Into Niaga's future:

Developing the decision-making tool towards
redesigning more circular products by using Niaga adhesive

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Tesla Minor, July 2018

Image retrieved from: https://www.happycactus.nl/klanten/niaga/

Executive summary

Niaga aims to redesign more products to facilitate recycling and remanufacturing. They developed a reversible adhesive (glue) that can 'un-stick', which enables disassembly of the product after use. After disassembly, the product can be remade into the same product, making it circular: there is almost no more need for raw materials in the production chain. Niaga already made a fully recyclable carpet, but are now investigating redesigning other products.

We designed a **decision tree** to help Niaga select products to redesign in a circular way. This tool can determine, in **less than 5 minutes**, which products are feasible and prioritize them on environmental impact and practical feasibility. This decision tree was **tailored to Niaga's needs**, current objectives and capacities.

We recommend Niaga to:

1. **Use our decision tree for a quick feasibility scan of any product idea which comes up.**
2. **Update the decision tree regularly as Niaga's situation develops.**

Through our process of investigating the Niaga adhesive and developing our decision tree we would also advise Niaga to:

3. **Estimate technical feasibility before considering other factors (e.g. environmental impact of a product's redesign).**
4. **Prioritize products that cannot be thrown away in household trash.**

We took the decision tool for a **test** run on **more than 60 products**, and share our **top 4** recommended products to Niaga, which scored high on all the important requirements for Niaga, including but not limited to technical feasibility, recyclability, bulkiness, and possibility to collect separately. Particularly, we recommend that Niaga should:

5. **Look into furniture containing polyurethane foam as their next project.**

This report contains details on how we arrived at the final selection criteria found in the issue tree, and on the elimination process we undertook to arrive at our final recommendation.

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Introduction

Making products using adhesives hinders their downstream recycling or remanufacturing. Most adhesives used in products are permanent and thus combine two materials irreversibly. Because of this, materials cannot be separated at the end of a product's life and end up together as whole products in landfills or being incinerated. This is a significant problem in the world today, given that adhesives (glues) are made to be permanent in such a way and that the **adhesive industry keeps on growing**, with an estimated 105 billion dollars of profit predicted for 2020.[1]

In 2014, Niaga developed a unique thermoplastic adhesive that can be easily decoupled by applying a specific temperature or vibration of a certain wavelength. Outside of these specific conditions, this adhesive is as strong as comparable commercial adhesives[2]. Because of its properties, Niaga adhesive can replace other hot melts but also most other types of adhesives including the most common waterborne ones[3], solvent-based[4], and others (e.g. PMDI – Polymeric Methyl Diphenyl Diisocyanate, cross links; see more on adhesives and Niaga's alternative in Appendix 1.2. On Adhesives and Niaga adhesive properties)[5]. By developing this technology, Niaga broke away from the traditional mindset that adhesive quality is defined by tenacious irreversible bonds. **Niaga's adhesive rather offers a step towards the transition to a circular economy** (see appendix 1.1). With Niaga's reversible adhesive, the materials from used products can be separated and thus completely recovered to be reused in manufacturing. Instead of ending up in landfills or being incinerated, the same product can be made again and again from its own waste.

This opened a new angle of approach in designing the growing number of products containing adhesives (see Figure 1). Niaga has developed a circular carpet and its associated production technology[6]. Redesigning carpet is an impactful choice, as this product is one of the biggest single contributors to landfills worldwide[7].

Yet, **Niaga is not just a carpet company**. It is in the innovation business. And it is now looking for more products to redesign with Niaga adhesives and according to Niaga philosophy. But which products should Niaga explore next? We assisted the Niaga scientists in their process of finding new products to redesign.

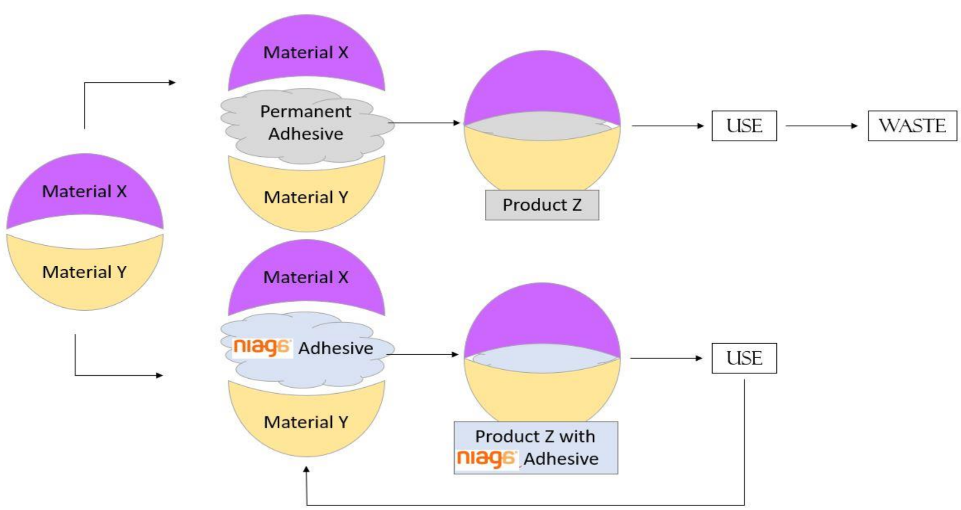

Figure 1: Recycling routes for the Niaga adhesive versus a permanent adhesive*. With a permanent adhesive, two materials are combined irreversibly. This often makes remanufacturing impossible and the product ends up as waste after use. With the Niaga adhesive, the materials are connected in a reversible way. The materials and the adhesive can be decoupled and collected after use and remanufactured into the same product.*

We conducted a series of analyses to find which products they should prioritize and why.

The research question was framed as following:

What is a currently environmentally harmful and an **unrecyclable product** in Europe which can be redesigned in a circular way, using Niaga adhesive to bind the materials, which **will have a large** social, environmental, financial, and practical **impact** in the world?

Our answer is delivered in two parts:

1. We created a **decision tree**, with questions and requirements for Niaga to use, to select potential new Niaga products and to establish a hierarchy of priority among viable options.

2. We proposed a **recommended product** for Niaga to redesign with high priority using their reversible adhesive, along with several other promising and feasible options.

Method

To reach our goals, we did the following:

Read **101 scientific papers and online papers,** including reviews in chemistry on adhesives, academic life cycle assessments, analyses of production processes (e.g. costs, operations, output), highlighting the state of (toxic) waste worldwide, how to implement a circular economy from diverse perspectives, and the current markets of different products.

Conducted **11 interviews with experts**, to dive in specifics on manufacturing processes, corporate objectives and mentality, scientific adhesive innovations, and global impact metric-calculations.

Thoroughly explored **1 European meta database** of the production value and quantity of **3900+ products** produced and imported on European soil.[8]

Attended **1 material science event** (Material Xperience 2018, March 13) presenting the latest trends in material science and the current leanings of the construction industry.

General Approach

Figure 2 illustrates how we structured our project. In order, we conducted full environmental, technical feasibility, and societal impact analyses.

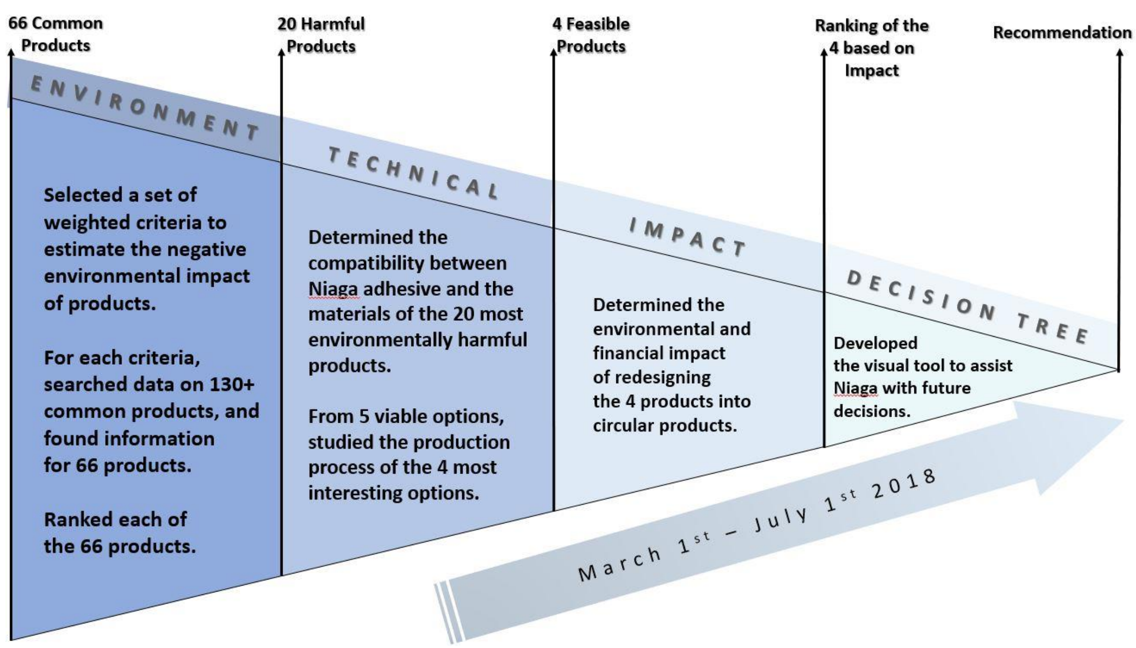

Figure 2: Our approach in four steps, with outputs and timeline.

The project lasted 5 months and was divided into 4 stages. We started with a list of 66 common products, which got shorter entering every new stage. Based on the insights in this process, the decision tree was designed.

Results

1. The Decision Tree

When a new product opportunity presents itself to Niaga, it is important to determine right away if it is a good idea or not. This decision tree enables Niaga to do so, in **less than 5 minutes**, with no additional research necessary on the product nor its manufacturing process. It is assumed that the decision tree will be used by scientists and specialists who have basic knowledge of what materials the products are made of and how much the product and its components are worth at retail value.

This tool provides a quick feasibility scan of **whether Niaga can and should redesign a product** using its adhesive and according to its philosophy.[9] It is the result of a collaboration with experts in the field of sustainable development and materials and of extensive research into products' environmental and societal impact, as well as manufacturing process (see the in-depth explanation of the decision tree's development in Appendix 2. **In-depth information about the decision tree**).

All elements of the decision tree are informative to Niaga's specific current situation. Because with the effort and care involved in redesigning each of its products, it is necessary that Niaga maximizes its positive impact on the environment. It is also important that a Niaga redesign involves financial gain, for example in using recycled rather than virgin products and ideally draws in positive attention from outside (e.g. manufacturers, NGOs, public). First and foremost, Niaga needs to make sure any starting project is technically compatible with Niaga adhesive's properties and cost.

The decision tree starts with:

- a 1st Phase of **fundamental criteria**

A potential product idea needs to meet them all to remain in contention.

- a 2nd Phase consisting of a **point-system**

Products are attributed points depending on the ease of collecting the product after use, and the environmental and financial impact the product currently has on the world, to establish a priority hierarchy among potential products.

The decision-making tree is depicted in Figure 4 (next page). The color-coded version of the decision tree can be found in Figure 4.

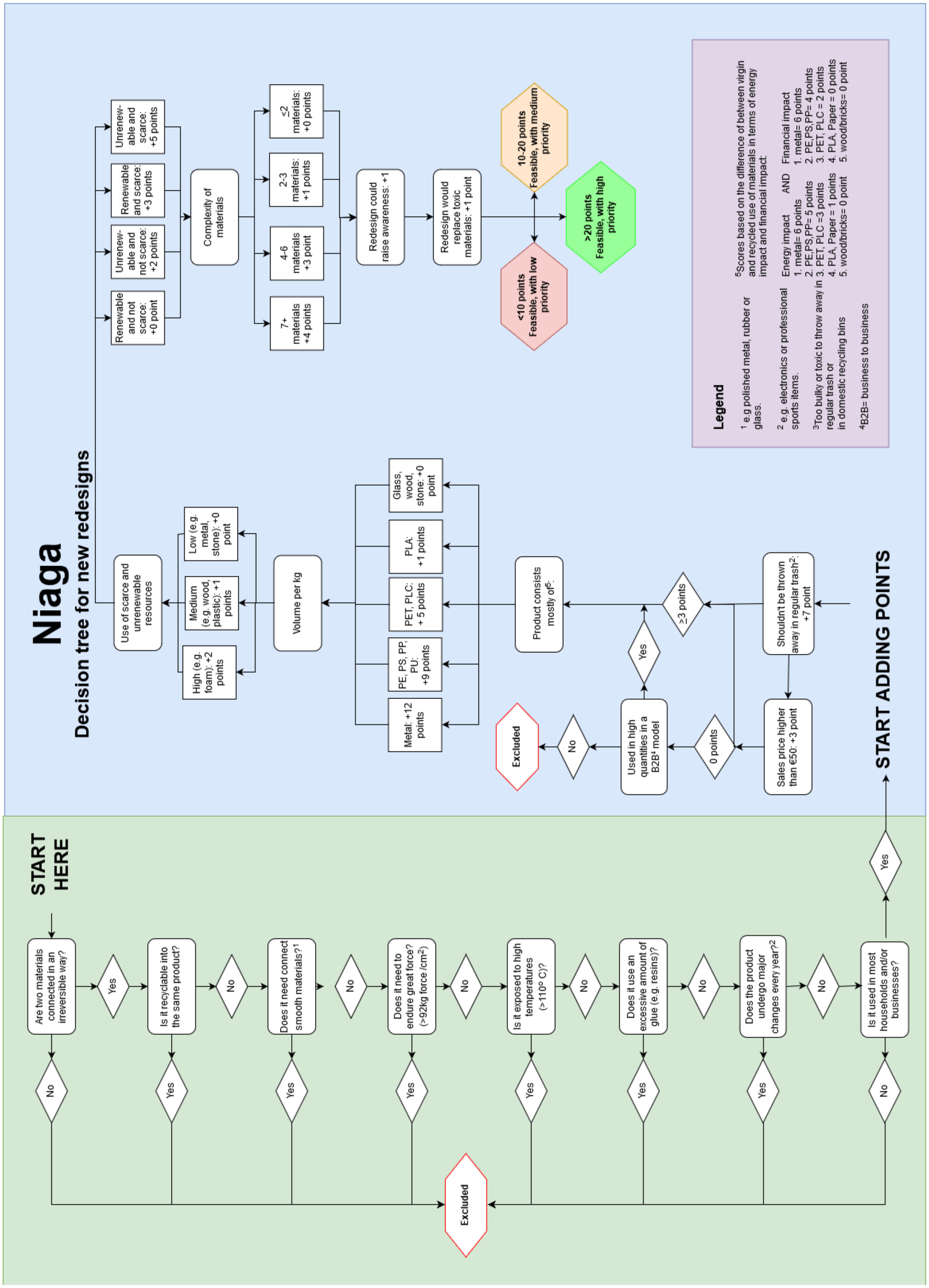

Figure 3. Decision tree for Niaga

Explanation of the questions in the decision tree

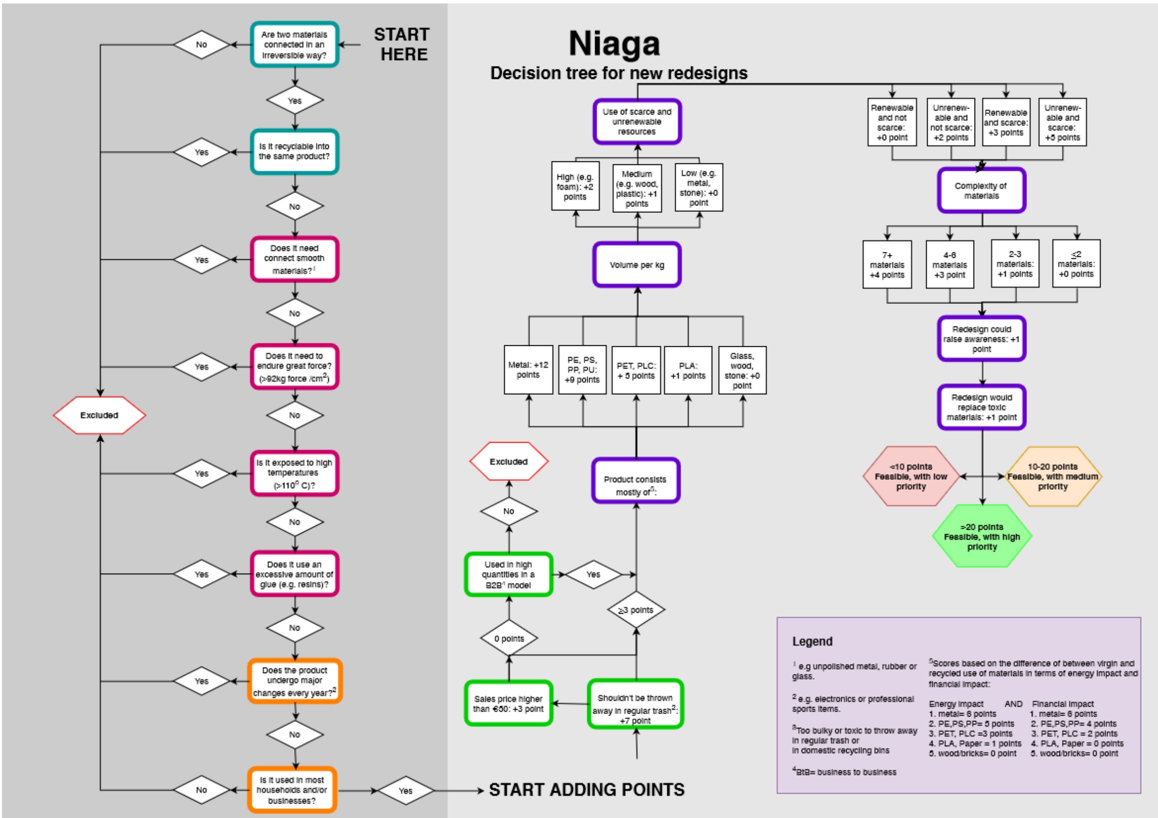

Figure 4: Categorization of the questions of the decision tree.

The essentials (blue)

Two **essential, basic requirements** are necessary for Niaga to have any impact at all. Firstly, incorporation of the Niaga adhesive will only add extra value if a product consists of two materials which are **coupled in an irreversible** way[b]. In addition, redesigning the product to be circular would have no or a minor impact if there is already a possibility of **recycling the product** into the same product again[b].

Technical feasibility (pink)

Due to the properties of the Niaga adhesive, some products can be immediately excluded if they have certain characteristics[c,d]. Appendix 1.2. On Adhesives and Niaga adhesive propertieselaborates on Niaga's adhesive properties.

1. Niaga adhesive cannot **bind to smooth surface material**, including glass, rubber, and polished metal.[c,d]
2. Niaga adhesive cannot be incorporated in products which endure **high temperatures**, as the adhesive decouples after 110°C[c,d].
3. The adhesive it is too costly to be integrated into products which use **a high amount of adhesives**, such as resins.[c,d]

4. The product cannot endure forces above **>92 N/cm²**.[c,d]

Worth Niaga's effort (orange)

The redesigned product has to make an **impact on the market and environment**. This impact will be low for a product that undergoes **major changes**. As redesigning these products, such as phones and high performance sportswear, is too time consuming to impact the market. In addition, the product should be **commonly used**. This would allow Niaga to have a greater positive financial and environmental impact.

Collection after use (green)

It is essential to consider the probability that the product can be **collected separately** after use, so that it can be remanufactured. Three factors were recognized as having an influence on the feasibility of collection. For extra information see appendix 2.1 Collection after use (green).

1. If a user already has to take **extra steps to throw away** a product, there is less added effort for a user to return the product to a remanufacturing center.[e]
2. **High sales prices** provides a financial incentive for the returning used products.[37] This is often done by giving users a discount on the new product.[38]
3. **A business-to-business (B2B)** model means that products are sold by a business to a business, such as construction materials. The collection of these products would be more efficient, as they are often sold in bulk and could be collected in bulk again.[e] In addition, there is higher client binding in business-to-business. This facilitates separate collecting of the used products, as the user contacts the manufacturer to order the new product, anyway.

Impact - environmental and financial (purple)

By redesigning a product Niaga can have both an environmental and a financial impact. When a product is entirely made from recycled materials, there is **no need to mine raw materials**.[10,e] Mining **costs energy, money** and often **scarce resources** (appendix 2.2 The Greens: Impact - environmental and financial (purple))[e]. Using recycled materials to produce a product will therefore have a positive environmental impact by reducing energy cost (appendix 2.2.1. Energy impact) and use of scarce resources (appendix 2.2.3 Use of scarce and unrenewable resources). In addition, it can be financially beneficial, when the recycled materials are cheaper than mining them (appendix 2.2.2 Embedded value). Recycling **reduces landfills** as well, especially voluminous products, as they occupy more space in landfill (appendix 2.2.5 Kilogram per m³ (in landfills))

Besides Niaga's effect on recycling using their adhesive, they redesign products using only a few materials, as products with **complex materials cost more energy** to produce and are therefore less sustainable[10]. Niaga can have the biggest impact when redesigning a product with a complex material composition, as they can reduce the materials used (appendix 2.2.4 Complexity of materials). In addition, a product with toxic materials, can be redesigned using **only clean materials**, increasing the impact of the redesign (appendix 2.2.7 Replacing toxic materials).

With redesigning a visible product Niaga can **raise awareness** on the environmental impact of a product (appendix 2.2.6 Raising awareness). In addition, the more visible a product, the more visible Niaga's name and brand, and consequently, the bigger the customer-base and profit.

2. Product recommendations

We took the decision tree for a ride and came up with 4 products which are feasible and desirable for Niaga to redesign. These **4 finalists** were part **of a list of 66 products**, gathered from lists of environmental harmful and unrecyclable products which are found in landfills or cause significant problems in the world today. Appendix 4. **Ranking 100 products following environmental criteria** describes how the list of 66 products was narrowed down to 4.

Table depicts points collected for the four remaining products using our decision tree. Polyurethane foam (PU) furniture scores highest, followed by sneakers, hardboard and bricks.

Table 1: Following our decision tree, total amount of points for the 4 final products

	PU furniture	Sneakers	Hardboard*	Bricks
Separate collection	7	0	7	7
Intrinsic value >€50	3	3	3	3
Energy impact	5	5	0	0
Embedded value	4	4	0	0
Volume	2	1	1	0
Scarce materials	5	5	0	0
Complex materials	4	4	0	0
Awareness	0	1	0	0
Toxic	1	1	1	0
Total	**31**	**24**	**12**	**10**

*hardboard: laminated hardboard.

Polyurethane foam furniture – 31 points

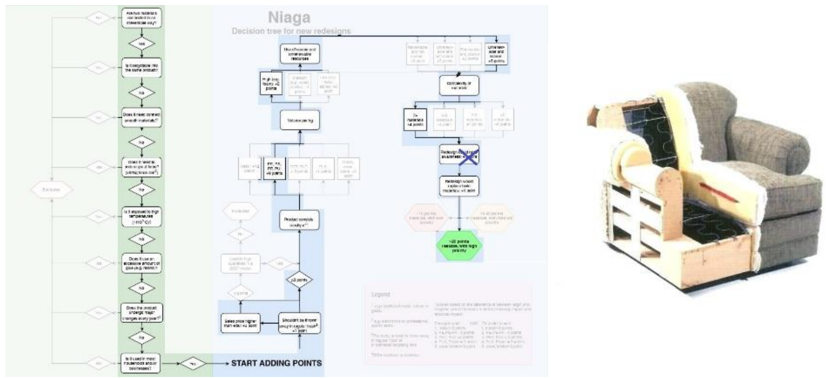

Figure 5: Journey of PU foam furniture in the decision tree.

Flexible polyurethane (PU) foams are used in furniture for softness, support, and providing shape. Polyurethane foam is used as filling material for seating cushions **in most furniture** worldwide[11]. The foam is **glued irreversibly** to the wooden frame which structures the furniture.[11,f]

PU foam is **unrecyclable**[12] and is very **commonly used**: three million m^3 is produced annually in Europe, with furniture one of its main applications.[8]

The **sales prices** vary highly but are generally above the threshold of €50. [13]
Furniture in general is typically bulky and **cannot be thrown away in regular thrash.**
The current **material composition** of this furniture is very diverse[12], which means a Niaga redesign can make a great difference in terms of sustainability and money. The **embedded value** of the materials in a PU foam chair is estimated on 10 euros for a chair that costs 50 euro's[14].

The production of PU foam is very **energy costly**[10], which makes recycling products that use it more attractive(s). For example, to produce one kg of PU foam 7.8 CO_2 is emitted (table, 6 appendix 4. **Ranking 100 products following environmental criteria).** It is furthermore made from oil, which is a **scarce and non-renewable resource.** Since PU foam cannot be recycled(s), Niaga will need to use a recyclable replacement.

PU foam furniture is **highly toxic** to produce, because of the required anti-inflammatory coating.[15] Niaga will therefore have a great environmental impact by taking on a new clean and circular design of this kind of furniture.

Sneakers – 24 points

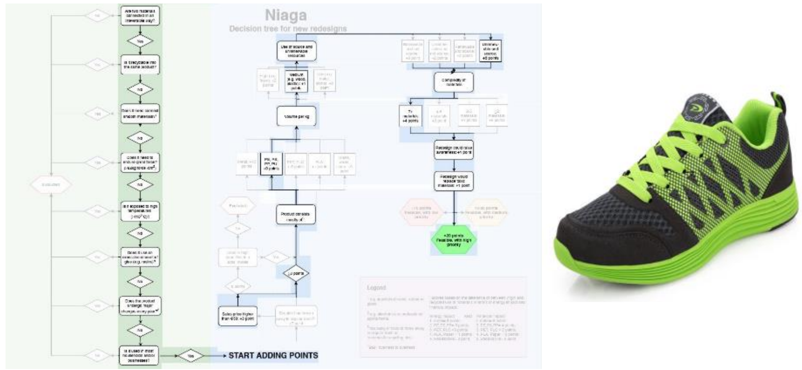

Figure 6: Journey of sneakers in the decision tree.

Sneakers are the most commonly used style of shoes, with millions of pairs sold by the biggest brands everyday.[16]Sneakers are **not recyclable**, as many of their components are either melted together through a process called vulcanization or glued with an **irreversible adhesive.**[17]
The **sales prices** of sneakers are averaging around €60 for non-designer items.[18] Although there are some initiatives for collecting used shoes, they **can be thrown away in regular thrash.** This makes it harder to collect them separately after use. However, as sneakers are a very visible and fashionable item, they might be effective in **raising awareness** about recycling and the circular economy. Furthermore, the adhesives and plastics in the shoes release **toxic** components during the production process, so the non-toxic redesign will be of use in this regard as well.

The bulk of the cushioning of a sneaker's sole is typically made of PU, of which the production is very **energy costly**.[10] In addition, to produce one kg of leather shoes 10kg of CO_2 is emitted (table 6 appendix 4. **Ranking 100 products following environmental criteria**). It is furthermore made from oil, which is a **scarce and non-renewable resource.**

A typical sneaker is made of ethylene vinyl acetate, PU, several kinds of rubber, textile, silicone and more.[19] This **complex material composition** means a simple Niaga redesign can make a great difference in terms of sustainability and money. The **embedded value** of the materials in a typical sneaker is estimated on around 8 euros.[20]

Laminated hardboard – 12 points

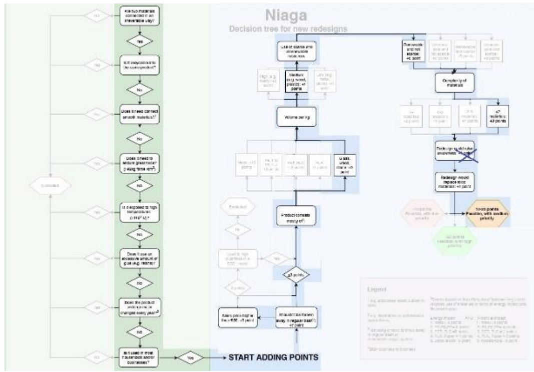

Figure 7: Journey of in the decision tree.

Hardboard is produced by consolidating wood fibers under heat and pressure. Often, multiple sheets of hardboard are **glued together** for additional strength. Laminated hardboard means that a layer of veneer is **glued** to the hardboard.[21] In addition, a top protective layer is often glued on top of the hardboard. Hardboard is **widely used** in for example table tops, part of furniture structures, and floors. Annually, around 2 million m^3 of hardboard is produced in Europe.[8] Currently, hardboard is discarded in landfills because the adhesive embedded in the wood cannot be retrieved.[21]
The **sales price** of laminated hardboard varies greatly with type and thickness, although generally it is not more than the threshold of €50.[22] Hardboard is generally used in bulky products, like furniture, and therefore **cannot be thrown away in regular thrash.**

The production of hardboard is relatively **not very energy demanding** [40]**,** as it is made of wood fibers, adhesive and a veneer top layer. For example 1kg of hardboard only produces 0.69 kg of CO_2 (table 6, appendix 4. **Ranking 100 products following environmental criteria**). Furthermore, it is made from softwood, which is **neither scarce nor non-renewable.**[23] The adhesive used to attach the veneer is **toxic** in production.[24] Therefore, redesigning this product with Niaga adhesive will solve this issue as well as making it circular.

Brickwork – 10 points

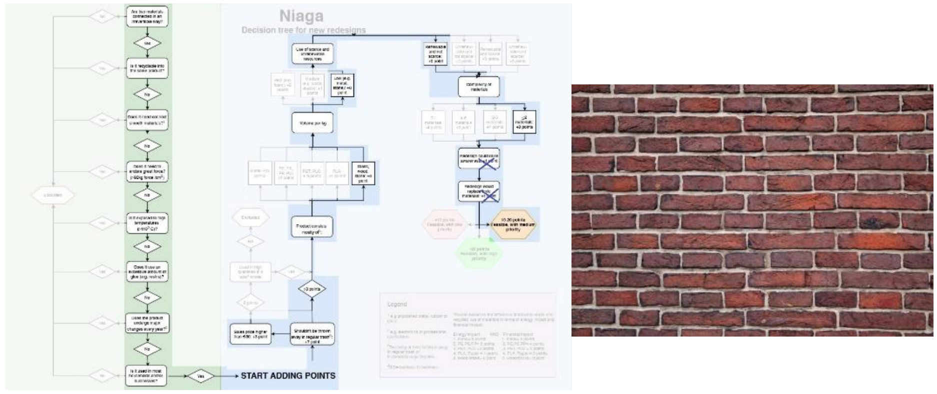

Figure 8: Journey of bricks in the decision tree.

Bricks are composed of natural clay minerals, sand, and water.[25] They are **widely used** as a building material to make walls, pavements and other constructed structures. Annually, over 5 million m^3 of bricks are produced in Europe. Mostly, they are stuck together using cement, but recently, adhesive has become more and more chosen as an alternative. Yet, separating either cement or adhesive is the same: it's difficult and damages the bricks. This prevents bricks from being **recycled** or reused.[j]

The **retained value** of undamaged bricks would be the same as their sales price, since it does not need to be remanufactured. Using Niaga adhesive would allow for bricks to be retrieved without damage. The **sales price** of regular bricks is around 1 euro per brick, so for most walls the threshold of 50 euros would be met.[26] All bricks of a brick wall are too voluminous and therefore **cannot be thrown away in regular thrash.**

Since bricks are made of clay, a material that is easily mined and labored, the production is **not energy demanding.**[10] For instance, 0.27 kg of CO2 is emitted for the production of 1kg of bricks (table 6, appendix 4. **Ranking 100 products following environmental criteria**). Furthermore, clay is a **scarce nor non-renewable** material and has a very low embedded value, as the estimated value of 1000kg of clay, used to make bricks, is around €6.[27]
Brickwork is not a highly marketed or visible product, thus might not be the best to raise **awareness** with.
Brickwork does **not** contain **toxic** elements, and therefore cannot be improved by Niaga on that part.
Although brickwork does not comply with all requirements set in the decision tree, it is extremely abundant in buildings and often ends up in landfills. The impact Niaga can make with redesigning brickwork is therefore big.

Key Recommendations

We advise Niaga to:

1. **Use our decision tool for a quick feasibility scan of any product idea which comes up.**

This tool can determine which products are feasible for Niaga and should be prioritized, based on environmental impact and practical concerns. Using this tool will speed up the selection process and provide a better overview of promising future products.

2. **Update the decision tree regularly as Niaga's situation develops.**

The decision tree and mainly the point system are not set in stone. It should be evaluated annually and adapted to Niaga's evolving priorities and focus. Furthermore, when there are important developments, technical or otherwise, the decision should be updated accordingly. For example, when additional prototypes of Niaga adhesives are available, some of the current restrictions on technical feasibility will no longer apply.

3. **Estimate technical feasibility before considering other factors (e.g. environmental impact of a product's redesign).**

When considering a product to redesign, this will save time. Many products have a negative impact on the environment, but for now, not all products are compatible with Niaga technology.

4. **Prioritize products that cannot be thrown away in household trash.**

When coming up with new ideas for products to redesign, such products should be considered first because they will be easier to collect. Other aspects of a product that make it promising are when it is very commonly used and when it only consists of two materials.

5. **Look into furniture containing polyurethane foam as their next project.**

PU foam furniture scores high on most of the requirements composed in this project. If Niaga likes this recommendation, they can choose to develop a circular prototype, which could be compared with the old situation using a LCA (appendix 1.3: Background on Life Cycle Assessments). Executing a LCA provides an extensive overview and scientific basis of the environmental impact of redesigning PU foam furniture. This could aid their argumentation when approaching potential collaborators and clients.
A successful redesign should not only be technically feasible, which is accessed with our decision tree, it should also be economically feasible. Market towards the redesign should be executed for PU foam furniture and future promising products.[28]
Redesigning sneaker shoes, laminated hardboard and brickwork also seems promising.

Considerations

The information we sought was sometimes incomplete or absent. We adapted our process and results accordingly.

Here are a few things Niaga should keep in mind when viewing our results:

1. Further post-decision tree analysis is needed

The purpose of the decision tree is to provide a quick overview of which products are feasible to redesign and with priority. Therefore, our decision tree gives an *estimation* of the technical feasibility and environmental impact of a product, and not the *exact* impact. We decided against requiring such precise information for a product because it would have hampered and lengthened the process of using the decision tree.

In addition, our decision tree is meant to provide a first-stage analysis of a product. We therefore chose to focus on the technical feasibility and the environmental impact of redesigning a product. However, we recommend that products coming out of our decision tree with high priority should undergo further business and market analysis. After this a well-rounded decision can be made about which products Niaga should continue with.

2. Financial impact is not included in this analysis

The financial impact of using recycled instead of virgin materials is based on the costs of the virgin material. However, a financial impact measure should also include the actual costs related to recycling materials. We decided not to include this latter metric because when redesigning products, Niaga would not necessarily include the materials used in the current products. Such metric can therefore not be considered at the stage the decision tree is used in. It should be included in a later stage, when a redesigned prototype of a selected product is made.

3. The residual value of the product is not included in the decision tree

The requirements that determine the feasibility of collection as it is now in the decision tree are based on the sales price and whether the product is disposed of in household thrash. It could be argued that the residual value, meaning the monetary value the materials in a product have after use, could also influence the feasibility of collection, as they have to be high enough to cover for the cost of transport and remanufacturing. However, it was observed that the future users of the decision tree, the scientists working for Niaga, were not able to estimate this residual value without doing additional research. Furthermore, this value is largely dependent on the design of the product, as the value lost compared to the original embedded value is mainly determined by the materials used and the way they are attached together. The design of the Niaga product is not known yet, because it will be made in a stage after the decision tree is consulted. For these two reasons, it was decided to leave the residual value out of the decision tree. However, finding the residual value of the redesign of a product should be a priority, once it is chosen by Niaga.

4. Energy figures are based on US data

The energy impact connected to production processes, such as glass or metal production, will vary depending on the technological route used, the location, which source of heat and electricity, and the type of metal or plastic. [29] We based the energy impact scale of our decision tree on US data. Energy impact following European data could be different. However, we exclusively used the data to scale energy impact, instead of using the exact numbers reported in this article. Therefore, we assume that the scale would not be altered significantly when using other data, for example, from different countries or with production processes.

5. CO_2 emission was the most reported metric in LCAs

We chose to focus on energy and CO_2 for our environmental impact analysis. Besides CO_2, there are 18 environmental categories in the life cycle assessment method (LCA, see appendix 1.3: Background on Life Cycle Assessments), such as water depletion and land occupation. Standardized analyses of these impact categories showed that CO_2 emission during a product's lifespan, from raw material extraction to after-use disposal and recycling, is one of the most significant environmental problems in today's world[30]. Therefore, we assume that CO_2 will give a sufficient estimation of the environmental impact of our products. In addition, we chose to narrow our focus because of the diverse nature of the products in the list, ranging from construction materials to consumer products, cannot be assessed via most measurements in an LCA.

When considering the ranking of our list of 70 products on environmental criteria, a few things have to be taken into account. Firstly, data were collected from different LCA reports that might include slightly different assumptions and energy flows. Additionally, data included in the LCA reports were from different countries and were conducted in different years. As a consequence, some results might be biased. It was assumed that the magnitude of these limitations would not influence the top 20.

Appendix

1: Background information

1.1: What is a Circular Economy?

Most products are made according to a so-called linear mode of production. In this model, raw resources are extracted, processed, and combined into commercialized products which are then sold, used, and disposed of. Valuable and scarce resources are used for production, without the possibility of reuse.[31–33] This mode of production leads to an accumulation of waste and pollution of air, water and soil, causing environmental and health problems worldwide.[33–36] Raw resources, for example, petroleum or phosphorus, are running out.[37] The harvesting of new resources also costs energy and more resources. On average, only 5% of the resources used in the whole supply chain are in the product. Therefore, the linear economy is not sustainable.[38]

The circular economy (CE) is a mode of production which addresses the problems of the linear economy. In a circular economy, products are reused, redistributed, remanufactured, or recycled after use.[2,3] This reduces the amount of raw resources used as well as the amount of waste produced; the consumption of finite resources is reduced, waste is recycled, products and materials are kept in use as long as their functional performance is retained, natural systems are regenerated, and renewable energy sources are used. Circular economy minimizes usages of matter, energy and environmental products without compromising on economic, social, natural and technical capital. It provides long-term resilience while providing environmental, social and economic benefits. The transition between the linear and circular economy is summarized in Figure .
The figure describes the negative consequences of a linear economy. These negative consequences can be resolved by a transition to a circular economy.

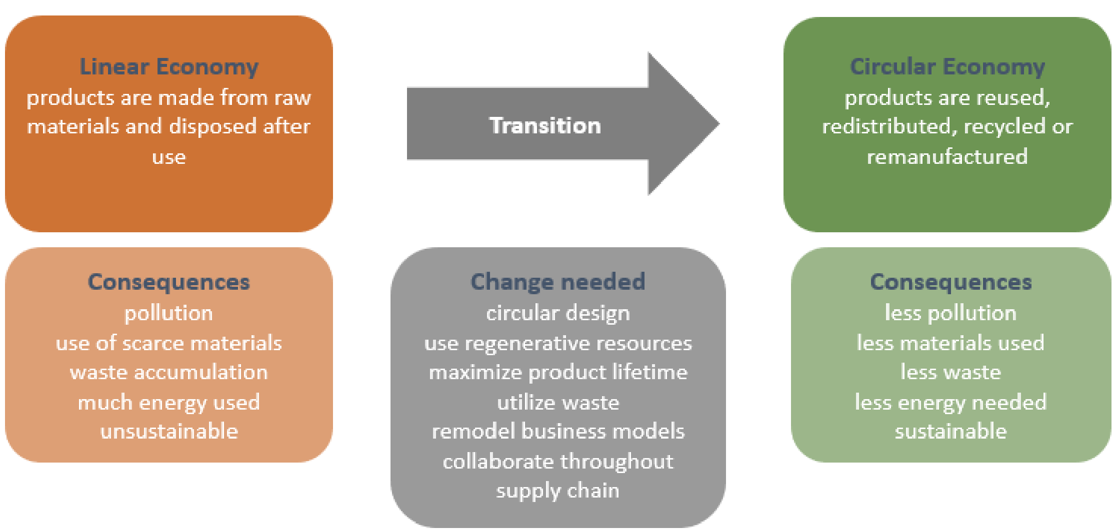

Figure 9: A summary of the transition from the linear to the circular economy

To achieve a shift to a CE the following changes need to be made.[31]

- **Redesign of products**
  To easily reuse, redistribute, remanufacture or recycle products, they need to be redesigned first. Designs should use standardized components and reusable materials. Secondly, the redesign needs to positively affect the product lifetime and the easiness of end-of-life sorting, separation or the reuse of materials. Lastly, the design needs to consider useful applications of byproducts and waste.
- **Usage of regenerative resources**
  To achieve a true circular economy only renewable resources can be used during the whole life time of a product. In addition, no toxic substances should be produced or emitted during the production or use of the product.
- **Maximizing lifetime of products**
  Products should be maintained, upgraded and repaired while in-use, to increase their lifetime.
- **Utilization of waste**
  After usage of the product, all the materials in the product are reused. Thus, no materials or products are wasted. For example, the Niaga carpet is disassembled after use and new carpet is produced from the materials of the old carpet.
- **Remodeling of business models**
  Business models need to be altered in such a way that profit is expected not only from selling new products but also from reusing old materials or products. For example, products which are remanufactured instead of thrown away can change the relationship between the company and the customer from seller-buyer to lender-borrower, which affects the business model as well.
- **Collaboration**
  Throughout the supply chain, corporations need to work together to ensure used products or their materials can be reused to produce new products.

1.2. On Adhesives and Niaga adhesive properties

Adhesives can be found all around us, from massive constructions to a sheet of paper. Humans have always used adhesives, first as plant-based coating in prehistoric times and as an animal-derived adhesive that bonded fabrics and materials togethe.r[39] Today, nearly 10 million tons of adhesives are being sold each year for annual profit of almost 50 billion USD, of which half belongs to 4 major companies: Henkel, HB Fuller, Dow Chemical Co, and 3M. [40]
Since the 19th century, with the discovery and improvement of synthetic adhesives, manufacturers and consumers have followed one principle: the stronger, the better. Adhesives have increasingly been designed to bind materials at all cost, often irreversibly[41]. Indeed, chemical adhesives, such as thermoplastic adhesive, known as hot melt, modifies the chemical bonds on the surface of materials it interacts with (breaking these molecular attractions using energy), thereby becoming 'one' with the material.[42] In addition, the chains of the polymers are not connected in thermoplastics, but can move relatively freely past each other. As a consequence, the plastics can be melted and recast. Another type of chemical adhesive are thermosets. Thermosets consist of polymer chains, too. However, in thermosets chains are cross-linked by covalent bonds. Therefore, they are typically stronger than thermoplastics. [43] =
Another class of adhesives are physical adhesives, such as polyurethane and PVC adhesive. These adhesives operate via mechanical interlocking by sticking and 'gripping' to the crevices and pores of non-smooth materials.[44] This intense adhesion performance is however not always necessary in everyday products, such as carpets or diapers, and is one of the barriers in the transition to a circular economy. Materials can only be recycled in their designated recycling stream with the same material. Therefore, if products cannot be disassembled they often end-up in landfill or combustion centers. In addition, products containing these adhesives are toxic to produce and become toxic waste when decomposing in landfills or create toxic elements when burned in combustion centres.[45,46]

Properties of the Niaga adhesive

Niaga is the first and currently only company to develop a reversible adhesive. This adhesive is strong under normal conditions but decouples when exposed to a specific (high) temperature for a fraction of a second. After the decoupling process the adhesive can be recovered.[c,d]
The Niaga adhesive is a polyester with a semi-crystalline structure. Therefore, it has a highly ordered molecular structure with a sharp melting point. The material does not get softer as the temperature rises, as compounds with an unordered molecular structure do. Instead, the adhesive remains solid until a specific temperature, after which it changes within seconds into a high viscosity (non-syrupy) liquid. Between 100 milliseconds to two seconds the adhesive hardens again as it cools down.[c,d]

The Niaga adhesive are is a plastic that can act both as a thermoplastic and a thermoset. The Niaga adhesive consists of polymer chains that are cross-linked, similar to a thermoset, but the links are made with weaker non-covalent bonds. Non-covalent bonds can be broken by raising the temperature. This provides the adhesive with the ability to melt, similar to thermoplastics, while still having comparable strength as thermosets: it has a strength of 9 megapascal (917,745 N/m^2).[c,d]
Niaga adhesive is a physical adhesive which works via mechanical interlocking. Consequently, it does not form covalent bonds with the surfaces, but is dependent on the crevices and pores of materials to hold on to.

Currently, there is one commercial version of the Niaga adhesive. Many more prototypes of adhesive with slightly different features are currently being tested. This commercial version decouples at 115 ^oC, with the prototypes ranging in decoupling temperature from 70 to 160 ^oC. The retail value is currently about 5 to 6 euros per kilogram, but prices can range with the nature of the product.[47]

Limitations of the Niaga adhesive

Because of these properties, Niaga adhesive can replace several important physical or chemical adhesives. The three limitations are as follows:

1. **Niaga adhesive cannot bind to smooth surface material.** This includes glass, rubber, polished metal, plastic wrappings. This limitation excluded car tires, bike tires, diapers, and rubber window seals from our list of viable ideas.
2. **Niaga adhesive cannot be incorporated in products which endure high temperatures.**
For example, given the impact absorption and temperature criteria imposed to tire manufacturers in the automobile industry.[48,49] Due to the potential fire risk in buildings, Niaga adhesive is not compatible with the construction industry. However, it is possible for Niaga adhesive to be paired with a mechanical interlock.
3. **It is not feasible to replace products which use a high amount of adhesives, such as resins, with the Niaga adhesive**.
The Niaga adhesive is sold at about 5 euros per kilo, which is more expensive than most adhesive, such as urea-formaldehyde, used in fiberboards, which is currently sold at about 0.40 euros per kilo.[50] Therefore, it is too costly to be integrated into products that use a lot of adhesive, such as epoxy floors or fiberboards (where the main component of is the adhesive itself). This limitation excluded concrete blocks from our list of viable ideas.

1.3: Background on Life Cycle Assessments

To determine the negative environmental impact of our list of 66 products and to investigate commonly used environmental metrics, we used life cycle assessments (LCA) of these 66 products. LCA is a methodological tool which enables evaluating the environmental impact associated with all stages of a product's life. *Life cycle* refers to the concept that a holistic, fair assessment requires a comprehensive evaluation of all input and output material flows of all the different phases of a product, including raw material extraction, manufacture, distribution, use, disposal and all transportation steps. Initially, this tool was developed to compare end products alternatives, such as diapers. During the 1990s, the LCA underwent major changes to incorporate it at higher strategic levels, such as decision and policy making. Currently, it is used for analyzing a wide range of activities and products beyond solely assessing end products, including energy systems, food production and transportation alternatives. The LCA has emerged as a valuable decision support tool for both industry and policy makers.[51]

The LCA includes four stages:[52]

- **Goal definition and scoping**: Identifying the LCA's goal and the products that are being studied, determining the system boundaries, impact categories chosen, assumptions, and limitations.
- **Life-cycle inventory**: Creating an inventory of flows of energy, raw material, and environmental releases associated with each stage of the product's life.
- **Impact analysis:** Assessing the significance of environmental impacts quantified by the life-cycle inventory.
- **Interpretation:** Evaluating, checking information and seek possible opportunities to reduce environmental impacts at the different stages of the product life-cycle.

The ReCipe is a recent and harmonized LCA approach[53,k]. The main objective of the ReCipe method was to convert the long list of life cycle inventory result, into end indicator scores. This resulted in 18 midpoint indicators that are converted into three endpoint indicators. The indicator scores reflect the relative severity of environmental impact categories, such as ozone depletion, human toxicity, or natural land transformation.

In ReCipe, the unit for Damage to Human Health is Disability-Adjusted Life Years (DALY), a measure of the number of years of life lost or lived disabled. This category is based on the notion that human health issues are created by influences of several types of pollution, including the ReCipe indicators, ozone depletion, photochemical smog, greenhouse gas emission, ionizing radiation, and creation of dust particles. The damage connected to Ecosystem Quality is measured by the number of species that disappear in an area as a consequence of contamination. This category includes ecotoxicity, eutrophication, acidification, occupation, and conversion of land. Damage to resource availability reflects the assumption that non-renewable resources should be available for future generations. This is based on the distribution of fossil and mineral resources and quantify how the use of these resources change the efforts to extract them in the future. The unit reflects the marginal increase of extraction costs caused by continued extraction[53].

2. In-depth information about the decision tree

The decision tree is a tool to provide a quick feasibility scan of the feasibility to redesig a product with the Niaga adhesive. The first part of the decision tree (blue area, see Figure 4) consists of closed questions. These questions represent essential criteria that a product has to comply with to be considered feasible. The second phase (green part) is a ranking system in which the products that came through phase 1 can collect points. To assess both how feasibility it is to redesign the product and to what extend the redesign will impact the world. The two phases are described in more detail underneath.

2.1 Collection after use (green)

In addition to the feasibility requirements addressed in the first part of the decision tree, the feasibility of collection is addressed. This is about the probability that the product can be collected separately after use, so that it can be remanufactured. This is essential for the business model of Niaga and the collaborating manufacturers[b,e,i]. Three factors were recognized as having influence on the feasibility of collection.

1. Not thrown away in regular thrash
If a user already has to take extra steps to throw away a product, there is less added effort for a user to return the product to a remanufacturing center. We assumed that this would make it more likely that products are returned. Reasons for products not being able to be thrown away in household thrash include large size and toxic ingredients.

2. Sales price
A financial incentive for the user can be a tool to promote returning used products.[54] This is often done by giving users a discount on the new product.[55] However, a discount would be most effective if the initial value of the product is above a certain threshold, so the absolute value of the discount is something users would want to take the effort for. This threshold was determined to be €50, in consultation with Niaga.

4. Business-to-business (B2B)
A business-to-business model means that products are sold by a business to a business. Construction materials fall into this category, other examples are medical supplies and semi-finished products. This

model can contribute to the feasibility of collection[e]. Firstly, products are often sold in bulk and could be collected in bulk again. This would make the collection more efficient. Secondly, there is higher client binding in business-to-business, compared to business-to-consumer models. This would make collecting the used products more likely, as the user contacts the manufacturer to order the new product, anyway.

2.2 The Greens: Impact - environmental and financial (purple)

When a product is entirely made from recycled materials, there is no need to mine raw materials[e,h,10]. Mining costs energy, money and often scarce resources[e,h,40]. All three are addressed in the decision tree, as materials can score very differently on the different aspects. Not all materials that are scarce are also expensive: even though oil is running out, the price often goes down[56], for example.
If the mining costs are high for the original product, this means the circular redesign the product will have a great impact. Both on the environment, as the redesign will save energy and scarce resources, and financially, on Niaga itself, as it will help them to make profit when the recycled resources are cheaper than the raw ones. Additionally, saving energy and scarce resources will indirectly save money as well.
For the three aspects of mining, a scale was made to be used in the decision tree. The scales for the financial and energy aspect were combined in the decision tree, because they are both determined by the material the product is made of. This was done by adding up the points of both scales for every material.

2.2.1. Energy impact

When products are made from recycled materials instead of raw materials, this means the energy used otherwise to mine and transport the raw materials is saved[e,g,h,10]. Additionally, using recycled materials could mean a great difference in energy needed for the production process. For example, to make a glass bottle from recycled glass instead of sand, the raw material, there is an energy saving of about 55%[1057]. The United States Environmental Protection Agency Office of Resource Conservation and Recovery (EPA-RCR) calculated the energy impact when using recycled materials instead of raw materials. In their calculations they included two energy benefits of using recycled materials.[10]

1. It offsets the energy required to produce a given material. The total energy reduction is a result of direct fuel and electricity reduction with raw material acquisition, manufacture and transport of materials.
2. It reduces energy losses due to embedded energy, energy inherently stored in raw materials. For example, the embedded energy in plastic comes from the petroleum used to make plastic. Because the petroleum used for plastic production has an inherent energy value, as it also could be used as an energy source. When plastic is recycled energy is saved by not using more petroleum.

We used the results of the energy impact of recycling calculated in the article of the EPA-RCR to create a scale of energy impact per materials, used in our decision tree[10]. We grouped products in a scale of five according to energy impact:

1. **Metal** (±182-160 Million Btu/Ton of Material Recycled (mBtu/TonR*)
2. **PU/HDPE/LDPE/LLDPE/PS/PP** (±50 mBtu/TonR)
3. **PET/PVC** (±30 mBtu/TonR)
4. **PLA** (±10 mBtu/TonR)
5. **Wood/Stone** (±2 mBtu/TonR)

*(mBtu/TonR) is Million Btu/Ton of Material Recycled. Btu is a unit of heat used to express energy. The definition is the amount of heat required to raise the temperature of one pound of water (0.45 kg) by one degree Fahrenheit.[10]

2.2.2 Embedded value

The financial impact is about the saved financial costs of mining if a product is redesigned to be circular. This was expressed as the costs of the embedded virgin materials, as these are the costs that a manufacturer of the product would make. The embedded value of materials was made into a four-point scale in order to be used in the decision tree. The scale is as follows:

1. **Metal:** Very valuable, around or above \$5000/m^3. [58]
2. **PE, PS, PU and PP.** Reasonably valuable, around \$3000/m^3. [58]
3. **Pet and PLC**. Only some value, around \$1000/m^3.[58]
4. **Wood/bricks, PLA and paper**: not valuable, <\$500/m^3.[58]

2.2.3 Use of scarce and unrenewable resources

The cost of producing the materials to make an object is not only monetary but also environmental. Extracting petroleum, for example, is cheap once the machinery is installed, as one installment will extract tons of petroleum daily for many years.[59] Yet, the true cost of extracting and processing high amounts of petroleum is that this resource is running out. Since petroleum is not renewable, taking millions of years to form naturally, the 'depletion' cost of extracting petroleum is extremely high.[59] This cost is eliminated by redesigning a product into a circular version which can be remanufactured by retrieving materials.
The scale we developed keeps track of the renewability and the scarcity of the natural resources used in different products. Scarcity was considered more impactful than renewability as it presents challenges in the short term. Products can be grouped on this scale of four according to raw resource depletion contribution of current design. The complexity of manufacturing was made into a five-point scale in order to be used in the decision tree. The scale is as follows:

1. Renewable and not scarce: Resources that are renewable (renew in <100 years) and won't face a shortage in 50 years

For example: Softwood

2. Unrenewable and not scarce. Resources that are nonrenewable (renew in >100 years) and won't face a shortage in 50 years

For example: Sand

3. Renewable and scarce. Resources that are renewable (renew in <100 years) and will likely face a shortage in 50 years

For example: Water

4. Unrenewable and scarce. Resources that are nonrenewable (renew in >100 years) and will likely face a shortage in 50 years

For example: Petroleum; Phosphate

2.2.4 Complexity of materials

The complexity of material composition in the product was also taken into account to determine the impact for Niaga. Complex material composition was defined as having a high number of different materials. Niaga wants to make a big impact. The bigger the change in design is, the bigger their impact will be, as more complex products generally cost more energy. Therefore, attempting to redesign a very complex product will have their preference over attempting to redesign a product that is already quite simple in material composition.

The complexity of manufacturing was made into a five-point scale in order to be used in the decision tree. The scale is as follows:

1. 2 different materials
2. 3-4 different materials
3. 5-6 different materials
4. More than 7 different materials

2.2.5 Kilogram per m^3 (in landfills)

All the products that pass phase 1 are used in most households and/or businesses. Therefore, it is likely the product contributes to landfill. However, the contribution of a product to landfill size is not only related to how many units of the product are produced and disposed of, but also to its bulkiness. The higher the product's kilogram per m^3, the more place it takes up in landfill. For example, a kilogram of post-it notes is multiple times more voluminous than a kilogram of concrete. Kilogram per m^3 was made into a three-point scale in order to be used in the decision tree. The scale is as follows:

1. **High e.g. foam**. Materials with a density of less than 100 kg/m^3.
   For example, PU foam has a density between 30 and 100 kg/m^3.[60]
2. **Medium e.g wood and plastic**. Materials with a density between 100 kg/m^3 and 1200 kg/m^3.
   For example, high density fiberboard has a density of 900 kg/m^3. [61]
3. **Low e.g. metals.** Materials with a density higher than 1200 kg/m^3.
   For example, aluminum has a density of 2712 kg/m^3.[62]

2.2.6 Raising awareness

Although Niaga is a B2B and therefore does not have direct contact with the consumer, they often sell their products to B2C companies, which are in direct contact with the consumer and are interested in what the end consumer wants.

The way a product is handled during after use ultimately depends on who is interacting with it and who is responsible for disposing of it. Certain products are invisible to the public eye, and are irrelevant in one's personal recycling behavior. While, other products are the customer's direct responsibility. For example, the layperson does not think about how bricks are recycled. In contrast, he has to take food packages and other waste to the neighborhood's trash and recycling bins.

In addition, the visibility of a product depends on the amount of marketing and customer-targeted sales efforts are spent on the product. For example, sneakers are omnipresent in physical and digital stores, online platforms, and commercials. On the other hand, less sales efforts and commercials are spent on window frame. We take this visibility factor into account when considering how likely publicity and public enthusiasm can be achieved when Niaga launches a new product. The more visible a product, the more visible Niaga's name and brand, and consequently, the bigger the customer-base and profit.

In addition, visibility of a product, promotes awareness on the environmental impact associated with a product's disposal or lack thereof. However, it is difficult to measure a product's visibility, and thus we only consider whether the average citizen sees the product as a purchasable commodity in daily life or not.

2.2.7 Replacing toxic materials

One of the three basic pillars of Niaga's philosophy is that they do not work with toxic materials. Therefore, it is important that the product can be redesigned by eliminating or replacing any toxic material. Toxic materials either release toxins that are harmful for the environment, irritating to humans, or are carcinogenic. A lot of products we daily use are toxic[63,64]. Luckily, products are constantly being re-designed and new materials are constantly being created. There are thus lots of opportunities available for Niaga to replace toxic materials in products. Products of which the original design contains any toxic elements will therefore have an advantage over products that don't have this, as Niaga will have extra opportunity to make a positive impact with the former. No research should be needed for this question, as clean natural ingredients (for example paper or sand) are easily identifiable. It is a binary question which doesn't require a scale, thus simplifying the decision tree.

2.3 Determination of requirement priority

The priority of the products that meet the basic requirement is determined using a point system. The more points a product has, the higher the priority. The order of importance of the questions in the second phase of the decision tree and can be seen in **Fout! Verwijzingsbron niet gevonden.**. The most important requirement was given 7 times as many points as the least important requirement. The points for the requirements in between were distributed linearly. For the requirements with a scale, the points were distributed evenly over the possible values of the scale, with zero points for the lowest value.
Carpet and mattresses, the products that Niaga is already working on, and thus considers high priority, were put through the decision tree. This was used to determine the thresholds for high, medium and low priority. The reasoning behind the order of importance is described below.

Table 2: Point distribution for the decision tree

Requirement	Importance	Number of categories	Points
Not thrown away in household thrash	1	1	7
Energy difference	2	5	6, 5, 3, 1, 0
Costs of embedded virgin materials	2	4	6, 4, 2, 0
Scarce/non-renewable resources	3	4	5, 3, 1, 0
Complex manufacturing	4	5	4, 3, 2, 1, 0
Sales price >€50 per unit	5	1	3
Kilogram per m^3	6	3	2, 1, 0
Toxicity	7	1	1
Awareness	7	1	1

1. Feasibility is more important than impact
We determined that the feasibility criteria in this part of the decision tree should have more points than the impact criteria. This is because the essential requirements for environmental impact, namely presence in landfill, commonly used and recyclability, are already checked for in the first part of the decision tree. The other requirements for impact are important, including energy cost of materials and use of scarce and renewable resources, but not essential. The feasibility of being able to collect the product for recycling is essential, however. The inability to throw the product away in household thrash is appointed the most points, as it directly influences separate collection. The sales price has a more indirect influence on separate collection, as it can provide a financial incentive for the user can be a tool to promote returning used products.[54] Therefore, we assumed that the sales price of a product was of lesser influence on the feasibility of collection than the other metric in this category and was awarded fewer points.

2. A product that is not feasible to collect should be excluded
The feasibility of collection is essential for the business model of Niaga. A product that is not able to be collected separately is not a viable option. Therefore, a product is excluded if it does not have one of the two factors of feasibility of collection, described in appendix 2.2.1. As explained in that section, a business-to-business model can promote the feasibility of collection, even if the product does not meet the three requirements. Therefore, if a product meets the business-to-business requirement, it will not be excluded, even if it doesn't meet one of the two collection requirements. Because a business-to-business model also has downsides (see 2.2.1.), there are no extra points added for meeting this requirement.

3. Feasibility of collection is more important than financial feasibility
The feasibility of collection is different from the financial feasibility. The first is about whether the user will return the product after use and the second is about whether recycling the product will create monetary value which is higher than the costs involved with recycling. Even though creating value is necessary for Niaga, it is not their sole interest, as expressed by their strategic growth manager. If a product is not the most profitable (but profitable enough), but would still have a major positive environmental impact, this would be preferred over a more profitable project with a lesser impact. However, users returning the products is essential to Niaga's business model. The more users return the product, the more profitable it will be. Furthermore, a major part of the costs of remanufacturing are in the collection and transport of used products. If this can be done efficiently, there is less created value needed for the product to be profitable. Taking this into account, it was determined that the requirements about feasibility of collection would have a higher priority than the requirements about the financial feasibility.

4. Products with complex material compositions have an advantage
The complexity of material composition has an important influence on the impact of redesigning the product. Niaga can redesign a product which consists of multiple materials into a simpler design with only two or three materials. This will in general have a greater impact than redesigning an otherwise similar product which already consists of two or three materials, since this would generally mean less energy needed and waste produced for manufacturing. Therefore, a product consists of seven materials will be preferred over an otherwise the same product which is less complex in material composition.

5. Volume and toxicity of the product are not essential in the decision
Part of the design philosophy of Niaga is that they will not manufacture products that contain toxic elements. Luckily, Niaga can replace al lot of toxic elements present in products, which will positively affect the environment. Replacing toxic elements is, however, not part of the main focus of Niaga, which is preventing landfill. In addition, it will not compensate for a low technical feasibility, such as difficult to collet separately. This metric can only make a difference for otherwise equal products. Therefore, this requirement is regarded as having lower priority than the others.

The same applies for the volume of the product. While this is important, since bulky products take more place in landfill, we decided not to give this requirement a high priority. This is mainly because a part of this requirement is already reflected in the requirement. Notably, in the requirement not being able to be thrown away in household trash, since these are typically products with a high kilogram per m^3 (volume). However, this is not the only reason; it could also be because the product is typically used in high amounts (like with bricks, for example). Therefore, kilogram per m^3 is still counted as a separate requirement, but with a lower priority.

3. Top 10: Testing the feasibility of redesigning 8 environmentally harmful products using the Niaga adhesive

Although the Niaga adhesive can be integrated in a great variety of products, its specific properties are not compatible with certain materials or types of products (see Appendix 1.2). Niaga adhesive is strongest when used in thin layers between materials, and is too expensive to produce to be used as a resin.
From the top 20 most environmentally harmful products, we selected the 8 products that did not have an excessive amount of adhesive used in the products. These products were assessed in detail about their compatibility with the adhesive.

Table 3: Compatibility of the list of 9 products with the Niaga adhesive. This table describes the reasons for every product of the list of 9 why they are or are not compatible with the Niaga adhesive.

Product	Compatible with Niaga Adhesive	Comment
Brickwork	✓	Is possible if you incorporate the adhesive with a mechanical interlock system for extra support.
Car tire	✗	Is a product which undergoes quick innovation, endures high temperatures, and is made of rubber.
Bike tire	✗	Is a product which undergoes quick innovation and uses rubber.
Shoes	✓	Niaga could make 100% polyester shoes, a material which they can adhesive and recycle.
Furniture with polyurethane foam	✓	Is possible to replace the adhesive and the toxic polyurethane foam.
Diapers	✗	The problem of diapers are the fibers in the diaper, not the adhesive.
Concrete	✗	The problem of concrete is the cement used, not the adhesive.
Laminated hardboard	✓	Is possible to glue the layers of hardboard on top of hardboard and adhesive the coating on.

4. Ranking 100 products following environmental criteria

We considered around 100 products which contain adhesives of any kind which are currently unrecyclable and thus end up in landfills or are being burned after use, according to the literature. To estimate the negative environmental impact that these products have during their life cycles, we considered several metrics.

4.1 CO_2 emission

First, the total amount of CO_2 (equivalent) emitted per kilogram of product was considered, as CO_2 contributes greatly to climate change. We used the amount of CO_2 during the production, distribution and after-use processing of a product. We chose to exclude the CO_2 emitted by a product during use, as it creates an artificial gap between products that do not produce any CO when being used (e.g. shoe) and products that do use electricity when turned on (e.g. air conditioner).
We found the amount of CO_2 and **equivalent gasses** for 70 out of our 100 initial products (table 1), in corresponding life cycle assessment publications. The remaining 30 products have not yet been assessed in the literature via life cycle assessments and did not have corresponding environmental impact information available online, which made it impossible to draw conclusions from them with confidence. We assumed that the lack of information or relevant studies on these products implied that they were not among the 20 most environmental harmful products.

4.2 Production quantity

Second, we found the production quantities for each of the 70 products, and calculated how much of this product is present (and therefore being wasted) in Europe (see Equation 1). We found this information in a European database[8]. This website described how much a product was produced in 27 European countries in 2012, how much of this produced amount was exported from Europe in 2012, and how much of this product is imported in Europe in 2012.

4.3 Quantification of total amount of CO_2 emission

Equation 1

Product's quantity (kg)= (kg produced in Europe) + (kg imported) - (kg exported)

Finally, we calculated the total amount of kg of CO_2 equivalent per kg product emitted in the production, transport, and disposal of each product, in relation to each product's quantity found in Europe (see Equation 2).

Equation 2

Total CO_2 emission associated to 1 kg of product = product's quantity (kg) x CO_2 emitted per kg of product

This gave a sense of the magnitude of the environmental problems caused by the 70 products. The year 2012 was chosen for the production quantities, as it was the most recent year that had data for all products. This gave the opportunity to score the products relatively, even though some slight changes may have occurred since then. We assumed that these were not of a magnitude that would influence the top 20. The 70 product were then ranked on the total amount of CO_2 emitted.

4.4 Recyclability, toxicity and volume

Furthermore, an estimation of the recyclability, toxicity and volume was made for each product. The volume was taken as the kilogram per m^3 (volume) of product. This assessment was done qualitatively, based on information from the life cycle assessments, news articles and general information of the materials used in the products. Toxicity is defined by the presence of harmful substances and gases emitted in the manufacturing, transportation, use, and end-of-life processing of the product. This can be either as components of the product or byproduct of the manufacturing process, which kills the fauna and flora upon direct contact, or components that are carcinogenic or poisonous to humans at high dose (e.g. hydrogen cyanide, nitrogen oxides and isocyanates). The scale used is depicted in Table 1.

Table 1: Scale for recyclability

	Recyclability	**Toxicity**	**Volume (per kg of product)**
1	Fully re-manufacturable into same product	No toxic substances involved in the manufacturing and end-of-life processing of the product	0.1 dm^3
2	Partly re-manufacturable into same product	Few toxic substances present in small amount in the manufacturing and end-of-life processing of the product	0.5 dm^3
3	Fully re-manufacturable into a product of lesser monetary value	Several toxic substances present in small amount in the manufacturing and end-of-life processing of the product	1 dm^3
4	Partly re-manufacturable into a product of lesser monetary value	Several toxic substances present in large amount during the manufacturing and end-of-life processing of the product	5 dm^3
5	Not remanufacturable; completely disposed in landfill or burned	Several toxic substances present in large amount at all stages, including during use, and manufacturing process creates several toxic substances	10 dm^3

Even though the original 100 products all appeared in landfill of garbage burn centers, some products were possible to recycle, scoring a 1 or a 2. Despite the possibility of recycling, this was usually not done, consequently they would still end up in landfill or incineration centers. As the environmental problem of the products with a score of 1 or 2 lie more in the coordination of the recycling process and not in their design, they were excluded from the list. The Niaga adhesive would be most effective in a product where the challenge lies in the circular design of the product. The top 20 products with a recycling score of 3 or greater were selected to continue with to the next phase of the project (table 5). The complete list is given in Table 3.

*Table 2: Environmental impact of the 20 products with the highest score according to our LCA analysis. --(red)= largest negative environmental impact (highest CO2 emission, highest annual production, greatest toxicity, largest volume and unrecyclable) . ++(light red) =lowest environmental impact. *= toxicity during production and use of product.*

Product (ranked)	CO2 emission	Amount produced	Toxicity*	Volume**	Un-recyclability
concrete	-	++	--	--	-
Polystyrene foam	++	+	++	+	++
Paper towel pulp	++	+-	-	++	+-
Glass fiber column	--	++	+	+-	+-
Marble chip tile	+	+	+	--	+
Quartz floor	+	+-	+	--	++
Brickwork	--	++	-	-	+-
composite lumber deck	-	+	++	+-	++
Plasterboard	--	++	+-	+	-
Tire	+-	+	+-	+-	++
Textile shoe	+	-	+-	+	+
Fiberglass in boat hull	+-	-	+	+-	+-
Leather shoe	++	-	-	+	+
Disposable diaper	+-	+-	+	++	++
Cement mortar column	--	+	-	--	-
Medium density spray foam	++	--	-	+	++
Hardboard	-	+-	--	+	+-
Polyvinyl chloride deck	+-	--	++	+-	++
Polyurethane chair	+	--	++	+-	++
Fiberglass in car	-	--	+	+-	+

Table 3: Results of the environmental analysis for the 66 products

Product	Total kg present in 27 EU countries in 2012	CO_2 emission equivalent (kg) per kg of product	CO_2 emission (kg) per amount of product in Europe	Recyclability (scale of 1-5)
1 kg of concrete[65]	**6.58E+10**	**2.9**	**1.91E+11**	**4**
Air conditioner[66]	4.50E+07	1.3	5.76E+07	4
Aluminum grating 50% recycled[67]	3.76E+08	5.8	2.18E+09	2
Aluminum grating 80% recycled[67]	3.76E+08	2.6	9.78E+08	1
Aluminum gratings not recycled[67]	3.76E+08	10	3.89E+09	1
Bike tire[68]	7.20E+07	3.8	2.72E+08	5
Brickwork (glued)[69]	**5.86E+10**	**0.27**	**1.56E+10**	**4**
Car tire[70]	**2.51E+09**	**3.3**	**8.27E+09**	**4**
Cement mortar column[71]	**4.31E+10**	**0.13**	**5.60E+09**	**4**
Ceramic tile[72]	1.54E+08	0.31	4.73E+07	3
Composite lumber deck[73]	**1.05E+10**	**1.3**	**1.38E+10**	**4**
Cork board[74]	5.29E+10	0.37	1.93E+07	2

Cork flooring[75]	5.29E+10	0.39	2.08E+07	2
Cross laminated timber[76]	3.36E+08	2.2	7.51E+08	4
Disposable diaper[77]	**1.69E+09**	**4.3**	**7.31E+09**	**5**
Epoxy Resin (general. glycerin based production)[78]	2.48E+08	4.6	1.15E+09	5
Epoxy resin column[71]	2.48E+08	1.1	2.75E+08	5
Fiberglass (general except for composite)[79]	5.47E+08	1.5	8.21E+08	4
Fiberglass resin in boat hull[80]	**1.15E+09**	**6.7**	**7.63E+09**	**4**
Fiberglass resin in car[81]	**1.15E+09**	**1.3**	**1.51E+09**	**4**
Glass fiber Column[71]	**6.17E+10**	**0.51**	**3.14E+10**	**4**
Glued laminated timber[82]	1.20E+09	0.75	8.95E+08	2
Gypsum and cement (fiber)board[83]	8.25E+09	0.27	2.19E+09	3
Gypsum wallboard in drywall[83]	2.46E+09	0.34	8.36E+08	2
Hardboard[84]	**2.12E+09**	**0.69**	**1.47E+09**	**5**
Ink cartridge[85]	1.94E+09	6.0	1.17E+10	2

Laminated veneer lumber[82]	1.43E+09	0.62	8.87E+08	5
Leather shoe[86]	**7.30E+08**	**10**	**7.56E+09**	**4**
Linoleum floor[87]	7.43E+07	0.66	4.88E+07	4
Marble chip floor tile[88]	**2.27E+09**	**10**	**2.35E+10**	**4**
Medium density fiberboard[89]	4.04E+09	0.31	1.24E+09	4
Medium density spray foam insulation[90]	**2.34E+08**	**24**	**5.57E+09**	**5**
Metal composite material[91]	4.08E+07	11	4.43E+08	4
Metal panel[91]	1.38E+09	11	1.53E+10	3
Oriented strand board[92]	1.72E+09	0.74	1.28E+09	4
Painted metal coil[91]	1.87E+10	8.3	1.55E+11	2
Paper towel pulp[93]	**1.52E+09**	**26**	**3.89E+10**	**4**
Particle board[94]	1.85E+10	1.2	2.22E+10	3
Phenolic foam insulation board[95]	1.60E+08	7.2	1.16E+09	4
Plasterboard[96]	**6.02E+10**	**0.21**	**1.29E+10**	**3**

Polyester reinforced PVC roof	3.64E+08	3.8	1.37E+09	4
Polyethylene Terephthalade (PET bottle, other products)[97]	3.48E+09	5.5	1.91E+10	2
Polystyrene foam board insulation[90]	**1.52E+09**	**38**	**5.68E+10**	**5**
Polyurethane chair[98]	**2.34E+08**	**7.8**	**1.81E+09**	**4**
Polyvinyl chloride deck[99]	**3.64E+08**	**6.1**	**2.22E+09**	**4**
PVC floor[87]	3.64E+08	2.9	1.05E+09	4
Quartz flooring resin[87]	**2.27E+09**	**7.1**	**1.61E+10**	**5**
Rolled metal cladding[91]	6.52E+07	3.2	2.06E+08	2
Rolled steel plate column[71]	2.61E+08	1.0	2.60E+08	3
Softwood plywood[100]	1.24E+09	0.79	9.85E+08	4
Steel grating[67]	1.99E+09	1.2	2.46E+09	2
Textile shoe[101]	**1.01E+09**	**7.9**	**7.90E+09**	**4**
Unsaturated Polyester Resin column[71]	1.04E+08	2.8	2.92E+08	4

Virgin wood plastic composite deck[99]	1.92E+09	1.0	1.94E+09	2
Wood wardrobe[94]	1.99E+09	0.010	2.10E+07	3

Expert Interviews

a) Shiju Raveendran Associate Professor- catalysis engineering |University of Amsterdam
b) Lukas Hoex Manager Strategic Growth at Niaga/DSM
c) Jelle van der Werf Project Leader R&D "New Business Development" | DSM Coating resins
d) Alwin Papegaij Application development specialist | DSM Coating resins
e) Andrea Rusman Associate |True price
f) Tim Bouwsma Upholsterer | Meubelvisie
g) Jeanine Sidran Senior Program Services Specialist | StopWaste
h) Tyler Rubright Biologist at US Environmental Protection Agency (EPA), Resource Conservation and Sustainability Division
i) Thijs van Velzen Corporate communication adviseur/ spokesman | AEB
j) Arie Mooiman Advisor Technique and Sustainability | Koninklijke Nederlandse Vereniging voor Bouwkeramiek
k) Mark Goedkoop Developer of ReCiPe method

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