immediately concluded that a redesign was needed. This was quickly made, but with a P90 target group, still the curve had to be quite small, because otherwise the saddle would be positioned too far to the rear which could lead to an unsatisfactory rider position, thus comfort and efficiency. This curve was on the edge but proved to be possible.
The Handlebars: 5 mm laminate is used instead of a round 30 mm rod.

The Seat Tube: A single bend is applied instead of a double bend.

The lower frame part: 2,5 mm thick boards are used instead of 5 mm.

The Fork: A temporary reinforcement is glued inside the arch.
During the prototype building phase and use testing a number of problems arose which need attention in the continuation of the project. Because for now this is the only prototype, no intensive user tests were performed. The use test (Fig. 148) consisted of sitting on the Rebicycle and testing its structural capabilities. After its press introduction it’s riding capacities were also tested.

According to the use test and prototype building process a number of parts need to be redesigned in the continuation of the project. These are:

- The fork
- The lower frame part
- The cranks, pedal axles and their construction
- The wheels
- The seat tube
- The saddle
- The handlebar

The lower frame part, seat tube and handlebar are already discussed in the area of production. However the improvised solutions also resulted in some use problems. These are discussed below.

The fork is not designed correctly. The problem lies in the type of loading which occurs inside the material in this design. At the top of the arch of the fork, the upward forces tend to make the material split along the grain, in which direction the material is very weak. A quick fix was improvised by inserting a horizontal oriented piece of wood to stop the wood from splitting. This works for now because it seems to be holding my weight. This is an undesirable solution since the orientation of the material in this design is flawed. Therefore the fork needs to be redesigned.

The lower frame part, even though I succeeded in making the part, also needs to be redesigned. First of all because it is highly undesirable to deviate from the thickness of 5 mm. This is the only part made from thinner wood. Also probably if the mould would be the negative of the mould used during the build, the lower frame part would have come out ok, but this will take a lot of force. Thus the conclusion is that a redesign is necessary, removing the small curve at the bottom. It is however still preferred for the crankshaft housing to be on top of the lower frame part.

The cranks simply lacks strength and stiffness, in the material as well as the joints. When cycling at a steady speed the cranks are OK, but if a person would stand on one pedal with his full weight they would fail. Therefore a complete redesign is needed.

The wheels seem to flex a little too much in between the spokes. This results in a slightly bumpy ride, feeling the spokes every time they point downward. Therefore a redesign is needed and two approaches are suggested: The spokes are a little too small to fit within the rim and are glued in tension, just as a regular bicycle wheel. If the tension is correct, the bumpy feeling should disappear. Wood is an excellent material to use under tension because of its high fatigue strength.

The seat tube needs to be taken a look at, but the improvised redesign seem to do the job and fit with the overall appearance.

The saddle was designed straightforwardly from an existing saddle design. The foam used on top of the saddle is inadequate, which was to be expected because no attention was paid to this detail. This caused the saddle to be uncomfortable, but a simple gel cover completely seems to solve the problem. Still a closer look is required for the continuation of the project.

The handlebars were also changed during the prototype phase. The change allowed me to make the part, but its strength was lost. The cause for failure was the same as with the fork, the material is loaded in a direction which causes splitting. Therefore the handlebars need to be redesigned.

Conclusion

There are a lot of parts in need of careful consideration and redesign. Not perfect yet, but I have to say quite close, since it has been possible to ride the Rebicycle. If it turns out that all of the mentioned problems can be solved, the Rebicycle might be well underway in becoming a serious option for implementation. It is however far too early to make such a claim, and other problems might probably will arise.

But I consider this project worth while to be continued and to gain more insights in the method for 100% sustainable product design.
Fig. 148: User Testing: It Works!
Assignment

The Design of a human powered transportation product (complex consumer product), using local naturally renewable materials for production and integrating functionality, ergonomics, aesthetics, manufacturability and closing the cycle to study the feasibility of the LPD approach.

This assignment was formulated according to the idea of using local naturally renewable materials to achieve a maximum sustainability level, because there wood be renewed resources, no transport, no external energy source necessity and no industrial waste.

It was however not certain whether it was feasible at all to attempt the design of 100% sustainable product. Therefore the analysis phase is treated as a Feasibility Analysis.

In the Feasibility Analysis it is shown that technically and functionally it is possible in present time to produce a bicycle made from 5 different materials only: Approx. 70 weight% can be made from local naturally renewable materials, Wood and Flax.

For the bearings, brakes, tyres and drive belt industrial materials are needed, Polyurethane for the tyres and drive belt, Epoxy for all joints and laminates and Steel for the bearings and braking system.

The current design would yield a reduction in ecocosts of approx. 75 % compared to a bicycle made from non-local natural resources without energy recovery.

In the materials Analysis it is also shown that Polyurethane and Epoxy are candidate materials for future developments in biopolymers. Especially with the use of Vernonia Galamensis, an african plant, this would be quite possible. The greenhouse needed for this crop could be powered with abundant energy and heat from the biological waste incineration.

The biowastes, mainly wood, are biodegradable, but wood for example releases methane when rotting. This is the foundation for incinerating the biowaste, which leads to an energy production of approx. 2 - 4 times the energy needed for the entire production process. The incineration is justified by the fact that e.g. carbon emitted during incineration has been absorbed by the tries while growing, closing the circle.

On the basis of future developments is it concluded in the Life Cycle Analysis that the Rebicycle has the potential of an ecocost improvement of 90+ % compared to a regular imported industrial city bicycle.

Economically there are indications that this approach is suitable in the current economic paradigm of industrialization, globalization and capitalism. This is however highly hypothetical. In a distributed economies paradigm the Rebicycle definitely would be an example of how to operate in such a system. It is based locally and uses external resources only when necessary.

Socially the Rebicycle concept would lead to an intensified relation with its consumers and its direct environment, and it could also lead to an increased understanding with the public about sustainability in general and what to think of it. The consumers would stimulate local economic development, local employment and themselves because of the relieved pressure on transportation and energy systems, in Friesland but also everywhere where this approach is used.

The general functionality leads to the selection of a bicycle as a basic concept, which is designed to fit P90 of the Dutch population. In order to function as a showcase product for sustainable development, it is decided that the appearance of the bicycle should be “cool” instead of having a treehugger image. This was translated into robust though elegant semantics, combining the three current bicycle trends I have defined. The design proposal is thereafter built as it was designed to reveal wrong assumptions and errors. The 1 : 1 prototype is tested for strength and functionality revealing several issues, but this was no reason to conclude that the project should end here. The fact that it was possible to drive the prototype quite comfortably is the proof of that conclusion.

Using local naturally renewable materials has been achieved for 70 weight% of the Rebicycle. In the future approx. 87 weight% might be possible. Functionality, ergonomics, aesthetics and manufacturability all were integrated in the design.

Closing the cycle combined with the use of local naturally renewable materials has lead to an ecocost reduction of approx. 75 % with the potential of 90+ % due to possible developments for Polyurethane and Epoxy.

Thus is the LPD approach feasible?

The approach is not feasible, because of the goal set to 100% sustainability. This is probably a pipe dream because every thing we disturb by using nature is not sustainable in a way. However setting the goal to 100% has lead to a considerable improvement, which for all I know is one of the first products to promise the kind of improvement necessary in 40 years, which is a predicted ecocost improvement factor of 10 - 50. This is a rough estimation of course, as indicated in this thesis, because of the near infinite amount of factors influencing ecocosts. This makes the estimation highly unreliable, and probably too optimistic. That’s why it is so important to design everything for and with the environment, because a relatively small experiment with nature gone wrong has the potential of being life-threatening, something I believe we cannot risk.
I believe there are enough indications that the LPD approach is technically, functionally and environmentally feasible to a large extent for the chosen product, a bicycle. Because of the unexpected interest of the press it is concluded that the idea of designing a showcase product like this has been a succes. However economically it is still very uncertain whether the approach makes sense. In my opinion there is only one way of proving that, which is to implement the idea.

1. A thorough redesign has to be made with the goal of series production of a bicycle, which in quality is similar to regular city bicycles. The basis for the redesign has been given by this thesis. The first focus areas for the redesign are:
   - The fork
   - The lower frame part
   - The cranks, pedal axles and their construction
   - The wheels
   - The seat tube
   - The saddle
   - The handlebar

2. It should be investigated whether the LPD approach could also be applied on other product types and families, determining the effective boundaries of the approach.

3. Local and national government need to be stimulated to investigate other paradigms by adjusting policy more radical, at least for showcase products like this.

4. A detailed Life Cycle Analysis comparison between the redesigned Rebicycle and the “normal” city bicycle should be made to show the real differences in ecocosts for each stage of the product cycle.

5. www.rebicycleproject.blogspot.com should be expanded to a complete website, explaining the idea up to the detail where others can understand the goal of the project and place suggestions or participate in the project by executing the same approach in another region, e.g. in third world countries.

6. Generate more outcomes for the approach. This can be best achieved in cooperation with other technical universities, executing several different projects in different ecosystems, cultures and circumstances. The products preferably aren’t bicycles as well, exploring the boundaries of product suitability of the LPD approach.

7. If it proves to be possible to stimulate consumers to close the cycle, it is recommended that the parts of the Rebicycle are first reused as e.g. furniture or building material. This would elongate the carbon lock-in of the materials, achieving a higher eco-efficiency overall. A good friend of my, studying to be a designer as well was willing to think of a possible recycle design from the parts of the Rebicycle. The result can be found in [Appendix G].


[3] Industrial design graduation nr. 2515 at the faculty of Industrial design engineering at the TU Delft, M.R. van der Woning, the design of a “one size fits all” frame for Batavus.


[5] Province of Fryslan, List of occurring Flora in Friesland


[8] Linsen, L., Hammond, E.G., Nikolau, B.J., In Vivo studies of the biosynthesis of Vernolic Acid in the seed of Vernonia Galamensis, Department of Food Science and Human nutrition and biochemistry and biophysics, Iowa state University, Ames, Iowa.


[23] Hawken, P., Lovins, A., Hunter Lovins, L., Natural Capitalism, creating the next industrial revolution

[24] Johan Molenbroek: Children’s bicycle design (not published)


[26] www.jimlangley.net/crank/bicycleseats.html


Geurts, G., Jonkers, A., Keune, L., Voor de Verandering – Alternatieven voor het neoliberalisme: Regionalisering als alternatief voor neoliberal globalisering, beleid en praktijk
Master Thesis Appendices
Integrated Product Design
Design for Sustainability

by Arno Scheepens

Graduation Commission:
Prof. Dr. Ir. H. Brezet
Ir. S. van de Geer
Ir. S. Beella

Graduation Date:
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For this project it is essential to have an overview of the technical feasibility. Is it possible to design a good bicycle with only local natural renewable materials? The bicycle as we know it nowadays is made this way because of the availability of industrial materials like steel, plastics, vulcanized rubber, etc.. Steel for example is a highly durable, strong material with excellent properties as well as rubber which for example is highly wear resistant. I want to minimize/eliminate the use of materials like steel in this project as much as possible, first because it is not a naturally renewable resource (or at least not in a time frame which is relevant to mankind), but also because it takes high amounts of energy to recycle the material as well as to incorporate the raw material in products. Rubber originally was a renewable natural resource, but because of its many applications demand rose to a level where nature couldn’t provide and synthetic rubber came in its place. Furthermore sulphur is added to improve its properties, especially wear resistance. For this project it is questionable whether I can use rubber at all, since it is not a local natural resource of Friesland. Preferably, I want to use native materials, because from a sustainability point of view this is the safest approach because these resources were naturally there and importing other species would increase the number of factors possibly responsible for higher order negative effects on the long term (e.g. elimination of native species because of wild growth of imported species). On the other hand, my designer’s freedom is enhanced significantly when I would allow imported species that grow naturally in Friesland, or even in a greenhouse. Then there are also (waste) materials present in Friesland, like scrap metal, paper, glass, rubber etc. which are already being collected separately for recycling. Though the use of these materials decreases the level of sustainability of the project, e.g. because of transport, it turns out to be possible to infinitely recycle the materials or even upcycle the material (Cradle2Cradle) it might be possible (sustainable) to use these materials as well.

Approach

To acquire a structured view of the feasibility of the project I will use the approach of deconstructing the current city bicycle into its basic parts with their respective functions and materials, mapped out to the available local natural materials in the province of Friesland. The inclusion of the functions of the parts is essential because these describe the required functionality for the currently accepted bicycle. When mapped, exchange of functions might become possible, perhaps circumventing some of the problems encountered by replacing industrial materials with local natural materials. When completed this approach should provide a clear insight into which problems are the most pressing ones revealing clear bottlenecks of which can be estimated whether they are permanent or solvable, helped by cross linking parts, materials and functions.

I have divided the current city bicycle parts into four main categories:

- Structural parts
- User contact parts
- Movement parts
- Connections
**Structural parts**

These parts provide the necessary strength to support the user and stiffness for efficiency and control for the user as well as a safe feeling. These parts are mostly made of hollow steel tubes connected by welding in a framework. Here it is very important to know which material they are made of, their cross-sectional area and the type of load when replacing the materials of these parts. Typically, the tensional strength for metals is higher than its compressive strength, since plastic deformation occurs beyond the material’s yield strength which results in strengthening of the metal. This will not hold as much for compressive loading. In natural materials the mechanism of strengthening of the material has not been observed (by me).

**Frame (and Fork)**

For the frame nowadays many different materials are being used. These range from (Reynolds) steel to aluminium, magnesium and carbon fibre. When replacing these materials with natural materials a number of properties have to be taken into account. These are measured according to three tests:

- Torsion stiffness
- Fork stiffness
- Bracket stiffness

Torsion stiffness tests are performed by fixing the rear axle and twisting a rod which is slid through the head tube. The retrieved value is measured in Nm/°. From a test performed in 2006 on 600 bicycle frames by fiets.nl these values range from approximately 50 – 150 Nm/°, so the frame made from natural materials should at least have a torsion stiffness of 50 Nm/°.

Fork stiffness tests are performed by loading the saddle and steering pin with weights and measuring the elongation between the front and rear axle. This is actually a test for the entire frame, but because of the structure of the frame there will relatively be no significant deformation in the frame, only the fork. Fork stiffness ranges from approximately 40 Nm/° up to 100 Nm/°, so the fork should at least have a stiffness of 40 Nm/°. The elongation of the fork is measured as the elongation of the distance between the two wheel axles and lies approximately between 1 and 3 mm. Therefore I will use the value of 3 mm as maximum value.

Bracket stiffness tests are performed to measure the sideways deformation as a result of drive forces: The user putting pressure on the pedals. It is measured by simulating the force put on a pedal with a weight. Bracket stiffness as measured by the test performed by fiets.nl ranges from approximately 30 Nm/° up to 70 Nm/°. The bracket should at least have a stiffness of 30 Nm/°. The bracket deflection is also measured and ranges from approximately 1 to 4 mm. so I will use 4 mm. as maximum value.

These measurements can be done with a prototype only, but they can be approximated with the aid of CAD software.

(The frames tested by fiets.nl are made from different materials, including steel, aluminium and carbon fibre)
The Rebicycle Project

Steering pin, Steering bar
Similar to frame, less stiffness and strength requirements apply here. Especially with the steering bar, less stiffness is required because vibration dampening capacities increase user comfort. However for the use of the brakes it is necessary to provide enough structural strength and stiffness to operate the handbrakes if these are required.

Saddle pin
This part has to be able to carry the biggest part of the load of the user. Therefore it has to be strong, but not necessarily that stiff. If this part would have elastic properties with high fatigue strength, this could enhance user comfort.

Conclusion
Bicycle frames (and forks) can very well be manufactured with natural materials, sometimes even enhancing user comfort whilst still providing required stiffness and strength. From what I know now the most promising material for the frame is wood, because of its strength, stiffness, alleged shock absorption qualities, easy processing and high fatigue strength. For (connection) reinforcement and weather proofing a natural epoxy resin from the Vernonia Galamensis plant could be used in combination with natural fibre mats a high quality lightweight frame with high durability can be realised. The downside of this construction is the possibly unnatural hardener which has to be used to acquire the required properties of the epoxy adhesive, but since this is only a small weight percentage of the epoxy and very small percentage of the entire Rebicycle, it might turn out that the relative contribution can be considered insignificant. A thorough Life Cycle Analysis should be able to make an assessment of its contribution.

Insights structural parts
- All structural parts together should provide maximum torsion stiffness because of efficiency and user perception
- Vertical and horizontal stiffness is less important, it could even provide shock and (micro) vibration absorbance (www.waldmeister-bikes.de), though for control, it remains very important to achieve a very stiff fork or the bike becomes wobbly.
- Bending strength should be significantly beneath yield strength because of safety of user: In case of bending the material should not fail soon afterwards (www.fietsica.be)
- Double triangle structure has been proven as best way to construct bicycle frame because this provides most ideal force distribution (www.fietsica.be)
- Hollow parts provide better strength/weight ratio then solid parts (Statics)
- Dynamic loads are hard to compute for a bicycle, generally a factor of 1.6 is used as the “bump factor” over the computed static loads. (Industrial design graduation nr. 2515 at the faculty of Industrial design engineering at the TU Delft, M.R. van der Woning, the design of a “one size fits all” frame for Batavus)
- Different parts of the frame are loaded differently: tension, compression and/or torsion
Movement parts

Chain drive, axles, wheels and controls have high structural demands as well as wear resistance. The parts with high structural demands are for example the axles, rims, bearings, chain, front fork etc. especially because they deal with highly dynamic repetitive loads. Important material characteristics are high impact resistance, high hardness, high young’s modulus, high wear resistance, low friction coefficient and high fatigue and yield strength. On the other hand there are the air inflated tyres which are used for surface contact, the drive chain and the braking parts. These are very important for the comfort and safety of the cyclist because they provide grip, shock absorbance, stopping ability and control. Important properties are high wear resistance, low Young’s modulus, high yield strength, high water and UV resistivity and high friction coefficient.

Axles

The axles are relatively easy to replace. They are currently made with steel rods/tubes fixed to either the chain and seat stays or the fork. Simply increasing the diameter should be enough to cope with strength and stiffness requirements, and the same natural materials and their techniques that can be used for the frame can be used for the axles. Problems might occur with the hardness of the material because it being softer might cause unwanted indentations by for example the bearings. Then again this is also solvable by using for example wider bearings or reinforce the axle surface with a harder material, e.g. bio composites. Note here is that the wear resistance of the axles is of no importance because the bearings take on this problem.

Crankshaft

This part is mainly loaded in torsion because of the force the user puts on the pedals and cranks. Again this part has to be very stiff and strong, so the same natural materials could be used as for the frame and fork.

Pedal axle

Similar to crankshaft and axles, only is the applied load distributed over almost the entire length of the axle, so shear strength also has to be sufficient.

Bearings

The bearings are probably the most difficult parts to replace with natural materials, because of their extreme requirements. They also are made with a special vacuum casting method to prevent impurities in the metal, which later on could be the cause of micro cracks in the material resulting in premature failure. They have to have an extremely high wear resistance, otherwise the efficiency of the entire bicycle will decrease rapidly. Depending on the life cycle of the bicycle, bearings could be more wear resistant than needed. For this we need some calculations:

http://www.leiden.nl/dspage.asp?objectid=47637&sessionid=1dv5UIcp7M0aGBhXOqKlXX1LdpDcXH51f8xG1nmb51BNDacGa19bs1WzcVjljs3

This link gives some figures about the distance covered by bicycle per person per day. Assuming they all use the standard 28 inch wheels we can calculate the mean number of rotations per year and compare that to the fatigue strength of some simple ball bearings to find out how many years these bearings can be used (and perhaps
re-used). On www.skf.com it is possible to calculate the fatigue life of rolling bearings. The circumference of a standard wheel is approximately 2.2 m.

An average distance of 2.5 km. results in 1120 cycles per day = 458 x 10^6 cycles per year

With the online tool from SKF I calculated the number of cycles able to put on a simple deep groove ball bearing loaded statically as well as dynamically while they are placed in pairs on an axle with 500 N each, statically and dynamically. The result that came out was 12800 x 10^6 cycles which comes to a mean life cycle of approximately 28 years. (See appendix SKF bearing select)

This seems a lot, but maybe some bicycles actually last that long. The Rebicycle however could be intended for a usage lifecycle of around 5-10 years, which makes it possible to recycle the bearings. Add to that the increased diameter of the axle made with natural materials and the usage lifecycle of the bearings could be even greater. I will not go into that since I haven’t determined the correct diameter for the Rebicycle axles yet, but for now recyclability is promising for bearings.

The known natural bearing material is selflubricating wood from the lignum vitae tree (tree of life). This wood contains around 25 % fatty oils and is extremely hard and wear resistant. This type of tropical hardwood is very rare and protected and it belongs to the Guaiacum family. There have been attempts to find similar natural sources for bearing material, being not quite as adequate as wood from Guaiacum Officinale. Some that are mentioned are: Swartsia and Zollernia from the Leguminosae family as well as Bulnesia Arborea.

On the long term this material could be grown in greenhouses, but the species is a slow grower, therefore importing the wood from its natural habitat, which is the Caraïbic region and northern Latin America, is probably more ecoefficient.

**Crankshaft bearings**

As with the wheel bearings, these parts are among the most difficult to replace with natural materials. Again, the diameter of the crankshaft will be larger, therefore the bearings as well.

**Pedal bearings**

Similar to other bearings, only here their size is important, they cannot be too large.

**Steering bearings**

Similar to other bearings, only here I feel these bearings might be a pure luxury. The movement of the steering axle is very restricted, though highly repetitive. The only reason for putting in steering bearings would thus be the elimination of wear and a little friction, but it remains to be seen whether that is necessary for the Rebicycle. It might result in some loss of steering precision, but this might be acceptable.

**Brakes**

http://en.wikipedia.org/wiki/Bicycle_brake_systems
http://www.sheldonbrown.com/brakes/index.html

There are several types of bicycle brakes:
- Coaster brakes
- Drum brakes
- Rim/Calliper brakes
- Disc brakes
- Flywheel brakes

Coaster brakes

Coaster brakes are very common in Dutch city bicycles.
They only brake the rear wheel, which is allowed in The Netherlands, but not in several other countries. This is however not relevant for the Rebicycle, since it is intended for the local market only. Coaster brakes are a quite complex system where the reverse motion of the drive chain pushes a Brass or phosphor bronze part directly onto the hub, resulting in a braking force. This sort of brake needs a reaction arm, often attached to the chain stay. This system is not easily made from natural materials.

Drum brakes
A bicycle drum brake operates like a car’s but has no ratching adjustment mechanism or hydraulic actuation. Two pads are pressed outward against the braking surface on the inside of the hub’s shell, which is packed with grease. Shell diameters on a bicycle drum brake are typically 70 – 120 mm. Drum brakes have been used on front hubs and hubs with both internal and external freewheels.

Rim/caliper brakes
Rim brakes are the simplest form of braking mechanisms in use on bicycles. In rim brakes, the braking force is applied by the rider squeezing a lever mounted on the handlebar; this causes friction pads (usually made of leather or rubber and mounted in metal “shoes”) to contact the rim of the rotating wheel, thus slowing it and the bicycle. There are many different types of rim brakes, all using the same principle of pushing the pads against the wheel activated by pulling a rod or cable.

Disc brakes
Disc brakes consist of a metal disc attached to the wheel hub that rotates with the wheel. Calipers are attached to the frame or fork along with pads that squeeze together on the disc. This system is more expensive than for example rim brakes because they require extra parts. They however do not wear the rim down, and for the Rebicycle the rim made from natural materials is not wear and high temperature resistant, therefore making it interesting for the Rebicycle.

Flywheel brakes
This is a relatively new development where the wheels are linked to a rotatable weight attached to a braking system on the hub. The braking is realized by the moment of inertia of the weight which starts to rotate when braking, slowing the wheel down. These systems are currently under development for energy saving braking systems on electric powered vehicles, because the rotating moment can be re-used during acceleration.

Spoon brakes
The spoon brake was one of the first types of bicycle brakes and precedes the pneumatic tire. They were first used on penny farthings with solid rubber tires in the late 1800s and continued to be used after the introduction of the pneumatic tired safety bicycle. It consists of a pad (often leather) which is pressed onto the top of the front tire. These were almost always rod-operated by a right-hand lever. In developing countries, a foot-operated form of the spoon brake is sometimes retrofitted to old rod brake roadsters. It consists of a spring-loaded flap attached to the back of the fork crown. This is depressed against the front tire by the rider’s foot. Perhaps more so than any other form of bicycle brake, the spoon brake is very sensitive to road conditions.
conditions and increases tire wear dramatically. Though made obsolete by the introduction of the coaster brake and rod brake, they continued to be used as supplemental on adult bicycles until the 1930s and children’s bicycles until the 1950s, in the West. In the developing world, they were manufactured until much more recently.

Cranking

http://www.nettally.com/palmk/crankset.html
http://www.machinehead-software.co.uk/bike/cranks/crank_calc.html
http://en.wikipedia.org/wiki/Crankset

The cranks are loaded with a variety of forces and moments. For efficiency and user experience the cranks have to be very stiff and strong, just as the frame and fork. Therefore the conclusion is that the natural materials possible for the frame and fork are also possible for the cranks, but because of leg movement and hip width there are dimensional restrictions for the cranks. The most widely used cranks have a vertical orientation but some have low profile cranks. These have a shorter crankshaft length and are sloped outward from the crankshaft to achieve the correct tread: the distance between the two pedals in top view. There are three reasons for having the correct tread:

- The hip joint is optimized for walking, and in normal walking the footsteps are pretty much in line, with little or no “tread.”
- For standing pedalling, the farther out the pedals are from the centreline, the harder you have to pull on the handlebar to counterbalance the tendency of the pedalling force to tip the bike sideways.
- The wider the tread, the higher the bottom bracket needs to be to prevent clipping a pedal while pedalling through a turn.

Another benefit for sloped cranks is the shorter crankshaft which as a result should be stiffer than a crankshaft which is longer with the same cross-section.

Gear wheels and drive chain

Because there are no real slopes in Friesland, only single speed drive systems are considered. If gear change is necessary, the construction might become too complex and demanding for natural materials. The most common for bicycles nowadays are toothed gear wheels combined with a chain, both made of steel. The chain is very efficient (efficiencies up to 98.6% have been measured, (Wikipedia)), though it needs regular maintenance and has to be protected to stop clothing getting stuck and dirty.

A relatively new development that solve these problems are the toothed drive belts, seen for example on the Strida folding bicycle. I feel this is very promising for the Rebicycle, as also the first drive chains were made with leather, though these were hardly durable. Combinations of natural fibres embedded in a natural resin combined with a wear resistant high friction coefficient natural material like leather could easily replace the steel drive chain, accepting a small loss in efficiency, against a great simplification advantage. The gear wheels of the Strida for example are made of plastics. Their geometry is much more simple than toothed gear wheels made of steel.

The challenge for the drive belt is to have enough elasticity to deform around the gear wheels, but not too elastic so that the user loses much of his efforts into the belt. This is a very complex issue, so it might be too much for this project to replace the drive chain with a drive
belt made with natural materials. But I feel that for the future the way to go with natural materials is to make a drive belt, because this is the simplest construction, so for this project I may have to use a similar drive belt, to prepare the design for the development of a drive belt made with natural materials.

Another solution that has been around since the late 1800’s is the cardan axle or shaft driven bicycle. It’s main advantages are that its maintenance free, compact, safe, reliable, consistent and clean. However, the system is very complex in manufacturing therefore expensive, heavy, less efficient and doesn’t allow a wide range of gear changes easily. It works with two couples of bevel gears allowing two 90° motion direction changes, thereby transferring the user forces onto the rear wheel.

One other thing to consider is the cadence, which is the number of revolutions per minute. Recreational and utility cyclists typically cycle around 60–80 times per minute. Racing cyclists have a cadence of around 80-120 where sprinters sometimes reach 170.

**Hubs**

Similar to frame and fork. These parts connect the rest of the wheels to the bearings on the rear axle and the drive system. The front hub mostly is fixed in a radial pattern of spokes. These hubs cannot absorb torsion forces which is not needed with the front wheels. This layout results in high forces in the hub. The rear hub is fixed in a crossed pattern of spokes. These wheels are able to be loaded in torsion, which makes them suitable for rear (driven) wheels.

**Spokes**

The spokes are parts of the wheel which are loaded in tension instead of compression. The reason for spokes is the weight reduction made possible by spokes instead of solid wheels. The cross sectional dimensions of the spokes are very small and their number varies from 32 to 36 in a standard bicycle wheel. There are different kinds of spokes:

- **Single butted spokes:**

  ![Single butted spokes](image)

- **Double butted spokes:**

  ![Double butted spokes](image)

- **Triple butted spokes:**

  ![Triple butted spokes](image)

- **Aero/Bladed spokes:**

  ![Aero/Bladed spokes](image)

The single butted spokes are the most common (cheap) but have the least quality. The variance in diameter in the other spokes improve handling and comfort because they can absorb part of the shocks on the rim of the wheel by bending. The spokes have to be maintained frequently to cope with loss in tension which is done by
tightening the spoke nipples where they are attached to the rim.

Rims

The rims have to be elastic enough to absorb shocks, but stiff enough to distribute the load over the spokes. They have other functions such as providing braking surface and holding the tyres. There are many examples of rims made from natural materials, mostly wood.

Tyres

A very successful invention was the inflated rubber tyre. It provides excellent shock absorption (inner tyre) and grip as well as wear resistance (outer tyre). Due to this invention the bicycle became much more popular. The amount of inflation can be controlled and thus the rolling resistance and comfort level. There are downsides to the inflated tyre though. The flat tyre is a very well known downside of inflated tyres. There have been many developments trying to minimize the risk of a flat tyre, all with limited success. Still the current tyres are very durable.

One of the most successful developments to eliminate this problem is the airless tyre which uses a PUR foam, the so-called airless tyres. From forums I’ve seen that they do not live up to their expectations, but this is compared to the air inflated tyre, which has less rolling resistance, and their overall performance is quite good. http://www.greentyre.co.uk/home.html

Greentyre claims that their production process is very environmental friendly:

"The process is clean, non carcinogenic, CFC free and releases no harmful toxins to damage the atmosphere... The tyres last longer (up to 3-4 times) than rubber and when the tyre wears down, it can be recycled."

There is one commercially feasible natural source of PUR, a biopolyol derived from the castor beans of the castor plant (Ricinus communis). This plant can be grown in greenhouses in Friesland, at a minimum temperature of 20 °C with added artificial light in autumn and winter. They require a lot of nutrients and water, as well as high humidity. Workers in regular contact with this plant suffer from serious side effects because of toxicity of the plants. This decreases the usability of this plant for the Rebicycle significantly. There are however more species of plants (probably also native) that contain the substances needed for bio production of PUR, but the quantities present are said to be too low to be commercially feasible.

Conclusion

The most difficult parts are the bearings and brakes because of their high strength, hardness and wear resistance requirements. Here it might be necessary to use small quantities of steel in the design of the Rebicycle which will have to be reused to minimize environmental impact.

The cranks and the gear wheels can be made with natural materials, here the connections and types of loads are important for material choice.

The rims, hubs and spokes have many examples that have been made with natural materials, e.g. wood, therefore I assume it is possible for these parts.

Depending on the environmental impact of PUR, the airless tyres are a good solution. They require a simple rim and consist of only one part, contradictory to air filled tyres, which consist of more than 6 parts: Outer tyre, inner tyre, outer tyre inlays, rim protection, valve tube, inner valve etc. Therefore even though there might
be a significant impact on the environment, the choice for PUR airless tyres might be justified. This material might also be necessary to achieve the requirements for the drive chain as well as the saddle and handles, because of its durability, wear resistance and weather resistance.

**Insights movement parts**

- For the drive chain a leather belt was used because of its high friction coefficient. This would simplify many parts of the chain drive, though under wet conditions this would not function properly.
- Some bearings might be redundant, e.g. head tube bearings. The steering might be a little less supple, but this might not be a real problem
- Airless tyres have already been developed which give opportunities to replacing the rubber with natural materials. They are now made with PUR foams
- Spokes in wheels are loaded in tension, not compression
User contact parts

These parts are usually made with different forms of plastics: Solid, foam, foil, etc. They provide some form of vibration dampening, insulation, protection, and grip. They also provide for anatomical variation because they are flexible. Here specific properties of the materials are used to increase the comfort level of the user. These properties include low Young’s modulus, low thermal conductivity, high impact resistance, high friction coefficient, high water and UV resistivity and low hardness.

Pedals

These parts simply provide grip for the feet of the user to be able to transfer force into a circular motion. The biggest problem are the bearings in the pedals because they cannot be too large, otherwise the construction becomes bulky and heavy.

Handles

These parts should provide shock absorption, grip, insulation and an ergonomic feel. These parts can easily be made with natural materials like leather, rubber, cork etc. I see no problems with these parts.

Saddle filling

The filling has the main function of distributing the load and providing shock absorption. Perhaps the same PUR foam as for the tyres could be used.

Saddle cover

This part solely serves as weather protection. Depending on material choice this part might become obsolete.

Conclusion

For this feasibility study these parts are of lesser importance, because there are many alternatives in design and materials. Generally it can be said that these parts will not be the bottleneck. The biggest problems I foresee are weather and wear resistance, and that the natural resources for these materials do not occur naturally in Friesland.

General design problem with the user contact parts (except for the pedals) is that they have to be adjustable to provide for a comfortable and optimal riding experience. This aspect increases the amount of parts, thus making the bicycle more expensive and complicated to manufacture. One solution might be the individual customization to rider height and reach, which is possible because of the close relationship between Rebicycle and their customers as a part of the Product Service System. An example would be an extended seat tube in different stock sizes to be fitted on customer demand, giving the customer a high customized feel. Here also the potential is increased because of the natural epoxy material. It can bond a variety of materials to each other, for example steel to wood.

Insights user contact parts

- The parts are relatively simple and can be replaced quite easily with natural materials. Even an improvement of comfort is possible with natural materials.
- Wood has a high fatigue strength and flexibility and thereby might reduce the number of parts significantly by integrating their functions.
Typical connections are welding and nuts and bolts. Clamping is also used for placement of moving parts. The connective material or method is highly dependent on the type of connection, the material and the requirements due to the type of loading. Current city bicycle frames are predominantly welded and the moving parts are connected to the frame with nuts and bolts. This is only possible due to the use of metals. With natural materials the obvious replacement for welded connections is an adhesive since there are many examples of biological adhesives, e.g. starch glue and even experimental bacterial adhesive which can be extremely strong. (http://www.cbc.ca/health/story/2006/05/24/bacteria-superglue.html)

Because of the dynamic loading of almost all connections in a bicycle a high strength adhesive is needed, which is also weather resistant. This is needed so the material fails earlier than the connection thus the material becomes the limit, similar to welds which are considered stronger than the welded material. The best adhesives are epoxies which are known for high strength and durability. Production needs to be accurate but is easy because when the two components are mixed an exothermic reaction takes place. PUR adhesives are also commonly used for connecting wood, but when loaded the wood is loaded dynamically the adhesive tends to detach from the material, therefore PUR adhesives are unsuitable.

Normally the epoxy adhesive resins are derived from oil and then combined with a form of amine as a hardener. The discovery of the Vernonia Galamensis plant might lead to a natural resource for epoxidised fatty acids, because its seeds contain triglycerides with three chains of single epoxidised fatty acids. The hardener might be more difficult to replace.

In order to make the glued connections as strong as possible the area over which the glue is used has to be maximized. For wooden connections a very good way is the use of finger joints. Another way to connect the different parts is with pegs in tight fittings securing them in place. On itself this method for connections is not that strong (only as strong as the smallest cross-section or surface) but they might be used as an addition to glued connections.

Clamping with natural materials could be done by laminating the connection with fibre mats or even rope windled around the connective area. This is an ancient technique which is very easy and cheap, but not very reliable for dynamically loaded connections.

Conclusion

Because the type of connection method and material is highly dependant on the material and shape to be connected, the conclusion remains general for now.

Insights connections

- The type of connection is highly dependent on the material, geometry and type of load.
- Epoxy adhesive is the best option for adhesives. It is strong, durable, weather resistant, translucent, selfcuring and it is possible to produce from natural resources present in Friesland.
- Geometric shapes can increase surface for adhesive effectively
- Pegs and holes can easily be used for fixing components in place
- If extra reinforcement is required, laminated textile can be applied, which also improves stiffness
Wood

Wood is the material first used to construct bicycles. It has reasonable strength and stiffness, more or less comparable to aluminium, which makes it very suitable for constructing the frame, fork, spokes and wheels. It can be machined easily (sawing, milling, sanding etc.) but that also means a high amount of labour, which results in a high cost price. But it requires relatively simple processes to acquire the material, since it grows naturally in the form of trees. This is also the main reason why it could be very suitable, since this is nature’s answer to dynamic bending loads. Wood is a natural composite material made for dynamic bending loads.

One problem that also occurs with aluminium frames is that its bending strength lies close to its failure strength, which means it will fracture soon after bending.

Laminated wood is also used for wooden bicycle frames, which probably improves its properties but also minimizes risk of unexpected failure due to natural irregularities in the material.

“Laminated wood is usually built by the parallel gluing of lumber boards in a variety of sizes and shapes according to intended use. The main products are load-carrying members, such as beams and arches. Parallel-glued veneers are sometimes used to produce specialized items (for example, furniture, sporting goods, and novelties). Laminated wood possesses several advantages over solid wood. It can be used to fabricate large members that are impossible to make from solid wood. The individual boards used in laminated wood, because of their relative thinness, can be properly dried without checking (cracking), and defects, such as knots, can be removed. Structures can be designed with laminated wood on the basis of required strength, and wood of low grade can be positioned accordingly. In addition, because laminated wood is glued, wood of small dimensions can be used, thus reducing waste.” (Britannica encyclopedia)

Renovo claims that wood has better impact resistance properties than metals, providing a smoother ride. They achieved a monocoque frame CNC milled and joined over the vertical cross section of the frame. They use a high strength glue combined with finger joints as connection, but maybe it could also be bonded with simple glue and then laminated, as they did with the bamboo bike from Calfee.

The pedals are very well suited for constructing them with wood, and because of their simple geometry will be easy and efficient to manufacture. I feel this is absolutely feasible thus for now I will not go in depth into the pedals.

Wood is not suitable for the other user contact parts, because the user needs a softer feel. However there are already wooden handlebars on the market by fastboy, which have no handles whatsoever, greatly improving simplicity of the design.

Another way to construct the frame might be a lightweight core material for the shape and compressive loads, combined with laminated fibre mats embedded in a natural resin.

This would probably result in the most lightweight construction, but has the same downsides as carbon fibre laminated products: they are very expensive due to labour costs.

For the Rebicycle project the amount of matrix material might compromise the sustainability goal of 100%, because the matrix material often is chemically based which either makes the material toxic or biologically inert.
There is only one recorded species of bamboo of which I found it to be growing in Friesland, Japanese bamboo or Fargesia Murieliae. It is used as a decorative plant in gardens. There are however many species of bamboo that will grow in Friesland. I for now discard the use of bamboo for several reasons.
- It is not a native species
- It doesn’t grow as fast as in its native surroundings, a greenhouse would be needed which has to be huge because the most usable species are the giant bamboo species.
- It has an Asian look, hardly fitting to the local surroundings of Friesland, so for a local appearance the material has to be altered, which is possible, but more expensive
- Its machining possibilities are limited, either the fibres are used to make a composite or the entire stem is used as a constructional beam

Under the trade name Spun Bamboo® EcoThreadz produces a natural fiber of bamboo. It is an alternative to cotton, wool, hemp and synthetic fibers like polyester and nylon. Bamboo fiber is soft, has a natural sheen to the surface and feels similar to silk or cashmere. You can throw it in the washer and drier. Bamboo textile drapes like silk, it feels as soft and good as silk, but it is more practical because it is durable and much less expensive and versatile. Bamboo is more antibacterial than cotton or wool, which are absorbent and hold moisture in. Because Bamboo wicks moisture away, it’s positive for circulation and skin. Due to bamboo fiber’s cross section which is composed of a matrix with various microscopic gaps, bamboo fiber is breathable, comfortable and thermal regulating. Bamboo fiber fabric and yarn are naturally bacteriostatic and require no harmful chemicals. The fibers contain an agent, “bamboo kun”, that prevents bacteria from cultivating on it thereby inhibiting body odor. The naturally occurring bacteriostatic property also helps prevent cultivation of yeasts, molds and fungus. This is a high quality material, however its application is hardly fitting for a bicycle. Therefore this material is not considered suitable.
Bio composites are generally made with a resin mixed with a certain weight percentage of natural fibres such as hemp, flax or jute. The resins used in bio composites come in two forms:

Thermosetting resins
Biological thermosetting resins are made on the basis of natural raw materials, which are afterwards chemically altered to achieve the required properties which are similar to epoxy. This makes the material suitable for carbon fibre like applications, because then the long fibre strength is used. Thermosetting resins are highly durable, partly because they are not biodegradable. All together thermosetting resins are not suitable for the purpose of the Rebicycle.

Thermoplastic resins
Thermoplastic resins are more easily acquired from natural materials. Their molecular structure is shorter than thermosetting resins, which possibly makes them biodegradable, but at least it is possible to melt the resins and recycle them. Therefore in applications of bio composites the thermoplastic resins are more suitable for the purpose of the Rebicycle. But they are less suitable for applications with long fibres, because the resin fails much earlier than the fibres.

These bio composites are currently in development at different companies, so very little is known about its properties. Their expected properties are promising, but according to NPSN it will take at least a few years before enough research has been done to say something about their properties and fabrication methods. Some things can already be said though.

Acquiring these materials from nature is more difficult than with materials such as wood, because it involves multiple steps, e.g. deriving the fibres from the hemp, flax or jute plants, but most of all the chemical processes involved with the resins. But bio composites are more easily given shape than wood and its labour intensive processing techniques, though still very little is known. Then again for example for injection moulding of the bio composites, moulds and high pressure equipment are needed which are expensive and they involve a lot of materials I’m trying to avoid.

The most often used production method is Shield Moulded Compound technique, where slags of semicured material is inserted in a mold. This technique is widely used in the automotive industry for bumpers, dashboards etc.

Another often used fabrication method is vacuum moulding, which is quite cheap on its own, the manual labour is what increases the price.

Depending on their exact properties, bio composites could also be used for manufacturing the axles if they live up to their expected strength and stiffness similar to glass fibre reinforced polyester.

Overall the complexity and uncertainties with biocomposites lead to the conclusion that these materials are less suitable for the Rebicycle than for example wood, which is already a biocomposite material, occuring naturally. Therefore these materials are only to be used if directly derived natural materials aren’t able to meet the requirements.
These materials are derived through chemical processes from either oil or plant origins, which require a high amount of energy for the polymerization process. Most of these materials classified as biodegradable only degrade under certain circumstances, for instance at 60°C and 90% humidity. They are however better resistant against weather influences and because they are based on plastics they are easily processed in current manufacturing techniques. As a structural material biodegradables are not very well suited. Only if they are reinforced with fibres (natural, glass, carbon, kevlar etc.) might the material be able to acquire enough strength and stiffness. Companies like NPSP are currently experimenting with these materials, which are biocomposites. This material only seems suitable for now as a material for accessories like fenders and protection strips.

Some examples of biodegradables and biocomposites:

**Cocolok/Hairlok®**

Enkev manufactures composites of natural rubber with animal hair and coconut fibre. The products include Hairlok® (natural rubber and hair) and Cocolok® (natural rubber and coconut fibre). These are products of purely natural raw materials. Their elastic, ventilating, insulating and pressure-spreading properties make them useful for a wide range of end products, such as mattresses, furniture, car seats, filters and gaskets. The properties of these materials make them very suitable, but the use of natural rubber makes the use of these materials impossible.

**Kollamat**

The Bader brand is known for its premium leather equipment of cars. Only leather is used which does not show any natural remarks such as crinkles and disruptions. The other leather surfaces which do have these characteristics are the basic materials for Kollamat; biopolymers extracted from the leather production are added. With the environment in mind, Bader created this compound–material Kollamat based on leather materials which can be used for all conventional methods of proceeding PVC materials. Leather typical characteristics such as the comfortable feel and natural optics are also features of the Kollamat system besides the technical advantages. Kollamat has characteristics which are typical for leather: Comfortable warm feel, lively surfaces, high quality image, good heat and acoustic insulation, good regulation of humidity, warm, natural colourings and flavour and smell of genuine leather. Kollamat has important technical advantages: Very short time cycles, low clamping force, low shrinkage and low energy theorem. Kollamat is ideal for a variety of applications, for example for Injection moulded components with high quality feel and optics similar to leather and press forming parts.

**Ingeo**

Ingeo is part of the Terratex-classified family of environmentally conscious fabrics and is made of biopolymer. Die–Cut Ingeo is lightweight and created by fusing, embossing and die–cutting the fabric with a swirling, circular cut–out pattern and is available in an elegant architectural white. The initial iteration of the fiber is derived from corn kernels. Currently the polymerization process takes corn from starch to sugar to polymer to fiber. The natural origins of the polymer allow it to be safely biodegradable at the end of its useful life. Ingeo is truly a closed–circle sustainable product. The DesignTex Group participates in the licencing program of the Solomon R. Guggeheim Museum. These materials are beautiful, but not suitable for a bicycle.
Cork

Cork has a soft feel, high friction coefficient and appealing look as well as dampening qualities making it excellently suitable for the steering handles and the saddle. The material can even be injection moulded.

Carbon rims, as on some disc wheels, generally have to use non-abrasive cork pads, because of the wear on the braking surface of the rims, which easily becomes critical. This could easily be applied to braking surfaces of natural materials, though the generated heat from braking activity would remain a serious problem, and in wet circumstances this system is much more inefficient. Cork Oakes don’t grow naturally in Friesland. They require a warm, dry habitat with sandy soil, and are mainly found in Southern Spain, Portugal and North Africa. Another drawback is that Cork Oakes need to achieve an age of 40 years before the cork can be harvested. This makes the species unsuitable for growing in greenhouses: Occasional transport of the material from a region where the oak grows naturally against the (eco) costs of maintaining a part of a greenhouse for 40 years is probably better for the environment.

Recycled cork is abundant and overall there is a shortage in demand for cork products. Using cork in this project is would not be completely sustainable, since it is not feasible to produce the material in Friesland. However as long as there is unused (waste) cork in Friesland it could aid the development of the product. For example the brake pads can for now be halved cork stoppers or ground cork could be used as filler material in the tyres.

Cork fabric , or cork leather as it is sometimes called, is a high quality fabric produced from thin cork shavings obtained directly from the bark of the cork oak tree. Much of the production is hand crafted. The innovative characteristics of cork fabric are unique and original. Cork fabric is available in a unique assortment of natural textures, patterns, and designs and is produced with different backing materials dependent on final use. Cork fabric is usually supplied in rolls 1.50 yards wide (1.40 meters wide) by 27 yards long (25 lineal feet). Depending on the matrix material used, the material could fit the Rebicycle project, e.g. as saddle cover. But because it is handcrafted it is expected to be more expensive than alternatives like PUR or even leather.
A new development is the discovery of the Vernonia Galamensis plant which seeds contain a high and therefore commercially feasible percentage of cis-12,13-epoxy-cis-9-octadecenoic acid, which is a naturally epoxidised fatty acid. The plant is native to middle Africa (Ethiopia, Somalia), but it has been successfully cultivated in greenhouses in the United States in the mid Atlantic region with 14 hrs. of artificial light at a temperature ranging from 20 to 25 °C, and for the flowering period 10 hrs. of artificial light [1]. It remains a chemical process but biosynthesis of vernolic acids is possible[1]. But then the hardener must be added to the liquid epoxy resin. Choice of hardener can vary the mechanical properties from elastic to plastic as well as the curing time. The hardener actuates an exothermic process where interlinking takes place between the molecules of the epoxy resin, resulting in a plastic structure which can either be very elastic or very stiff. The use of this natural epoxy adhesive greatly improves the feasibility of this project, because it enables me to create high strength bonds between wood, metal glass etc. but also it can be used in composites or laminates like carbon fibre. When designing with Epoxy based composites it is important to design for stiffness and glass temperature.

Starch adhesives are mostly used in paper, because starch is made of carbohydrates similar to the carbohydrate cellulose in paper. It’s also used to bond wood, e.g. fibre boards, and to strengthen cotton. The starch adhesive can be derived from various natural resources, for this project the most important ones are potatoes and corn of which corn is used most often. The carrier for starch glue is water, and if the adhesive is applied the water has to evaporate or be absorbed for the adhesive to stick. This is the immediate downside of starch adhesives. Though starch is not considered soluble in cold water, the bond is weakened significantly if the bonded materials are wet or in a wet environment.

Overall the bonds formed by starch adhesives are not considered very strong, not weather resistant, but biodegradable. Because of the high strength and weather resistance requirements starch glue is not likely to be a viable option but because of its natural basis it will be kept in mind.
This material gradually takes on the shape of which it is in contact with. This makes it ideal for the saddle, as seen on internet forums where generally the leather saddle is rated best for comfort. Leather can be grown naturally but its processing requires a lot of labour and processing agents (tannins, which can also be derived from plants) which make it an expensive material.

Old brake pads were made with leather on wooden rims, because of its high friction coefficient. The biggest problems with replacing the materials are the wear resistance and heat resistance. For wear resistance one solution might be increasing the size of the brake pads. The braking power would not increase, but the amount of wear would decrease.

Derived from animals (mostly sheep) wool has unique properties on insulation, weather resistance and antibacterial capacity. It can be used as saddle cover for instance, or rope can be spun to reinforce connections or act as braking cable. However the material is not very strong, and is food for moths.

Overall I do not consider this material to be highly suitable for this project, but it has to be considered because it is 100% natural, and if the need exists later on in the project, e.g. accessories, the material might be an option.
This material is also very suitable for the handles, for the most obvious reason that many handles are currently made with rubber. But also the saddle cover could very well be made with rubber, because of its high friction coefficient and for its water tightness.

Rubber producing trees only grow within a region 10° off the equator, preferably on hilled slopes. This makes it very hard to grow in greenhouses in Friesland, if not impossible. Therefore if I want to make use of rubber, I will have to turn to recycled rubber, of which there should be an abundance in the form of used car and bicycle tyres. The upside of making this compromise is that the rubber is already made for the purpose of tyres, therefore no alteration in the material is needed. The recycled material is in the form of granulates for which a matrix material is needed to bond the granules. The other form of recycled rubber is high quality powder which is usually remixed into rubber compounds. However, recycled rubber granules emit zinc to the environment when reused, which makes this material less suitable.

http://www.3rrubber.com/home.html
http://www.rivm.nl/milieuportal/dossier/rubbergranulaat/index.jsp

Because it does not grow naturally or in a greenhouse in Friesland, it is principally impossible to use this material in this project, but if there is no alternative, it can be a natural material with unique properties which have to be kept in mind.

Of the four species of fibre plants that will grow in Friesland the two most promising are Hemp and Flax.

Hemp has slightly better properties than Flax:
- Hemp has an E-modulus of 3 – 10 GPa and Flax 2.9 – 8.5 GPa
- Hemp has a yield strength of 200 – 400 MPa and Flax 150 – 338 MPa
- Hemp produces longer fibres (up to 4 metres) than Flax

But, Hemp is much more vulnerable to a species of fungus which kills large amounts of crops in wet circumstances. Flax has been grown in the Netherlands for a long time, presumably it is better resistant against the Frisian climate, not needing toxic detergents. Also the planting to harvest time is a little shorter for Flax than for Hemp: 100 days and 120 days respectively. Then again Flax can only be harvested from the same piece of land every 6 – 7 years.

For now I conclude that either crop can be used for the production of fibres usable for the Rebicycle. Ropes will be yielded easier from hemp, but a higher quality of fabric can be made with Flax. However, Flax harvests also yield linseed oil which can be used for the production of natural PUR, therefore the preliminary choice is Flax.

In comparison: Carbon fibre can achieve E moduli between 370 – 390 GPa and yield strengths between 1800 – 4300 MPa so for example it’s a factor 50 stiffer and a factor 10 stronger than natural fibres.

Nevertheless, because the natural fibres can be oriented and thereby reinforcing structures in specific areas and directions, the application of natural fibres can be beneficial as connective material, reinforcement, added
Varnish

Varnish is acquired by solving a natural resin e.g. from pine trees in oil or alcohol, whereafter it might be boiled to achieve the required viscosity and/or a drying agent like linseed oil can be added. Violin builders for example prefer oil solved varnish because it spreads more evenly, but the drying time is longer.

For the preservation of natural materials varnish is a very good option, because it can be derived easily from natural resources, but in case of damage to the finish, the material beneath is exposed. In the case of a bicycle, damage is to be expected, therefore another form of weather protection is needed in combination with varnish.

Applying varnish requires much labour since the varnish has to be applied by hand, probably several times to ensure total coverage. This makes the choice for varnish more expensive, but maybe there are possibilities for (semi) automization of this process.

The finish varnish leaves is very beautiful, especially in combination with natural materials, revealing the structure of the natural material since varnish is transparant.

Because this material can be made with 100% natural materials, this is a very good option for the Rebicycle project. The only downside is the enormous amount of labour that goes with the application of several layers of varnish, but if the preservation techniques leave are inadequate or not beautiful, varnish is a solution.


stiffness and because of its matrix material can provide weather resistance.
An alternative for rubber tyres are the PUR foam tyres, which have as a main selling point that the tyre never goes flat. The only known commercially feasible natural resource for PUR is Castor oil from the Castor plant which grows in India and China. Workers for harvesting these plants suffer from serious health problems e.g. nerve issues because of the toxicity of the plant. But if I use the fibres of the Flax plant, I might as well use the oil from Flax, linseed oil. This way it might become more economically feasible, because I use two products from one yield.

A big advantage of using PUR for the tyres is that the material can also be used for the drive belt, the saddle, handles, brake pads etc. The process of producing PUR is a complex process. The general process is described as:

\[
\text{MDI/TDI} + \text{polyol} \rightarrow \text{PUR} + \text{heat}
\]

MDI = methylene diphenyl diisocyanate
TDI = Toluene diphenyl diisocyanite
Polyol = Linseed oil (and/or derivatives)
PUR = polyurethane

Different additives are used during this process: Catalysts, chain extenders, cross linkers, surfactants, pigments and blowing agents.

PUR can be produced as thermoplastic or thermosetting. The most widely produced are the thermosets, for which I haven’t found a clear reason, but I think it is because of the cheapness of the exothermic reaction and the possibility to create foams.

Thermosets
The main problem for this project is that the MDI used for PUR production is oil based, which I try to avoid. However if the PUR could be recycled the amount of oil used in (re)production might turn out to be insignificant. Thermosets are hard to recycle, at best they can be “downcycled”. Because the material is biologically inert it cannot biodegrade and thus ends up in landfills. There are methods of chemically recycling thermosetting PUR, but these have halted in development, because of the economical infeasibility.

Thermoplasts
For the Rebicycle project thermoplastic PUR (TPU) is much more interesting, since it can be melted and reprocessed much easier extending the number of lifecycles very significantly. The problem I foresee now is the foaming of TPU, though I haven’t found anything on that yet.

http://www.polyurethane.org/s_api/sec.asp?CID=910&DID=3623

After consulting Prof. Picken at the ChemTech faculty I now know that the thermoplastic PUR is a linear polymer, not a network polymer. Therefore it will have different properties than thermosetting PUR, but if it turns out that thermosetting natural PUR is too inelastic, thermoplastic PUR could also be a good solution.
Cork as a recyclable material is high potential because of its unique properties and high availability. For the Rebicycle purpose the material is less suitable, however some applications might be served with recycled cork. For example the brake pads could very well be made with used cork stoppers, or the material could be ground into powder and used as a filler material. However, the Rebicycle concept is meant to be oil independent and there is no indication that recycled cork will be available forever: It is a natural resource, but impossible to grow in Friesland, thus it will have to be transported. Therefore I discard the use of recycled cork for now: It has no unique properties the Rebicycle needs and it cannot be grown locally. It can be used in the period where there is abundant recycled cork, but on the long term this material has to be avoided.
Recycled steel can be a high grade material for which the use in a bicycle might be justified by its properties on strength, durability, safety and wear resistance. Especially the bearings and braking cables might have to be made from steel, because of the specific requirements for those parts.

However, the recycling of steel requires high amounts of energy for transport and melting, because the material has a high density and a melting point of around 1400 °C. This means large, heavy equipment to render the process economically feasible.

Therefore I want to minimize the use of steel in the Rebicycle. The use of recycled steel is a lesser problem since the Rebicycle is supposed to return to the company at the end of life stage. However, the amount of energy needed for melting, cleaning and reproducing the parts is high, as well as the amount of equipment needed. To maintain the required level of quality it might be impossible to exclude steel as a material, but its volume could be minimized. Nevertheless, the exclusion of steel is likely to have a positive contribution on the sustainability of the Rebicycle, given that this will not affect consumer opinion negatively. Therefore I’m not accepting the inclusion of steel as a material for the Rebicycle, because steel is likely to compromise the goal of 100% sustainability in this project.

Glass is also a recyclable material with unique properties. Its high hardness and transparency make it a material which is widely used. For the Rebicycle the transparency properties are only interesting as a wind and rain shield. I do not consider these parts absolutely necessary, therefore on that basis the material will not be considered. It might however be considered for its hardness and its capacity to reinforce materials like polyester or epoxy. The use of fibre glass is widely spread, especially fibre glass reinforced polyester, which might be incorporated into biobased plastics or composite resins.

Another application might be the use of glass reinforced epoxy as a bearing material. Companies like NPSP Composites, Haarlem, are currently investigating properties and producability of these composite materials, but not much is known. They claim the results to be “promising”, but are experiencing a lot of difficulties.

Fibre glass production from recycled glass also requires a lot of energy since glass has a melting point of around 1500 °C. Therefore on an energy basis steel would be a better option, though glass raw material is ubiquitous, and glass doesn’t oxidize, therefore it is more durable.
As said in the natural rubber paragraph, the only form of rubber present in Friesland is recycled rubber, with the downside that a matrix material is needed to produce with recycled rubber and the granulates emit zinc to the environment. The question is whether the ecocosts for using recycled rubber are higher than the transport ecocosts required for natural rubber and the ecocosts for plantations in tropical regions. For now however the use of recycled rubber is discarded because of the aforementioned reasons.

Paper is made of wood fibers and starch glue. The paper and packaging industry is however preparing for a switch towards hemp paper as I now from an interview I conducted with a manager from Smurfit Kappa, a producer of corrugated cardboard packaging.

Paper has hardly potential in structural applications except when it is manufactured in a framework, e.g. honeycomb structure.

For the Rebicycle it has some potential for example as core material for laminated parts, but the big problem is weather resistance, since it is based on starch glue. This glue could easily be replaced with for example epoxy glue, but then the amount of epoxy is increased dramatically while natural wood could be used just as well. The use of paper would be the use of wood with multiple steps in between, and only a few advantages. The big advantage would be the production possibilities, since it is easily formed and shaped and the properties would be more or less the same in every direction of loading.

It is possible to build a cardboard bicycle, but this design is hardly durable and I have doubts on comfort, safety and efficiency.
In order to converge the knowledge I acquired during the reconnaissance part of the analysis phase I reviewed the natural materials on their suitability for this project. Only the materials I found promising enough or that have specifically useful characteristics are taken into consideration. Also recyclable materials present in Friesland are taken into account. The result of this suitability analysis is the matrix to the right. I used eight criteria which I found to be important to judge the suitability of the materials for this project which are weighed intuitively on a scale of 0 – 1, multiplied by each other to reveal the relative suitability of each material. I chose to multiply the criteria weights because this way a low score is weighed more then with addition. The order in which the factors are placed is random for now, since the general outcome of the approach, for now, is more important.

**Criteria**

The criteria used for determining the material suitability for the project are formulated according to the knowledge acquired during the research on the feasibility. The entire life cycle is taken into account to ensure that no part of the life cycle is forgotten when choosing the materials.

**Durability**

This factor entails the longevity of the material in its proposed functions and environment. This includes wear resistance, weather resistance, fatigue strength and robustness.

**Local naturally renewable**

This factor shows the degree to which the material naturally exists/grows in Friesland. There are three levels to this factor: The first level is the native species, which grow without climate control. The second level is the species that grow in greenhouses and the third level is the species that are very difficult to grow in Friesland.

**Variety in production methods**

Some raw materials have a high variety in production methods used in the production process, either because the raw material is very versatile and/or the material has been around for a time frame which has allowed the development of a variety of methods.

**Wastes usability**

From raw material retrieval, material processing, manufacturing and end of life, waste is a by product of (almost?) every consumer product. Some wastes compared to other wastes are better suited for (re)processing/using than others.

**Properties suitability**

Material properties are suited for a limited number of functionalities within the system of a bicycle. This factor weighs the difference in material suitability for the same (general) functionalities.

**Diversity in application**

This factor is closely related to the latter factor but some materials have properties which make them suitable for several functionalities required in the system of a bicycle thereby decreasing the number of raw materials needed to produce the product.

**Growth ability**

This factor could also be described as a cost factor because it denotes the rate of renewability, which might almost have a linear correlation with costs. The higher the rate of renewability, the fewer land is needed to grow the same amount of material, thereby decreasing costs.

**Chemical additives needed**

Some processes and/or materials that I’ve come up with still might require some kind of additive, catalyst etc. to really make the material suitable for its application and achieve a preferred level of quality. This complicates the process, sometimes decreases the level of sustainability, e.g. in case of petroleum derived chemicals, but I’ve allowed some additives for now since they are either inert to the process or consist of such small amounts that compared to the entire product they for now might be considered negligible.

**Conclusion**

The selected materials should provide possibilities for all parts of the Rebicycle. The selected materials are placed in the functionality analysis to ensure that every part is covered by a material option. If an elementary function or part isn’t provided for by a selected material, materials with lower scores will have to be considered. This holds even more when the project enters the concept phase when more detailed problems are encountered, possibly rendering a choice impossible. But first a more in depth analysis of the selected materials has to be performed. The three materials needing a closer look are wood, because this material is crucial in order to succesfully design a frame and other structural parts, PUR and epoxy, because the exact material production process and necessary equipment is still too vague.
## Suitability Index

<table>
<thead>
<tr>
<th>Material</th>
<th>Durability</th>
<th>Local naturally renewable</th>
<th>Variety in production methods</th>
<th>Wastes usability</th>
<th>Properties suitability</th>
<th>Diversity in application</th>
<th>Growth ability</th>
<th>(Chemical) additives needed</th>
<th>/100</th>
<th>Suitability index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bamboo</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
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<td>0.9</td>
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<td>0.053</td>
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<td>0.4</td>
<td>1</td>
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<table>
<thead>
<tr>
<th>Material</th>
<th>Durability</th>
<th>Recyclability</th>
<th>Variety in production methods</th>
<th>Wastes usability</th>
<th>Properties suitability</th>
<th>Diversity in application</th>
<th>Availability</th>
<th>(Chemical) additives needed</th>
<th>/100</th>
<th>Suitability index</th>
</tr>
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<tbody>
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<td>Glass</td>
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<td>0.3</td>
<td>0.9</td>
<td>0.8</td>
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<td>Paper</td>
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<td>0.5</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
<td>0.9</td>
<td>0.5</td>
<td>0.001</td>
<td>0.099</td>
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<td>Recycled rubber</td>
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<td>0.9</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
<td>0.000</td>
<td>0.048</td>
</tr>
<tr>
<td>Steel</td>
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<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>0.5</td>
<td>0.9</td>
<td>0.5</td>
<td>0.105</td>
<td>10.498</td>
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</tbody>
</table>
I combined mean mechanical property data from the CES database with the list of occurring flora in Friesland [3], thereby limiting the available wood species to 17. These are listed to the right. The data is arranged from top to bottom starting with the species having the highest E-modulus/density ratio which yields the stiffest wood species per unit of weight, which turns out to be the Picea Abies tree, also known as the Norway Spruce (Fijnspar, NL). This species also has the highest Yield Strength/density ratio, and shares the lowest cost per Kg. This leads to the choice of Picea Abies wood as the material to use for the frame fork and similar parts.

It remains questionable whether the data provided by CES is accurate, but an alternative wood species is selected easily.

There are two main problems with wood. Its manufacturability and its weather resistance.

The possibilities for mass production of wood in products are limited. But there are methods of shaping wood. One I found very promising is the shaping of thin sheets of wood with steam and simple moulds. The wood is cured at a certain temperature and its moisture content is raised so the wood becomes malleable to a certain extent. When finished, the wood maintains its strength and form. This technique would allow me to manufacture a hollow frame at relatively low costs. Another technique which has been developed recently is the Plato method [2]. The process cures the wood in two steps: The first step is carried out at a temperature of 150-180 °C with steam, and the second step is carried out at 150-190 °C in dry conditions. This procedure changes wood from normal spruce (Class IV) to hardwood (Class I), improving durability massively. This is partly the answer to weather resistance as well. Of course, the layer of epoxy and/or varnish will protect the wood, but in case of damage, I want the wood to be as durable as possible. After a consult with Plato International B.V., I have to conclude that the Plato technology is not suitable for dynamically loaded applications. The process chemically alters the material, leaving it very brittle. Therefore for structural parts I cannot use Plato wood, however it would remain suitable for fenders and chain protection. The other solution is the Accoya method, where anhydride is used to enhance wood durability. This is probably worse for the environment, on the other hand, if the life cycle of wood is shortened because its durability hasn’t been improved, the ecoburden is estimated to be many times higher. Therefore the choice is the Accoya method to enhance wood durability.
<table>
<thead>
<tr>
<th>Species of wood that grow in the Netherlands</th>
<th>Latin Name</th>
<th>Dutch Name</th>
<th>native</th>
<th>Cost/growth rate EUR/kg</th>
<th>Density Mg/m3</th>
<th>Elastic moduli E GPa</th>
<th>Yield strength MPa</th>
<th>E/density ratio</th>
<th>Strength/density ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce medium density</td>
<td>Picea Abies</td>
<td>Fijnspar</td>
<td>no</td>
<td>1.1</td>
<td>0.51</td>
<td>16</td>
<td>48</td>
<td>31</td>
<td>94</td>
</tr>
<tr>
<td>Fir</td>
<td>Abies procera</td>
<td>Spar/ grenen</td>
<td>no</td>
<td>1.1</td>
<td>0.44</td>
<td>13</td>
<td>40</td>
<td>29</td>
<td>90</td>
</tr>
<tr>
<td>Spruce</td>
<td>Picea Rubens</td>
<td>Zilverspar</td>
<td>no</td>
<td>1.1</td>
<td>0.45</td>
<td>12</td>
<td>40</td>
<td>26</td>
<td>88</td>
</tr>
<tr>
<td>Oak</td>
<td>Quercus spp.</td>
<td>Eik</td>
<td>no</td>
<td>9.2</td>
<td>0.92</td>
<td>23</td>
<td>48</td>
<td>25</td>
<td>52</td>
</tr>
<tr>
<td>Douglas Fir</td>
<td>Pseudotsuga menziesii</td>
<td>Douglas spar</td>
<td>no</td>
<td>1.1</td>
<td>0.54</td>
<td>13</td>
<td>48</td>
<td>24</td>
<td>88</td>
</tr>
<tr>
<td>Birch</td>
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<td>Berk</td>
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<td>0.69</td>
<td>16</td>
<td>53</td>
<td>23</td>
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<tr>
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<td>Lork/Lariks</td>
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<td>1.1</td>
<td>0.58</td>
<td>13</td>
<td>53</td>
<td>22</td>
<td>91</td>
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<tr>
<td>Oak medium density</td>
<td>Quercus falcata</td>
<td>Eik medium dichtheid</td>
<td>yes</td>
<td>2.5</td>
<td>0.77</td>
<td>17</td>
<td>61</td>
<td>22</td>
<td>79</td>
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<tr>
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<td>Wilg</td>
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<td>0.35</td>
<td>8</td>
<td>27</td>
<td>22</td>
<td>77</td>
</tr>
<tr>
<td>Ash</td>
<td>Fraxinus nigra</td>
<td>Es</td>
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<td>2.5</td>
<td>0.55</td>
<td>12</td>
<td>43</td>
<td>21</td>
<td>78</td>
</tr>
<tr>
<td>Pine</td>
<td>Pinus spp.</td>
<td>Den</td>
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<td>0.49</td>
<td>10</td>
<td>41</td>
<td>20</td>
<td>83</td>
</tr>
<tr>
<td>Maple</td>
<td>Acer saccharum</td>
<td>Esdoorn</td>
<td>no</td>
<td>1.8</td>
<td>0.71</td>
<td>14</td>
<td>56</td>
<td>19</td>
<td>78</td>
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<tr>
<td>Cherry</td>
<td>Prunus avium</td>
<td>Kers</td>
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<td>0.61</td>
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<td>50</td>
<td>18</td>
<td>81</td>
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<tr>
<td>Walnut</td>
<td>Juglans regia</td>
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<td>9.2</td>
<td>0.69</td>
<td>13</td>
<td>62</td>
<td>18</td>
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<td>2.5</td>
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<td>65</td>
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<td>11</td>
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<tr>
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<td>n.a.</td>
<td>n.a.</td>
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<td>7.85</td>
<td>210</td>
<td>315</td>
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</table>
Because wood is selected as the material most suitable for constructing the frame, it is important to gain insight in the behaviour of the material when loaded. For now only tensile strength, bending and the weight are considered, later this will have to be elaborated on e.g. compressive strength, fatigue strength. The calculations are based on an assumed cross-sectional dimension of an outer radius (Ru) of 15 mm. and an inner radius (Ri) of 13 mm. The dimensions of the tube cannot be too big because otherwise the user will not be able to put his feet on the pedals. The tensile strength of the tube is calculated to be 55 kN, which is considered more than adequate. This load is used to calculate the dimensions of a wooden tube. The bending is calculated on deflection of a tube with an assumed force of 10 kN. For these calculations the moment of inertia had to be calculated for both cross-sectional areas. The control calculation is the weight of each tube over a length of 1 m. The weight of the wooden part cannot be much higher than the steel part, otherwise the frame and other structural parts will become too heavy.

**Calculations**

If wood is to have the same tensile strength as a steel tube with Ru = 15 mm. and Ri = 13 mm. the dimensions of the wooden tube will be a cross-section with Ru = 30 mm. and Ri = 13 mm. This is not too big for a frame tube, and since 55 kN is a very high load, the dimensions will not have to be this large to cope with tension loads.

**Tensile Strength**

**Steel**

\[
\begin{align*}
R_u &= 15 \text{mm} \cap R_i = 13 \text{mm} \\
\sigma &= \frac{F}{A} \\
\sigma &= E \cdot \varepsilon \\
\sigma &= 315 \text{MPa} \cap E = 215 \text{GPa} \rightarrow \varepsilon = 1.5 \text{mm} \\
A &= \pi R_u^2 - \pi R_i^2 = 176 \text{mm}^2 \rightarrow F = 55 \text{kN}
\end{align*}
\]

**Wood**

\[
\begin{align*}
E(PiceaAbies) &= 16 \text{GPa} \cap \sigma = 48 \text{MPa} \cap \varepsilon = 1.5 \text{mm} \\
\sigma &= E \cdot \varepsilon \rightarrow \sigma = 24 \text{MPa} \ll 48 \text{MPa} \rightarrow A = 2292 \text{mm}^2 \\
p R_u^2 - p R_i^2 &= 2292 \text{mm}^2 \\
if &\rightarrow R_i = 13 \text{mm} \\
R_u &= 30 \text{mm}
\end{align*}
\]
The bending is investigated to get an insight in the deflection of a wooden tube in contrast to a steel tube with the same tension strength. The calculated cross-section from the tension strength calculation is used to compare with the chosen steel cross-section. The deflection of the steel tube under a load of 10 kN is calculated to be 0.9 mm over a tube length of 1 m. The same calculation only then for a thickwalled cross-section for the wooden tube yielded an outcome of 0.27 mm, which is approx. 30% of the deflection of the steel tube. This would mean that a wooden tube with the same tension strength as the steel tube is approx. 3 times stiffer than the steel tube.

These results don’t mean anything unless the weight of the wooden tube is comparable to the weight of the steel tube with the same tension strength. This is an easy calculation using the density of the material and the volumes of the two tubes. The steel tube is calculated to weigh around 1.38 kg. and the wooden tube is calculated to weigh around 1.49 kg. This is an increase in weight of approx. 6.5% which is not desirable nor a disaster. If the frame of the current city bicycle would weigh around 12 kg., the Rebicycle frame would weigh 12.78 kg., which is adequate. The question remains whether the parts that are not loaded along the grain of the wood can have the same strength/volume ratio, but the majority of parts are loaded along the grain, thus the increase of weight is not expected to be high.

### Bending

#### Steel

\[
I_{zz} = I_{yy} = \frac{1}{2} I_p \\
I_p = \frac{1}{2} \pi (2R^2 + \frac{1}{2}t^2) \cdot (2Rt) \\
R = 14 \cap t = 2 \rightarrow I_{zz} = 17.6 \cdot 10^3 \text{mm}^4 \\
w = \frac{T \cdot t^3}{3E \cdot I_{zz}} \\
If \rightarrow F = 10kN \\
w = 0.9\text{mm} \\
\]

#### Wood

\[
Ru = 30\text{mm} \cap Ri = 13\text{mm} \\
I_{zz} = 781 \cdot 10^3 \text{mm}^4 \\
If \rightarrow F = 10kN \\
w = 0.267\text{mm}! \\
\]

### Weight

#### Steel

\[
r = \frac{m}{V} \rightarrow r = 7850kg / m^3 \cap V = 0.000176 \cdot 1 \\
\rightarrow m = 1.38kg \\
\]

#### Wood

\[
r = 510kg / m^3 \cap V = 0.00292 \cdot 1 \\
\rightarrow m = 1.49kg \\
\]
Still the problem remains of the oil derived MDI needed for the production of PUR, but in the future this might be solved by a recent development in PUR manufacturing techniques:

“In a different approach towards polyurethanes fatty acid derivatives were carbonated in supercritical carbon dioxide.[5,6] The resulting cyclic carbonates can be converted to polyurethanes with primary amines avoiding the use of isocyanates (usually phosgene is used for isocyanate synthesis). Recently, such an approach was applied to carbonated soybean oil that was reacted with ethylene diamine, hexamethylenediamine and tris(2-aminoethyl)amine to obtain polyurethane networks with Tg values of approximately 34 °C, 18 °C and 43 °C, respectively.[7]"

This process indicates that there are possibilities to circumvent the use of the oil based MDI’s for the production of PUR and possibly TPU. For now these processes are not available for use in products, but in the future these materials might well be applied in the Rebicycle. Important is the preparation and flexibility of machinery for these processes and materials.

After a consult with Professor Picken of the ChemTech faculty at the TU Delft, I have to change the set up of materials.

The source for natural PUR has shifted from Linseed to Vernonia, because the Linseed oil has to be epoxidised in preparation for the PUR manufacturing process which is not needed for Vernonia because it contains a naturally epoxidised oil. By circumventing the epoxidisation the use of formic acid and hydrogen peroxide is avoided. Also the natural PUR derived from Linseed oil has glass temperature values of around 77 °C, which probably yields a too inelastic plastic for the purpose of the tyres, saddle and handles. This property can for example be influenced by the amount of catalyst, the amount of crosslinkers and the choice for filler material. But since the soya oil fatty acids (oleic acids, fig ??, 1) largely resemble the Vernonia oil fatty acids (vernolic acid, fig ??, 9) the outcome is expected to be closer to the PUR derived from carbonated soya oil with glass temperatures around 34, 18, and 43 °C. Adding a filler to this material has a high probability of being capable to exactly produce a material with the required properties: the glass temperature of natural rubber is around -60 °C. One choice for filler material could very well be recycled cork.

Deriving supercritical CO2 is not as complicated as it sounds. Supercritical CO2 is CO2 under specific conditions where a homogeneous state is achieved. For CO2 this is at around 40 bar and 46 °C, which can be achieved with a simple compressor and abundant heat from the energy production process.
This means that I will need a larger greenhouse, but on the other hand I will not need hydrogen peroxide and formic acid used in the epoxidisation process of Linseed oil and since my preliminary LCA indicates that I will have more energy and heat than I need for the process, this is the better solution.

This means that I no longer need oil flax, and I only have to derive one oil: epoxidised Vernonia Galamensis oil. I can use this oil for epoxy adhesives as well as natural PUR, probably using the same hardener for both e.g. in the form of ethylenediamine, hexamethylenediamine and tris(2-aminooethyl)amine, which are simple substances that should be easy to derive from nature.

The Rebicycle Project

A natural source for the epoxy adhesive has been found in the Middle African plant Vernonia Galamensis. This plant doesn’t grow naturally in Friesland, however it has been proven possible to grow the crop in a greenhouse in the U.S. in the midatlantic region at a temperature of around 20-25 °C with artificial lighting which is considered not a problem because of the amount of energy and heat that can be produced from the wastes.

An epoxy adhesive consists of two components: resin and hardener/curing agent. The resin can be made directly from Vernonia oil because the oil naturally contains epoxidised fatty acids. E.g. Linseed oil needs to receive a treatment of formic acid and hydrogen peroxide. Bio synthesis of the Vernonia fatty acids is possible [1].

A common form of curing agent is ethylenediamine, a chemical which is derived quite easily from its raw materials: ethylenedichloride and ammonia. The resulting substance is ethylenediamine with the by-products of sodiumchloride (salt) and water. Ethylenediamine is liquid at room temperature and has a light ammonia-like odour, therefore if there is a leak it is detected easily. This is necessary because the vapour is lightly toxic and flammable. However because it is expected to be used in small quantities the negative effects of using this substance are considered insignificant, however in the design it has to be taken into account.

In the Rebicycle company the amount of ethylenediamine is too low to justify the investment for the equipment to manufacture the material in-house. Therefore it will have to be bought. The price of ethylenediamine is around 100 USD per liter.

Latest addition: Biosynthesis from biowaste through fermentation yields a feasible way for production of ethylene. The barrier is the economical feasibility, oil prices would have to rise with a factor 5 in order to render biosynthesis economically interesting [9]. This means however that there are ways to produce organic chemicals from biowaste without the need for petroleum.

![Chemical Reaction of Ethylenediamine](image_url)
The process for the production of an epoxy adhesive is simple: put the two components, mix them and apply. The exothermic reaction does cure the mixture. Depending on the curing agent the properties of the adhesive can be influenced.

The production of Vernonia oil and its fatty acids derived from the oil can be performed in-house, but the production of ethylenediamine (or other curing agent) is too complex and economically infeasible because of the small quantities to produce in-house.

The application of the epoxy adhesive and the mixing of components prior to that is very important, because of the potential environmental and health risks, mainly because of the vapours released from the ethylenediamine itself and during the mixing and curing of the components.

The largest part of epoxy adhesive can be derived from natural resources, the Vernonia Galamensis seeds. The curing agent is chosen to be ethylenediamine because this is a common curing agent for PUR as well as epoxy. However if this curing agent doesn’t yield the required properties another curing agent can be selected.

Overall it can be said that the choice for an epoxy adhesive doesn’t yield a 100% sustainable material because of the necessity of the curing agent. This substance is flammable, toxic, irritating etc. though because it is used in small quantities its impact is considered insignificant.

If it turns out the material is very harmful to either the environment or the workers another curing agent might be selected.

For now because of its excellent properties the choice has to be an epoxy adhesive.
A Life Cycle Analysis is the evaluation of all Life Cycle Inventory analyses. A LCI is the mass and energy balance, or the sum of all inputs and outputs.

Goal

This LCA is meant to explore the impact of the proposed materials in this feasibility analysis. I've made preliminary decisions on which parts of a bicycle can be replaced with natural materials and for which parts it is probably (yet) impossible. Some of these parts have a longer life-cycle than the product itself. But most of all it is necessary to have an idea of the impact made by the use of natural materials, especially the end-of-life point, the deletion of transport and the energy production from waste materials.

Scope

Within this LCA the scope is on the Rebicycle, its materials, the production and end-of-life. Normally the end-of-life is not considered in LCA, it handles with input output only. For this project however it is very important to include this product stage, because the project uses the natural cycle to reach a sustainable product.

Functional unit

In order to make a comparison a functional unit is needed with which the amount of ecocosts are estimated. For this LCA a functional unit is chosen of 10,000 Rebicycles. This is the estimated series production numbers for the Rebicycle company.

LCI

Because of limited time in this project I discussed with an expert in the area of life cycle analyses, dr.ir. J.G. Vogtlander, how to best approach the Rebicycle life cycle analysis. We concluded that I have to summarize the ecocosts for the natural materials used excluding the energy and transport inputs and outputs, because we expect that the waste materials would deliver more energy than needed for the process itself, redistributing energy to the grid, instead of using energy from the grid. I could use the Simapro software, which combines in this case the Ecoinvent unit processes and Idemat 2008 database with ecocosts 2007. The resulting ecocosts have no meaning on themselves, at least not in this project, but they serve as a comparative mean to gain insights into what is better. I would prefer a system that determines what is good instead of better (or less bad), but if the sum of ecocosts is negative in total, I for now have to assume that that is good.

So I made life cycle inventories of the materials proposed in the feasibility analysis and for each step in their respective processes I excluded the energy inputs and outputs. I also excluded transport because all material production is to be done locally.

www.ecocostsvalue.com
http://www.rivm.nl/milieuportaal/dossier/lca/
The EcoInvent database in SimaPro uses unit processes and combines them into general processes. In order to exclude energy and transport ecocosts, the origin of those ecocosts have to be found at the basis of each process.

A LCI is made for each of the selected materials from the suitability index matrix. These LCI’s are then combined in the Life Cycle Analysis.

The energy inputs are removed from all steps in the process. This is justified by the assumption that the natural wastes produce more energy than needed in these processes. Since these wastes are derived directly from nature, the only ecocosts that remain are dust and emissions from burning. However it still remains debatable whether these are actual ecocosts since their origin is 100% natural, therefore the emissions have to be equal to the input, only in another form and/or state.

For now the ecocosts of emissions from the burning of natural wastes are not included, because I feel that whenever nature’s cycle is utilized, harm can’t be done to the environment, at least not significantly.

The transport ecocosts are also removed from all steps in the process. This is justified because the natural resources are grown in the direct vicinity of the production company. Hereby all transport ecocosts are removed, from land occupation for roads to the steel and fuel necessary for the transport means.

The result of the ecocost analysis are ecocosts of the material, land occupation of the material, equipment, labour and machinery for processing the material with a separate total of energy and transport requirements.

Hereby only the energy amounts are important to complete the equation and estimate the degree of sustainability of the project.

Of course the real problem of LCA persists because not every input and output is known for each process, and some inputs and outputs are weighed with estimations from experts in their specific field and industry while other inputs and outputs are left out. Therefore no absolute result can be yielded, but a comparison can be made. In this phase I want to make the comparison between the use of natural materials the way they are utilized nowadays and the use of natural materials produced locally combined with energy production from their wastes.

This comparison will provide insights in the degree of improvement in ecocosts for the idea of local production and closing the cycle. It will not provide any insights into the relative improvement on regular bicycles, for which a separate Life Cycle Analysis is needed.

In order to estimate the quantity of ecocosts, the amount of materials used have to be estimated. I made the following assumptions for the required amounts of material per bicycle:

- 10 kg. Softwood
- 3 kg. PUR
- 1 kg. Steel
- 0.5 kg. Epoxy
- 0.5 kg. Flax textile

After the design is finished and the exact inputs and outputs are known the life cycle analysis will be expanded to include land usage. This has to be done to obtain insights in the degree of sustainability of the project as a whole: How much land does it take to produce 1 bicycle over what time span?

Then I will have to make a selection between different methods for assessing the impact, or suggest a system of my own:

The amount of land available in Friesland divided by the total of inhabitants yields the average amount of land per person. These can be divided into segments like urban, agricultural, natural, industrial recreational etc., where the Rebicycle land would be placed in the industrial segment. If this yields 1%, that result would be very promising, if it yields 50%, this means the Rebicycle has used half of the industrial land intended for the consumer. I like the logic of this theory, since it focuses on the most important actor in sustainable development: The government and policy-makers, because it yields indicational data for future development in the region. For example if the Rebicycle is succesful and uses 1% of industrial land available in the region, and together with other industrial products only 98% of industrial land is used, the policy makers could then conclude that 2 % of industrial land has to be shifted to another segment of land use.

Off course a lot of research has to be done to validate this theory and in this project I won’t be able to do that, but I can test it to see what results it would yield.

In order to obtain insights on the relative sustainability improvement of the localized product development method (LPD) the final LCA of the Rebicycle has to be compared to the LCA of the current bicycle design.
The Rebicycle Project

The life cycle of wood is considered from the stage where the trees stand in their plantation to the stage where the wood is sawn into beams and scaved. The exact size of the beams is not known, but they are assumed to have standard sizes. This is not the stage from where the Rebicycle production can start, therefore the computed ecocosts are expected to be lower than in reality. On the other hand, because the processing is done in-house, the sawing can be performed more efficiently because the sizes needed for the Rebicycle can be produced directly.

Another assumption is that all wood waste can be collected and burned in a furnace, though there is a loss to be expected. This loss however is considered insignificant.

Another important thing to consider is that some wood wastes are not suitable for using them in other products, but some are, e.g. sawdust. The value of sawdust and other wastes from the processing of wood could be worth more than fuel for heat and energy at the Rebicycle plant. Since the calculations show that the Rebicycle process could produce more than four times the required energy, some waste materials might have to be sold to other companies in the area.

The ecocosts data as computed with SimaPro are depicted as a linear graph, because the process for the material requires only one resource (trees) and proceeds in steps from there, each adding ecocosts. The added ecocosts for the Rebicycle are significantly lower than the normal ecocosts for wood, because of the removal of energy and transport.
Ecocosts with energy and transport per m³ (€)

Ecocosts Rebicycle without energy and transport per m³ (€)
<table>
<thead>
<tr>
<th>Functional unit</th>
<th>EcoInvent unit process</th>
<th>Ecocosts with energy and transport per m³ (€)</th>
<th>Ecocosts Rebicycle without energy and transport per m³ (€)</th>
<th>Loss/waste (MJ)</th>
<th>Input Amount</th>
<th>Unit</th>
<th>Conversion (MJ)</th>
<th>Transport (tkm)</th>
<th>Transport unit process (€)</th>
<th>Ecocosts transport (€)</th>
<th>Total ecocosts transport (€)</th>
<th>Output MJ</th>
<th>heat, waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>m³</td>
<td>Softwood, standing, under bark, in forest/RER U</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
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<tr>
<td>m³</td>
<td>Round wood, softwood, under bark, u=70% at forest road/RER U</td>
<td>3.25</td>
<td>0.849</td>
<td>0.32</td>
<td>102</td>
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<tr>
<td>m³</td>
<td>Round wood, softwood, debarked, u=70% at forest road/RER U</td>
<td>3.85</td>
<td>0.866</td>
<td>0.02</td>
<td>28.1</td>
<td>MJ Diesel</td>
<td>28.1</td>
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<tr>
<td>m³</td>
<td>Sawn timber, softwood, raw forest, debarked, u=70% at plant</td>
<td>11.8</td>
<td>2.54</td>
<td>0.64</td>
<td>31.4</td>
<td>KWh</td>
<td>282.6</td>
<td>50</td>
<td>Transport, lorry &gt;16t, fleet average/RER U</td>
<td>0.0272</td>
<td>1.36</td>
<td></td>
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</tr>
<tr>
<td>m³</td>
<td>Sawn timber, softwood, raw, air dried, at plant</td>
<td>12.9</td>
<td>2.79</td>
<td>0.1</td>
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<tr>
<td>m³</td>
<td>Sawn timber, softwood, planed, air dried, at plant</td>
<td>19</td>
<td>4.56</td>
<td>0.13</td>
<td>30.8</td>
<td>KWh</td>
<td>277.2</td>
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<tr>
<td>Kg</td>
<td>Ecocosts per Kg Picea Abies</td>
<td>0.0373</td>
<td>0.00894</td>
<td>1.69 kg.</td>
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<td>m³</td>
<td>Wood waste per m³</td>
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<tr>
<td>m³</td>
<td>Plato step 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>m³</td>
<td>Plato step 2</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1 Kg</td>
<td>hout 10-15% geeft 16 MJ warmte energie low heating value x m³ / soortelijk gewicht</td>
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</table>
Common Polyurethane is made from MDI or TDI with a curing agent like ethylenediamine. Also surfactants, blowing agents, catalysts, filler materials etc. are added to control the process and the material properties. Natural Polyurethane to be used for the Rebicycle however is made from the natural polyol Vernonia oil, Supercritical CO2, ring opener, catalyst, surfactants, blowing agent (which is considered to be water) and ethylenediamine.

The ecocosts for common and natural polyurethane are compared to see what influence local production and natural materials have on the ecocosts for the material. A number of assumptions had to be made in order to estimate the ecocosts.

First the Vernonia Oil was not represented in the Ecoinvent database used with Simapro, therefore the data from a similar natural oil were used to calculate the ecocosts. The data for Soya oil were used instead, therefore the ecocosts of building, heating, maintaining and lighting the greenhouse are not included. Heating the greenhouse however is obsolete because a high amount of waste heat is expected. Lighting the greenhouse can be done with electricity from the process, so only building and maintaining the greenhouse should be included to get a more realistic estimation.

Secondly the processing ecocosts are not considered for ethylenediamine. The basic Idemat ecocost score was used, which is justifiable since it is a basic chemical.

Thirdly the ecocosts for supercritical CO2 were estimated using extrapolation of the ecocosts made by compressed air processes, which range from 6-12 bar in the ecoinvent database while 40 bar is necessary.
Appendix C

Ecocosts including energy and transport per kg.

Ecocosts Rebicycle per kg.

- Soya oil, at plant/RER U
- Fatty acids, from vegetarian oil, at plant/RER U
- Polyurethane, rigid foam, at plant/RER U
- Compressed air/CO2, average generation, <30kW, 40 bar gauge, at compressor/RER U (estimation)
- Total

Total Ecocosts including energy and transport per kg.
<table>
<thead>
<tr>
<th>Functional unit Kg</th>
<th>Ecoinvent unit process</th>
<th>Ecocosts Recycle per kg (€)</th>
<th>Loss/waste Kg</th>
<th>Ecocosts (€)</th>
<th>Input Amount</th>
<th>Conversion (KWh) &gt; (MJ) factor</th>
<th>Transport (tkm)</th>
<th>Transport unit process</th>
<th>Ecocosts transport (€)</th>
<th>Total ecocosts transport (€)</th>
<th>Output (MJ) heat/waste heat/waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Soya oil, at plant/RER U</td>
<td>0,48</td>
<td>0,369</td>
<td>0,02</td>
<td>0,64</td>
<td>0,64</td>
<td>1,46</td>
<td>Transport, lorry &gt;16t, fleet average/RER U</td>
<td>0,0272</td>
<td>0,039712</td>
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<td>0,389 Kg.</td>
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<tr>
<td>1 Fatty acids, from vegetarian oil, at plant/RER U</td>
<td>0,534</td>
<td>0,409</td>
<td>0,03</td>
<td>0,11</td>
<td>0,11</td>
<td>0,78</td>
<td>Transport, freight, rail/RER U</td>
<td>0,0084</td>
<td>0,006552</td>
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<tr>
<td>0,386 Kg.</td>
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<tr>
<td>1 Polyurethane, rigid foam, at plant/RER U</td>
<td>0,825</td>
<td>0,3</td>
<td>0,02</td>
<td>0,417</td>
<td>3,753</td>
<td>0,211</td>
<td>Transport, lorry &gt;16t, fleet average/RER U</td>
<td>0,0272</td>
<td>0,0057392</td>
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<tr>
<td>1 m3</td>
<td>0,5681</td>
<td>0,0516</td>
<td>1,026</td>
<td>9,234</td>
<td>3</td>
<td></td>
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<tr>
<td>1 Kg</td>
<td>Total</td>
<td>1,393</td>
<td>0,352</td>
<td>1,540 KWh</td>
<td>14,726 MJ</td>
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</tbody>
</table>
The EcoInvent database doesn’t have a unit process for epoxy adhesives, therefore the unit processes for the components were analyzed. This is possible because for epoxy the formation process is the mixing of the resin with a hardener (curing agent). The reaction is exothermic and depending on the resin and choice of hardener the epoxy hardens either fast or slow. Sometimes a curing temperature is required.

For Vernonia oil the data for soya oil is used, because it is a very similar substance. Here the ecocosts for transport and energy are relatively low, because probably the main ecocosts are caused by land use and the material itself. For the fatty acids derived from vegetarian oil, the data for soya oil were imported into the process of deriving the fatty acids from a single vegetarian oil.

The highest relative ecocosts originate from ethylenediamine, a basic chemical widely used as curing agent. However since it percentage of the epoxy adhesive as a whole is small (10% is assumed) its contribution to the final product is minimal.
Ecocosts including energy and transport per kg. (€)

Ecocosts Rebicycle per kg. (€)

- Soya oil, at plant/RER U
- Fatty acids, from vegetarian oil, at plant/RER U
- Ethylenediamine, at plant/RER U
- Epoxy adhesive at plant RER U
Current process tree Epoxy

Rebicycle process tree Epoxy
<table>
<thead>
<tr>
<th>Functional unit Kg</th>
<th>Ecocosts including energy and transport per kg. (€)</th>
<th>Ecocosts Rebike per kg. (€)</th>
<th>Loss/waste Kg</th>
<th>Ecocosts Ecocosts transport (€)</th>
<th>Total ecocosts (€)</th>
<th>Output (MJ) heat/waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Soya oil, at plant/RER U</td>
<td>0,48</td>
<td>0,369</td>
<td>0,02</td>
<td>0,64</td>
<td>0,64</td>
<td>1,46</td>
</tr>
<tr>
<td></td>
<td>0,35</td>
<td>0,35</td>
<td>0,35</td>
<td>0,072 kWh</td>
<td>0,648</td>
<td>12,1</td>
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<tr>
<td></td>
<td>0,0272</td>
<td>0,0272</td>
<td>0,0272</td>
<td>0,81</td>
<td>Transport, barge/RER U</td>
<td>0,0103</td>
</tr>
<tr>
<td>Total</td>
<td>1,638</td>
<td>0,083</td>
<td>0,26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,9 Kg</td>
<td>1,474</td>
<td>0,083</td>
<td>0,234</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1 Fatty acids, from vegetarian oil, at plant/RER U</td>
<td>0,534</td>
<td>0,409</td>
<td>0,03</td>
<td>0,11</td>
<td>0,11</td>
<td>0,78</td>
</tr>
<tr>
<td></td>
<td>0,48</td>
<td>0,48</td>
<td>0,48</td>
<td>0,025 kWh</td>
<td>0,225</td>
<td>0,225</td>
</tr>
<tr>
<td></td>
<td>0,025</td>
<td>0,025</td>
<td>0,025</td>
<td>0,010088</td>
<td>0,010088</td>
<td>0,010088</td>
</tr>
<tr>
<td>Total</td>
<td>2,855</td>
<td>0,0091</td>
<td>0,081</td>
<td></td>
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</tr>
<tr>
<td>0,9 Kg</td>
<td>2,5695</td>
<td>0,0091</td>
<td>0,081</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Ethylenediamine, at plant/RER</td>
<td>1,15</td>
<td>1,07</td>
<td>2</td>
<td>0,333</td>
<td>0,333</td>
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<td>0,0289616</td>
<td>0,0289616</td>
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<td>Total</td>
<td>4,997</td>
<td>0,0017</td>
<td>1,2</td>
<td></td>
<td></td>
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<tr>
<td>0,1 Kg</td>
<td>0,4997</td>
<td>0,0017</td>
<td>0,12</td>
<td></td>
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<td></td>
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<tr>
<td>3 Epoxy adhesive at plant RER U</td>
<td>0,604</td>
<td>0,475</td>
<td>0,430</td>
<td>0,041</td>
<td>0,041</td>
<td>0,153</td>
</tr>
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</table>

Appendix C
The Ecoinvent database has no information on flax, therefore a similar material is chosen: Jute. Jute can be used as estimation, because it is a similar natural resource used to produce yarn and from that textile. For the Rebicycle flax fibre mats (textile) might be needed for specific reinforcement and connections.

The production of jute is however done in low-wage countries, in this case, India. This means that the amount of labour is much higher than in Western Europe for the same amount of costs. This however does not affect the ecocosts, only it might have to be considered that producing the textile in Friesland will have to be automated more which brings higher ecocosts for equipment and a higher energy consumption, though energy consumption is not relevant since the wastes could produce more than enough.

The ecocosts for growing the fibres is considered equal to the ecocosts in Friesland.

The yarn production consists almost entirely out of transport and energy ecocosts.

These two taken together yield the total ecocosts of yarn per kg.

The weaving of that yarn also consists primarily out of energy and transport ecocosts, which together with the yarn yield the ecocosts for jute textile which thus is considered similar to flax textile.
Jute fibres, rainfed system, at farm/IN U
Yarn production, bast Yarn, jute, at plant/IN U
Weaving, bast fibres/IN U
Textile, jute, at plant/IN U

Ecocosts including energy and transport per kg. (€)
Ecocosts Rebicycle per kg. (€)
Product: Textile, jute, at plant/IN U
Method: Ecocosts 2007 V1.00 / eco-costs 2007
Selected weight: Single score, (euro)
Node weight: Including inputs
Node cut-off: 6.8%

3.4 MJ
Electricity, production mix DE/DE U
0.028

0.0928
1.58 MJ
Electricity, production mix ES/ES U
0.0478

0.0518
1.7 MJ
Electricity, production mix IT/IT U
0.0518

0.0476
1.7 MJ
Electricity, production mix PL/PL U
0.0518

0.371
3.4 MJ
Electricity, production mix UCTE/UCTE U
0.00308

0.00499
43.2 m²
Fertilising, by broadcaster/CH U
0.0113

0.0303

0.00624
0.0136 kg
Lubricating oil, at plant/RER U
0.00342

0.00456

0.0128 kg
Soya oil, at plant/RER U
0.00612

0.0128 kg
Soy beans IP, at farm/CH U
0.00456

0.0196 kg
Diesel, at regional storage/RER U
0.00249

0.0156 kg
Ammonia, steam reforming, liquid, at plant/RER U
0.00624

0.0196 kg
Diesel, at refinery/RER U
0.00343

0.036 kg
Diesel, at refinery/RER U
0.00438

0.0019 kg
Diesel, as N, at regional storehouse/RER U
0.00103

0.0183 kg
Disposal, paper, 0.183 kg
0.0196 kg
Diesel, at refinery/RER U
0.00249

0.0036 kg
Urea, as N, at regional storehouse/RER U
0.00449

0.00612

0.00456

0.00249

0.00249

0.00348

0.00469

0.00438

0.00449

0.00449

0.00624

0.0196 kg
Ammonia, steam reforming, liquid, at plant/RER U
0.00624

0.0196 kg
Ammonia, steam reforming, liquid, at plant/RER U
0.00624
## Appendix C

<table>
<thead>
<tr>
<th>Functional unit</th>
<th>Ecoinvent unit process</th>
<th>Ecocosts including energy and transport per kg. (€)</th>
<th>Ecocosts Recycle per kg. (€)</th>
<th>Loss/waste</th>
<th>Input Amount</th>
<th>Unit</th>
<th>Conversion (KWh) &gt; (MJ) factor 9</th>
<th>Transport (tkm)</th>
<th>Transport unit process</th>
<th>Ecocosts transport (€)</th>
<th>Total ecocosts transport</th>
<th>Output (MJ) heat/waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jute fibres, rainfed system, at farm/IN U</td>
<td>0.179</td>
<td>0.179</td>
<td></td>
<td></td>
<td>2.73 KWh</td>
<td></td>
<td>0.001035</td>
<td>Transport, lorry &gt;16t, fleet</td>
<td>0.0272</td>
<td>2.81384E-05</td>
<td></td>
<td>9.82</td>
</tr>
<tr>
<td>Yarn production, bast fibres/IN U</td>
<td>0.267</td>
<td>0.0111</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25</td>
<td>Transport, lorry &gt;16t, fleet</td>
<td>0.0272</td>
<td>0.0068</td>
<td>9.82</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.82</td>
</tr>
<tr>
<td>Yarn, jute, at plant/IN U</td>
<td>0.536</td>
<td>0.213</td>
<td>0.16</td>
<td>1.026 KWh</td>
<td>9.234</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.68</td>
</tr>
<tr>
<td>Weaving, bast fibres/IN U</td>
<td>0.5681</td>
<td>0.0516</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>2.68</td>
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<tr>
<td>Total</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textile, jute, at plant/IN U</td>
<td>0.627</td>
<td>0.221</td>
<td>0.02</td>
<td>3.756</td>
<td>33.804</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>
The life cycle of steel is not considered as thoroughly as the natural materials, because steel is not considered feasible for in-house production because of the high energy and heat requirements for collecting, melting, cleaning, and processing scrap steel. The amount of equipment therefore is considered too high to produce steel parts at the Rebicycle company. However, since probably the axle diameter is increased in relation to the current city bicycle for which the bearings have been calculated to last around 28 years, the recycling factor is estimated to be 10. This means that, at the end of life of one Rebicycle, the bearings could be directly reused and repeated up to ten times. Thus, the ecocosts of steel are considered to be 1/10 of the original ecocosts. Thus for now the ecocosts for the material have been taken directly from Idemat 2008 and combined with the EcoInvent process of average metal working. The outcomes, because of the recycling, simply have been divided by 10 as an estimate.
Appendix C

Ecocosts with energy and transport per kg. (€)

Ecocosts Rebicycle divided by 10 because of recycling per kg. (€)

<table>
<thead>
<tr>
<th></th>
<th>Ecocosts with energy and transport per kg. (€)</th>
<th>Ecocosts Rebicycle divided by 10 because of recycling per kg. (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idemat2008 30CrNiMo8</td>
<td>1.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Steel product manufacturing, average metal working/RER U</td>
<td>0.5</td>
<td>0.005</td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Total Ecocosts: €2.10

Rebicycle Ecocosts: €0.06
## Appendix C

### Ecocosts

With Rebicycle divided by 10 because of recycling per kg.

<table>
<thead>
<tr>
<th>Functional unit</th>
<th>Ecocosts with energy and transport per kg.</th>
<th>Ecocosts Rebicycle divided by 10 because of recycling per kg.</th>
<th>Loss/waste</th>
<th>Input</th>
<th>Conversion to KWh (KWh)</th>
<th>Transport (tkm)</th>
<th>Output (MJ) heat/waste</th>
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</thead>
<tbody>
<tr>
<td>1Kg Idemat2008 30CrNiMo8</td>
<td>1,92</td>
<td>0,192</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>1Kg Steel product manufacturing, average metal working/RER U</td>
<td>0,441</td>
<td>0,0441</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
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<td><strong>Total</strong></td>
<td><strong>2,361</strong></td>
<td><strong>0,2361</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MJ : KWh = 8,14 : 1 (Electricity, oil, at power plant/NL U)
The Rebicycle Project

All LCI’s were put together in order to get an overview of the contribution of each material and especially the effects of removing transport and energy from the process. The ecocosts portrayed are calculated with a functional unit of 10,000 Rebicycles per year.

First, the results indicate an overall saving on ecocosts of approximately 75%, due to the removal of transport and energy ecocosts. This is too high a percentage because of assumptions that had to have been made and lack of data. However it can be concluded that there will be a significant reduction in ecocosts when removing transport and energy from the system. Moreover, the ecocost reduction compared to the current city bicycle design can become something in the order of 75% reduction of the 10% which is left after 90% reduction caused by the use of natural materials, instead of steel, rubber, etc. I for now have no insight into the exact percentages, but the expectation is that there will be a huge reduction in ecocosts, especially because here transport and energy can also be excluded. This comparison will be made after the design is finished, because then detailed information is available. This means that the Rebicycle concept is going in the right direction, though the goal of 100% sustainability is not yet reached. However, in Life Cycle Analysis theory, the produced energy from the process could be interpreted as negative ecocosts, reducing the total of ecocosts generated by the Rebicycle. This is however for a later stage in the process, when more detailed input output data has become available through the design of the Rebicycle.

The largest negative contribution to the ecocosts of the Rebicycle is made by the polyurethane (more than 50%), then steel, epoxy, flax and wood. Especially wood has an ecocost which is close to zero while it is the main material used to produce the Rebicycle. The negative contribution of PUR and epoxy is mainly caused by the curing agent ethylenediamine.

This confirms the hypothesis that the use of local naturally renewable materials is more sustainable. Whether it is 100% sustainable remains questionable because of lack of data and comparative means, but the indications are that there is an estimated improvement of 75%, which is considered to be quite good, especially if the comparison is made between the Rebicycle and the current city bicycle design.

The Life Cycle Analysis of the current city bicycle design will have to be made to obtain insights into the level of sustainability of the entire project, which will be made at the end of the detailing phase because then all materials and their quantities are known.

Conclusion

Life Cycle Analysis
1. Business Strategy
This is big picture thinking that encompasses the most important questions for any corporation: cash flow, product creation and distribution, and overall operations. Marketing strategy and tactical strategy fall out of overall business strategy and support the overall business needs. To make a bold generalization: this is the area that designers often impact the most, with the least desire of input by the business principals. After all, we have BFAs, not MBAs.

2. Overall Marketing Strategy
Based on our business needs, what actions should we take in the market to better sell our products or services? This is an aggregate view of tactics that can be taken concerning long-term brand equity and value as well as short-term sales gains. Most designers want to own this space, as they can predict and control each project that they engage.

3. Tactical Marketing Strategy
What is the approach that governs each individual interaction that we need to take, and in what channel(s)? This is where we get to do the tangible design work, and reap the rewards of implementing a project properly.

For the business strategy the goals are set by the formulation of the assignment and the general idea of the project: using local natural resources and delete transport necessity in order to internalize the value chain.
and minimize ecocosts for which in the future more and more must be paid, justifying increased production and labour costs, eventually leading to an oil independent regional economy. Hereby the negative aspects of globalization, besides ignoring ecocosts, exploitation of non-western population and standardizing of products for a global market, are solved. Other problems that follow from capitalistic globalization are also expected to be solved [8]:

- Food security for North and South
- Packaging reduction
- Social contact and production transparancy
- Less consumption has besides environmental benefits also mental health benefits
- Natural cycles are closed more easily (naturally)
- Increased biodiversity
- More attractive landscape
- Physical health is improved
- Regional economy is stimulated, creating more jobs and utilities
- Diminished dependence on multinationals, politically as well as personally
- Less sensitivity to global market fluctuations
- Decreased chance for conflicts over resources.
- More effective usage of funding.

The chosen overall marketing strategy for meeting the business goals, which is also the tactical strategy in the case of the Rebicycle, is a bicycle made with local natural materials only. With this product, which already is considered quite sustainable, a showcase is created to generate awareness among consumers about the possibilities for sustainable product design whilst still providing desired functionality and quality.

The three scenarios depicted combined with the goal of the project, lead to the conclusion that the third scenario serves as the best base for the strategy because of several reasons:

- The required R&D is high for developing the internal power plant and the development of a new economy, which should mean an accelerated development of sustainability. After the installation is developed, it can be copied to other areas with similar natural resources, just as the development of the micro power plant intended for home usage.

- Since it is a showcase, exposure is very important, therefore location near urbanized areas is recommendable

- It brings diversity and nature closer to the city, instead of farther away

- The decreased efficiency might be less with a micro power plant, but this can be compensated with the diminished loss of heat energy (facility heating and greenhouse)

- The amount of transport is very low

- The challenge is to bring the natural resources to the company near the city, but this might have advantages as well, e.g. recreational benefits. Though a plantation generally is dull, the way it is planted might solve that.

- Because it is situated next to the city, the home-work travelling is minimized and service is easily provided

Every year about 1.32 million new bicycles are sold in The Netherlands (2006) This number is growing, since in the first half of 2007 it relatively increased by 10% and seen from 2005 to 2006 there was an increase of 7 %.

The average price of a Dutch bicycle is around €600. Total annual turnover = €770.000.000.

BOVAG expects electric bicycle sales to be around 150.000 at an average price of €1800. (!)

Approximately 594.000 second-hand bicycles are sold every year (2006)

“It is a very conservative market, but there are numerous possibilities for innovation. “
I now know that there are indications that the Rebicycle company would produce two products: Energy (electricity and heat) and bicycles. Though the company would produce theoretically more than four times the energy needed in their production process, the largest part of their turnover comes from the increased added value to the materials in the form of bicycles. Therefore it is for now pleasant to have abundant energy, assuming that a factor 4 error is adequate. Hence the Rebicycle production is hardly complete since there are many factors to consider. Therefore the energy consumption by the Rebicycle production is not completely accounted for but an important part of it is. In order to get a feel for the overview of the project, I create three different scenarios to concentrate on one regional strategy for the company derived from these scenarios. I do this to obtain a clearer focus in the project.

Scenarios

In order to get a feel for the overview of the project, I create three different scenarios to concentrate on one regional strategy for the company derived from these scenarios. I do this to obtain a clearer focus in the project.

Scenario 1

The Rebicycle company is located near an existing power plant running on bio waste from the Rebicycle process. Excess heat from the power plant is reused in the Rebicycle process and facilities. This way the investment total is decreased with the installation or erection of a new power plant and a higher conversion efficiency can be achieved. On the side of funding and subsidies this approach is highly acceptable since the risks are shared with other companies which nowadays is a requirement if one wants to obtain funding. Socially this approach creates job opportunities in a region where it is needed. However the location inhibits the concept to be noticed by the larger public, therefore a duplicate factory in an urbanised region will be needed quite rapidly in order to fulfill the goal of a showcase. Economically, there will be a slight increase on the short term, but on the long term development will not be that fast since the power plant and the Rebicycle company already cooperate closely, leaving few opportunities for other companies to start there as well.

Context Scenario 1
Location at resources and near medium sized bio waste power plant

This approach requires a medium investment because Rebicycle does not own the power plant, but the costs are higher for the transport to and from the power plant as well as the urbanised areas. The power plant is a newly built separate installation for which also investment is needed. Furthermore it will have become less efficient to transport the excess heat from the power plant to the Rebicycle company. There are benefits in that the natural resources can be grown next to the company, and the consumers are more likely to reach the company. The Rebicycle company provides a higher density in jobs relative to traditional agricultural companies, which eventually leads to de-urbanization of the nearby urban areas. The exposure of the concept will be moderate. The positioning of the company allows the resource area to be connected to nature areas leading to increased living space for animal life and recreation. It also allows them to harvest trees from other areas such as road side plantations or urban recreational park plantations, reducing the amount of agricultural land occupied by the company.

The short term economic benefits are moderate, but the long term benefits will be higher since clustering would occur. The power plant will have spare capacity which can be used for the procreation of companies using the Rebicycle concept as an example, eventually leading to an oil independent industrial area, with low transport necessity.

Location near resources with internal micro sized bio waste power plant

This approach requires the highest amount of investment, since all has to be realized within the company. The transport costs to the consumer is insignificant, but the transport of resources is increased. The power plant is a miniature adjusted to the needs of the Rebicycle company, which produces energy for the surrounding area. The company provides high density in jobs relative to traditional agriculture, aided by the increased value per unit of natural resource produced. Because it is situated near urban areas the exposure of the concept will be high. The positioning of the company allows local sale of the products, but the natural resources have to be transported over a (short) distance. Here also the use of road side plantation and urban recreational park plantation could be implemented.

The company would become completely stand-alone, providing urban areas situated next to the company with electricity (and heat). It could become a blue print for other production facilities, but it would not lead to highly localized clustering. This would inhibit some efficiency improvements, but on the other hand would lead to more efficient spreading of industry throughout the region, because companies can choose where they are best located based on other arguments than traditional arguments, achieving a more widely spread clustering confined to a specific region.
Now that the basic concepts have been reduced to three, it is time to start generating ideas. This will be done in six design problem areas defined to maintain the overview of the complete design problem: facilitating human powered transportation over a distance of max. 20 km. in urban as well as rural areas.

These design problem areas (Subproblem areas) are divided as follows: Construction, Actuating, Wheels, Brakes, Suspension and Bearings.

Even though it is probable that I will have to use steel bearings of the shelf, I still want to investigate the possibilities of natural materials to keep an open mind.

To select the ideas with the highest potential the ideas were compared in a Harris profile on the General Requirements. The most important four criteria are discussed for each subproblem area, providing arguments for the selection. Only those ideas were selected that scored positive on each of the first four criteria and that were promising on the rest of the criteria.

On this basis ideas nr. 1 & 2 were selected, however one exception was made: A combination of ideas 3 & 5 would also meet the criteria, therefore idea 3 with direct drive is also selected.

1) A double triangle structure which makes it very efficient, this offers advantages on material use. Rider position offers a good overview. Very efficient, though aerodynamically not optimal. Efficient material use, therefore more bicycles can be produced with same amount of plantation. 2) Slightly complicated structure to be expected, especially the head tube. Middle rider position, thus limited overview in traffic. Aerodynamics are quite good. Though a slight increase in material use, still considered affordable.

3) Difficult structure, though not impossible to construct from wood, because of the compact structure. A low rider position is not considered safe. A 33% increased in rolling resistance and wheel bearing resistance is very high. Because of the complicated structure and inefficient material use the price is likely higher.

4) Very long construction, therefore inefficient material use. Very low rider position is considered unsafe. Highly efficient in usage because of excellent aerodynamics. A slightly inefficient structure but still considered affordable.

5) Difficult construction around the head tube, though reasonable efficiency in material use. The front tyre needs to be large for speed, but then the forward sight is limited which is not safe. Direct drive and two wheels create high efficiency. A reasonably efficient construction and no drive system make this idea very affordable.

6) This is on of the easiest and most efficient constructions thus well made from natural materials. However, riding head first with limited view is highly unsafe. Direct drive is very efficient. Simplicity makes this an affordable option.

7) Funny idea, but it will be very hard to get it to work well. A dynamic frame is not considered very safe. Adaptation of the rider position to type of use has potential for efficiency. The complicated structure will increase the price.
Subproblem solutions

Appendix E
1) Made easily with natural materials, however the connection between the balls and thread might be problematic. This system is very safe, also because of the possibility of reverse motion. Friction and strain are higher than with a steel chain, but not too much. Gear wheel shape and chain assembly render it cheap nor expensive. 
2) Only natural PUR can be used besides leather, but these are both highly suitable. High safety is expected with this system, also because of the possibility of reverse motion. The efficiency of the drive belt on bicycles has been proven adequate. 

3) Wear is an issue for the natural materials here. The toothed gear wheels will need a cover, otherwise safety is compromised. Can be efficient, however with natural materials that is more difficult. Shaping all gear wheels renders this system expensive.

4) It is possible to make this out of natural materials. No reverse motion is possible, therefore safety might be compromised. It needs very few parts, therefore likely to be affordable.

5) Wear and a complicated construction makes it difficult to make from natural materials. Because it can be completely enclosed, it is very safe and reliable. The system can be quite efficient, though less than a chain or drive belt. Because of the complicated construction it will be quite expensive.

6) This is a very easy system to make with natural materials. No reverse motion is possible, therefore safety might be compromised. Because it is a static part, it is highly efficient. It needs very few parts, therefore likely to be affordable.
Subproblem solutions
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>6)</td>
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</tbody>
</table>

### Natural Materials
- Highly efficient, though the reliability of the material might be an issue.
- Load distribution is optimal, therefore well suitable for natural materials, only the production of the textile will be quite elaborate.
- Easy damage to the textile renders this option unsafe.
- The production of the textile will make this option more expensive.

### Safety
- Very efficient, with only the amount of labour high.
- Very efficient, with only the amount of labour high.
- Very efficient, with only the amount of labour high.
- Very efficient, with only the amount of labour high.
- Very efficient, with only the amount of labour high.
- Very efficient, with only the amount of labour high.

### Efficiency
- Highly efficient, though the reliability of the material might be an issue.
- Load distribution is optimal, therefore well suitable for natural materials, only the production of the textile will be quite elaborate.
- Easy damage to the textile renders this option unsafe.
- The production of the textile will make this option more expensive.

### Affordable
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.

### Comfortable
- Despite the lightweight construction, it is likely to be damaged during assembly.
- Despite the lightweight construction, it is likely to be damaged during assembly.
- Despite the lightweight construction, it is likely to be damaged during assembly.
- Despite the lightweight construction, it is likely to be damaged during assembly.
- Despite the lightweight construction, it is likely to be damaged during assembly.
- Despite the lightweight construction, it is likely to be damaged during assembly.

### Durable
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.
- Only the amount of labour is high, very efficient, this is quite affordable.

### Fit life style
- Very efficient, this is quite affordable.
- Very efficient, this is quite affordable.
- Very efficient, this is quite affordable.
- Very efficient, this is quite affordable.
- Very efficient, this is quite affordable.
- Very efficient, this is quite affordable.

### Eye catcher
- This is a much more elaborate solution, though the material is likely to be damaged during assembly.
- This is a much more elaborate solution, though the material is likely to be damaged during assembly.
- This is a much more elaborate solution, though the material is likely to be damaged during assembly.
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- This is a much more elaborate solution, though the material is likely to be damaged during assembly.

### Customizable
- The material use is high, this is quite affordable.
- The material use is high, this is quite affordable.
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- The material use is high, this is quite affordable.
- The material use is high, this is quite affordable.

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**Subproblem area: Wheels**

1. This is the best option to make with natural materials. It has high reliability and is quite affordable. However, the material use is high, which makes it less efficient.
2. The only problem here is the connections of the parts, which are brittle. There are many small parts and connections, which make this an expensive option.
3. This is a much more elaborate solution than the 2nd solution. It makes it difficult to construct with natural materials. The production of the textile will make this option more expensive.
4. This is the most direct option for natural materials. However, it can be very efficient due to the ideal shape of the spokes. The material use is high, which makes this an expensive option.
5. This is the most direct option for natural materials. However, it can be very efficient due to the ideal shape of the spokes. The material use is high, which makes this an expensive option.
6. Load distribution is optimal, therefore well suitable for natural materials, only the production of the textile will be quite elaborate.
Subproblem solutions

1. Solid wood
2. Laminated wood
3. Rope
4. Laminated wood
5. Laminated wood
6. Textile
Subproblem area: Braking

1) It’s a very simple system which is easily made with natural materials. Reasonably safe, only wet circumstances may result in longer braking distances. Because the axle is used as braking surface, a high braking force is needed even though more than 3/4 of the total surface can be used. Because of its simplicity it is likely to be affordable.

2) This is the most common braking system, reasonably suitable for natural materials. High reliability and relatively low braking forces needed render this system very safe. The further the brakes are positioned from the axle, the more efficient. Efficient material use though slightly complicated system makes it reasonably affordable.

3) Very easy to make with natural materials because of simplicity. Very unreliable in wet circumstances, which makes it unsafe. Braking on the tyres is not highly efficient. The system on itself is very affordable, but the increased wear on the tyres redeems part of that.

4) This system is very difficult to construct with natural materials because of the disc and clamping mechanism materials. It is a highly reliable and safe system originating from motorized vehicles which operate at high speeds. Very efficient system, because of heat transfer and high braking power with little force. Hydraulics, materials and construction render this system very expensive.

5) Easily constructed with natural materials because of simplicity of the system, though the high requirements of the materials due to high braking forces might be problematic. These high forces necessary to achieve the required braking distance render the system less safe. Efficiency is low because the axle is used as braking surface. Because of the high material requirements the system is expected to be quite expensive.
Subproblem solutions

1. Axle
2. Tyre
3. Snow brake
4. Disc
5. Brake
Subproblem area: Suspension

1) Natural materials are highly suitable in this application. Only material failure could result in unsafe situations, but wood has a high fatigue strength. (e.g. Snowboards) If suspension is applied to the seat pin only and the frame remains stiff, there is no loss in efficiency expected. Integrating many parts into two makes this very affordable.

2) Natural materials are highly suitable in this application. Steering suspension is unlikely to lead to unsafe situations. Steering suspension will not compromise efficiency. Efficient material use renders this option quite affordable, though slightly complicated manufacturing is needed.

3) This is quite difficult to make with natural materials, because the torsional stiffness of the frame is compromised. This will result in a wobbly unsafe feeling and in high loading might lead to insafe situations. This will also lead to a decreased efficiency of the force transfer from the user. The flexibility has to be adjustable to the user, which makes this an expensive option.

4) The only problem here are the connections of the parts of the wheel, because it is a radial construction so if this wheel is driven, there will be extreme stresses on those connections on the hub. Because it is flexible, failure of the material is unlikely, but not impossible. The flexibility of the wheel is bound to decrease the efficiency. The complicated construction isn’t cheap, but there aren’t that many different parts, therefore it remains likely to be affordable.
Subproblem solutions

1. PUR foam
   LAMINATED WOOD

2.

3. LAMINATED WOOD

4. LAMINATED WOOD
1) A ball bearing is not feasible with natural materials, because of the extreme requirements for the material: Hardness and wear resistance. Only steel alloys are commonly used because the material properties are highly suitable. Because of the low chance of failure and the low impact of failure this bearing is very safe. This type of bearing is highly efficient because the only contact surfaces are points due to the spherical shape of the balls. Because bearings are commodities, they are quite affordable.

2) Solid bearings don’t distribute the load therefore natural materials are not suitable, because they are not very wear resistant. The construction doesn’t allow complete failure even when the bearings are worn, therefore it is considered safe. Because the load isn’t distributed evenly, it is likely to be less efficient. Because it is such a simple system it is likely to be affordable.

3) This type might be suitable for natural materials, because the load is distributed over more material, therefore decreasing the specific load and wear. The only safety issue would be unexpected failure due to temperature or wear which is unlikely if lubricated well, therefore still considered safe. Due to material and production costs this system will be less affordable.

Because all three types of bearings could be used in combination with the other solutions to the subproblems, they are not taken into account in the next step of combining the subsolutions into complete ideas. In the concept phase the idea of the hardwood rod bearing will have to be investigated further, not only to reach the goal of 100% sustainability, but also because it will become one of the key features in communicating the approach to sustainability in this project.
Subproblem solutions

1

2

3

Solid Bearing

Appendix E
The upright position provides overview within the city and reasonable comfort for longer trips. Small turning radius is desirable. The appearance is highly recognizable, but hard to distinguish from regular bicycles. It is hardly a crossover, there is only the resemblance with the city bicycle. The wood is only utilized in the saddle suspension. Production can be highly efficient, because circular cross section for the frame is possible.

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The semi upright position might provide enough overview within the city as well as improved aerodynamics in longer trips. Large turning radius is undesirable. Though different it remains recognizable as a bicycle, but clearly distinguishable. It is hardly a crossover design in the desired direction. The wood is only used in saddle suspension. This shape requires much material, thus production is less efficient.

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### Comparison Table

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1. Suitable
2. Familiar
3. Distinguishable
4. Crossover
5. Utilize properties
6. Efficient production
The semi upright position might provide enough overview within the city as well as improved aerodynamics in longer trips. The shape and construction are highly different from regular bicycles, therefore this idea is distinguishable. This is hardly a crossover in the desired direction. The wood is only used in saddle suspension. Steering transfer and shape require many parts and much material, therefore production is highly inefficient.

#### Table

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The upright position provides overview within the city and reasonable comfort for longer trips. Small turning radius is desirable. The appearance is highly recognizable, but harder to distinguish from regular bicycles. It is hardly a crossover, there is only the resemblance with the city bicycle. The wood is utilized in the saddle suspension and front wheel suspension. Production can be efficient, but two different wheels and the suspended wheel complicate production.

The upright position provides overview within the city and reasonable comfort for longer trips. Small turning radius is desirable. The appearance is highly recognizable, but harder to distinguish from regular bicycles. It is hardly a crossover, there is only the resemblance with the city bicycle. The wood is utilized in the saddle suspension and front wheel suspension. Production can be efficient, but two different wheels and the suspended wheel complicate production.
The high semi-upright position provides overview as well as aerodynamic advantages. The small turning radius is desirable.

The shape and construction is hardly recognizable, but distinguishable from the regular bicycle.

The crossover is very far from this idea.

The straight frame shape as well as saddle and wheel suspension make good use of material properties.

Production is highly complicated due to difficult structure and diversity in parts.

The upright position provides overview within the city and reasonable comfort for longer trips. Small turning radius is desirable.

The appearance is highly recognizable, but hard to distinguish from regular bicycles.

It is hardly a crossover, there is only the resemblance with the city bicycle.

Saddle and steering suspension is aptly used.

Similarity in parts and material use result in efficient production.
The upright position provides overview within the city and reasonable comfort for longer trips. Small turning radius is desirable. The appearance is highly recognizable, but hard to distinguish from regular bicycles. It is hardly a crossover, there is only the resemblance with the city bicycle. Saddle and steering suspension is aptly used. Similarity in parts and material use result in efficient production.

Low rider position results in too low overview within the city. There are no similarities with a regular bicycle, but therefore highly distinguishable. This is not a crossover in the desired direction. Properties of the natural materials are minimally utilized. The loads are not distributed ideally, therefore material use has to be very high resulting in inefficient production.

The semi upright position might provide enough overview within the city as well as improved aerodynamics in longer trips. Large turning radius is undesirable within the city. Large turning radius is undesirable. Though different it remains recognizable as a bicycle, but clearly distinguishable. It is hardly a crossover design in the desired direction. Wood properties are utilized in saddle and steering suspension. This shape requires much material, thus production is less efficient.
The width of this idea restricts movements within the city. This is hardly recognizable, but therefore distinguishable from regular bicycles. This is not a crossover in the desired direction. The properties of wood are utilized in the direct drive. Material use is highly inefficient.

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THE PURSUIT OF A 100% SUSTAINABLE CONSUMER PRODUCT.
The Rebicycle case
A.E. Scheepens - Student Industrial Design Engineering - Design for Sustainability