Mattress Ticking Waste

Creating Circular Products

Master thesis
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Preface

During my education at the TU Delft I have done many projects of which this last project was the most challenging one. To find a solution for an apparent waste material was not the main focus of the education, but overall design techniques are also suitable to apply to waste problems. The result for the waste ticking challenge can be read in this thesis.

First of all I would like to thank Ruud Kortink of Matras Recycling Europe for providing me with the chance to try and come up with a solution for waste ticking. And of course for providing me with his insights in the mattress recycling industry.

I would also like to thank my coaches from the technical university Delft, Henk Kuipers and David Klein. Thank you for your patience during my project and for the feedback given during our meetings. And of course for keeping me on track during this project.

And to my parents and sister, thank you very much for believing in me and your support during my graduation. And just like my coaches for keeping me focussed on finalizing this project.

Of course I would like to thank Amandine Marie for pushing to finalize the project and helping me during the research and final stages of the project.

And of course thank you to all others who have helped me during the project.

I hope that the readers of this thesis will become more aware of how difficult some products are to recycle and help them to keep thinking about the end-of-life of their products.

Tjerk E. Alewijn

Executive summary

On a yearly bases approximately 1,5 million mattresses are discarded in the Netherlands. Matras Recycling Europe (MRE) is an Utrecht based company that specialises in disassembling mattresses. MRE is able to recycle 250.000 to 300.000 of the 1,5 million mattresses.
Most of the pieces that are separated from these mattresses can be re-used in other applications. The outside layer of a mattress, known as ticking, has not found a useful application yet. In order to fit in a circular economy it is desirable to be able to re-use the ticking waste. In this thesis, the possibilities are researched for the application of mattress ticking. The main research question is therefore:
How can recycled mattress ticking be treated to design useful applications?

Starting Point
At the start of this thesis the common solution for the re-use of ticking waste is to shred the material and press it into sheets. The name for these sheets is TEPA. It can be used as insulation in renovated or new floors in buildings. However, the amount of ticking waste is greater than the amount of TEPA used. This is also a reason to find another application for ticking waste.

Processing
For recycling purposes it would be desirable to be able to separate the different materials For the most part it is made of polyesters, cotton and other natural fibres. At the moment this is hard and too expensive to seperate these materials. . There are no large scale separation processes for this purpose. Several other processing techniques where analysed to find a useful one for ticking waste. A choice was made to use an adjusted version of the existing process. The adjustment means that the waste material is pulverized into smaller, dust like, pieces to create a material that is more homogeneous than TEPA.

A product
After the waste material is pulverized, a sheet can be pressed and a product proposal can be made. The unique properties of this sheet point in the direction of an acoustic solution. Acoustic solutions can be a suspended ceiling or wall panels. After a cost analysis comparing these solutions a choice is made to design wall panels.

These wall panels are called Acoustic Ticking. During the production process several shapes and surface finishes can be pressed into the sheets. The installation of the panels can be done using a profile that can be screwed onto the wall and the acoustic panels. These profiles will hook into each other. The acoustic properties of the room will also improve because the profile creates a gap between the wall and the panels. Also the removal of these panels is easy because they can be lifted off the wall and sent to the manufacturer to be recycled again.

Dilemmas

There are however a few factors to take into account. The flammability of the untreated Acoustic Ticking, just like TEPA, is high. This can be reduced by treating them with a solution that is also used for curtains and furniture. The other factor to take into account are the dimensions of the fibres to not be hazardous for people. The dimensions of polyester and natural fibres however are large enough for the human body to safely dispose of.

Recommendations

At the end of this thesis recommendations are given for mattress manufacturers to simplify the recycling process of their products. These recommendations include use of fewer materials, fewer layers of ticking and use other material for their stitches.

Recommendations for the future development of the material are to see how the ticking waste responds to another round of recycling and if it is possible to be coloured. Another recommendation is to look into how the material responds to the flammability solution.

The design of the Acoustic Ticking could be improved by looking into other hanging systems for the panels, see what other shapes can be manufactured and if it in some way can be used as a construction material.

The final result of this thesis is an acoustic panel that extends the life-cycle of ticking waste materials. This solution uses no virgin materials and fits the circular economy diagram made by the Ellen MacArthur Foundation. Also, the manufacturing of the acoustic panels has the possibility to process a large amount of ticking waste that would otherwise be incinerated.

Contents

1

Project description

1.1. Assignment

On a yearly basis around 1,5 million mattresses are discarded. Most of them end their life in the incinerator. Before 2012, all mattresses were sent to Germany to be incinerated and/or recycled there. After some regulation changes this was no longer allowed.

Some companies in the Netherlands started recycling mattresses after these regulation changes. One of these companies is Matras Recycling Europe in Utrecht. They found that most of the mattress can be recycled. For the ticking however, no useful purpose to recycle it has been found yet. Ticking is the outside layer of a mattress. This material is still discarded after use. All other components of the mattress can be recycled in one way or another. The springs for example can be shredded and sent to a metal recycler. The foams on the inside of the mattress are used as acoustic floor panelling, dashboard insulation or gym mats for example.

On a weekly basis a 40 foot container is filled with ticking waste of the recycled mattresses, this is about 8000 kilograms.

A previous project was done with this material which had a nightstand as outcome. However, the material was still not usable. The improvement of this material will be one of the focus points of this assignment.

The Dutch government (Rijksoverheid) is also focussing on making the use of materials in the Netherlands more circular. They have stated this in 2003 in the LAP (Landelijk Afvalbeheer Plan/ Waste management plan). The goal is for the Netherlands to become completely circular in 2050.

1.2. Problem definition

The problem that this project deals with, is: When recycling a mattress, the ticking becomes waste, for which no purpose to be able to reuse it has so far been devised.

In order to produce less waste in the Netherlands, in this case the mattress industry, materials should be used more than once, preferably endlessly. So, this project will be about using ticking waste to create a material that can be used to make products. This material should have the property of being used more than once.

1.3. Assignment description

The assignment is to find new applications for the use of mattress ticking waste.

The material should also be used more than once in one way or another in order to fit in a circular economy. During the course of the project the material is studied and improved in consultation with different parties.

Because the expectation is that there will be more waste in the coming years it is important to show how to be able to use waste in a usable, useful and valuable way.

1.4. Result

This project shows how seemingly non-recyclable, non-virgin material can be used to create products. In this way companies do not have to create waste but only products.
The final result of this thesis is a product proposal about what to do with ticking waste. Also recommendations are made for future development of these ticking waste products and future mattresses.

Furthermore, they can think about retrieving the used products to their companies to create other and new products.

1.5. Research questions

1. How can the material be used in a circular economy
2. Why choose mattress ticking to recycle instead of other parts of a mattress
3. How can recycled mattress ticking be improved to be usable
4. What improvements can be used to create value to the material
5. What are the properties of the improved material
6. Can the improvements be implemented in a circular economy

7. How can the material be improved by adding as few additions as possible
8. What are the unique properties of the different materials
9. What do current recycled products look like and are these products suitable for use in a circular economy
10. How can the current shredding and pressing method be improved to create different properties
11. Can the material be treated with heat to create an improved material
12. How can the shredded material be improved to not be perceived as ‘confusing, messy or disgusting’
13. Is it possible to create layered material with different fibre directions
14. What is the role of hygiene while using this material
15. What materials are used in mattress ticking

1.6. Reading guide

The start is an analysis of literature on this topic for a better understanding and a view of the problem that this assignment deals with.

This analysis will include a look into a previous project about recycling mattress ticking to see the current state of recycling mattress components. Also different theories on waste management are looked into.

Following this information a look into mattress ticking is given. Some tinkering will be done with the material to get a feel for its properties.

When the properties are roughly discovered several waste managing processes are looked into. A choice between these processes in done based on feasibility, suitability for the material and cost.

After the choice is made on which process is to be looked further into a comparison is made with a similar material to discover the unique properties of the new material.

Based on these unique properties a product proposal is made on what to do with the material. The proposal that is made could have gone in different directions so a specific choice is made based on the cost of the production process to get to a final product.

The second to last chapter will include answers to the research questions and a conclusion on the project.

The final chapter will discuss recommendations for future development of the material, design and improvements for mattress manufacturers. A personal evaluation on the project can also be found in this last chapter.

This chapter describes the context of this thesis. A look is taken into the company and its stakeholders. Also mattresses are described and in particular the part of the mattress this thesis is about, namely ticking.

2
Context

2.1. Company

The previous project has been done for the company Matras Recycling Europe (MRE). This is a Dutch company which is based in Utrecht. The idea for the company came when the current director was on a visit at a recycling plant in Germany and saw a Dutch truck delivering mattresses. After the visit Matras Recycling Europe was founded with two companions.
Currently, MRE recycles 250.000 to 300.000 mattresses every year. Around 1200 mattresses can be recycled every day. This last number can however only be attained in case of a constant supply of materials. This does not take into account mattress deliveries, the ratio of complex versus easy mattresses and holidays. The actual throughput, taking all factors into account, is about 750 mattresses per day.

According to director Ruud Kortink of MRE, mattresses are becoming more complex in production. More and more materials are used in the mattresses. This makes them harder to recycle. Kortink also mentioned that earlier mattresses, which can still be found in the factory, are much easier to recycle because they consist of fewer materials.

Because other countries in Europe are also getting into recycling the market is flooded with waste material. This creates a threat for Dutch companies since this waste material is also offered to Dutch waste processing companies. These waste companies can only process a portion of the offered waste.

Recycling hall
A graphic representation of the recycling hall can be found on page 19.

Number one in figure 1 is the disassembly line for mattresses. The mattresses are laid on workbenches where they are cut open to remove the inner layers.
The ticking is then put into large carts next to the disassembly line awaiting being sent to a processing company.
The cores that contain springs are put on the conveyor belt next to the workbenches and will end up in a

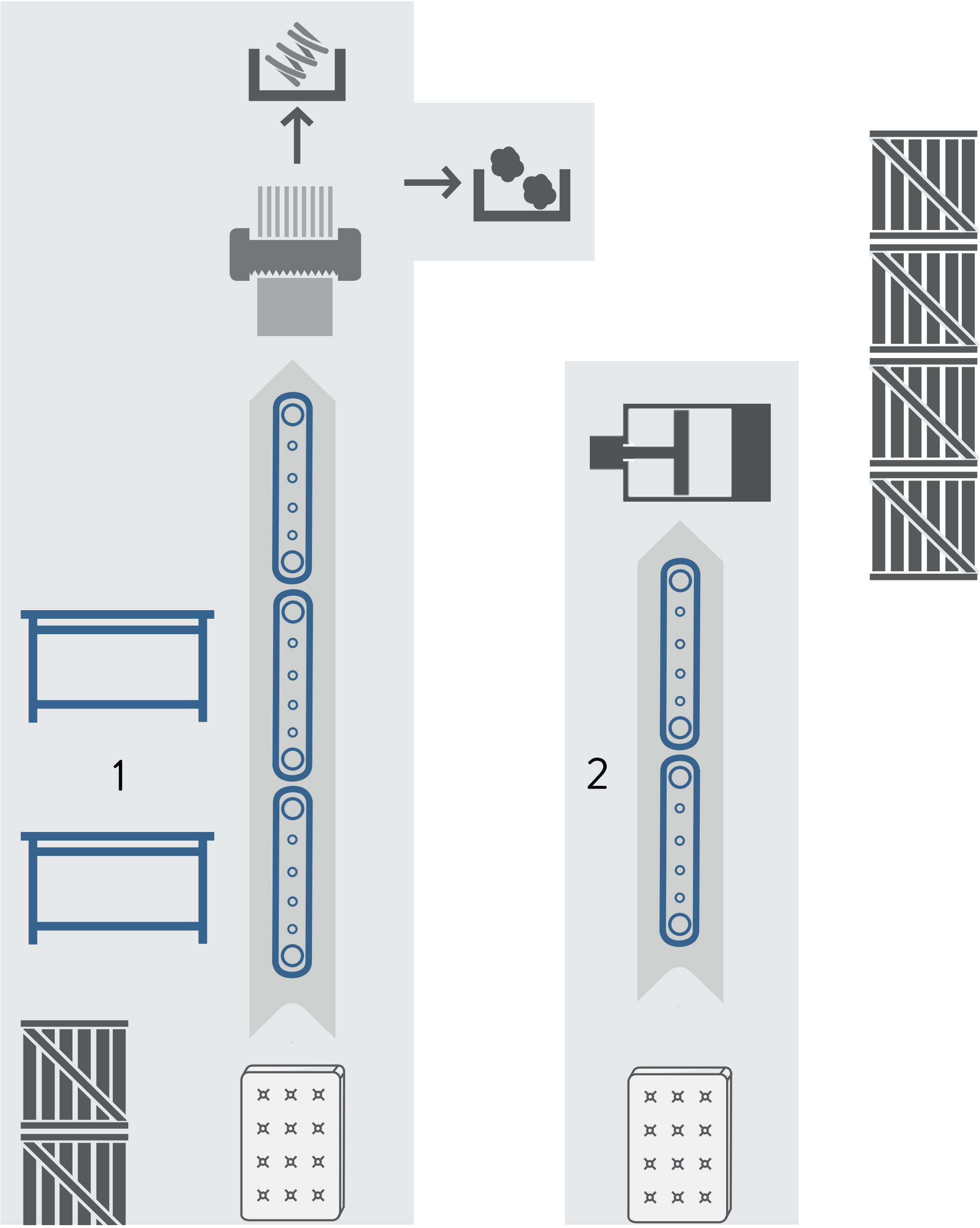


Figure 1: Overview recycling hall

shredder that separates the springs from its textile wrapping.
The foam cores are put on the conveyor belt at number two. These cores are pressed into bales and are sent to a company that processes it further.
As becomes clear, MRE is only a disassembly company. The separated waste streams are sold to other companies to be processed further.

Competitor

The main competitor in the Netherlands is RetourMatras. They claim their factory can recycle up to 400.000 mattresses a year. The headquarters of RetourMatras can be found in Nieuwerbrug aan den Rijn. Their recycling plants are located in Lelystad and Alphen aan den Rijn.
Auping has a deal with RetourMatras to recycle mattresses. Auping calls this its take back system.

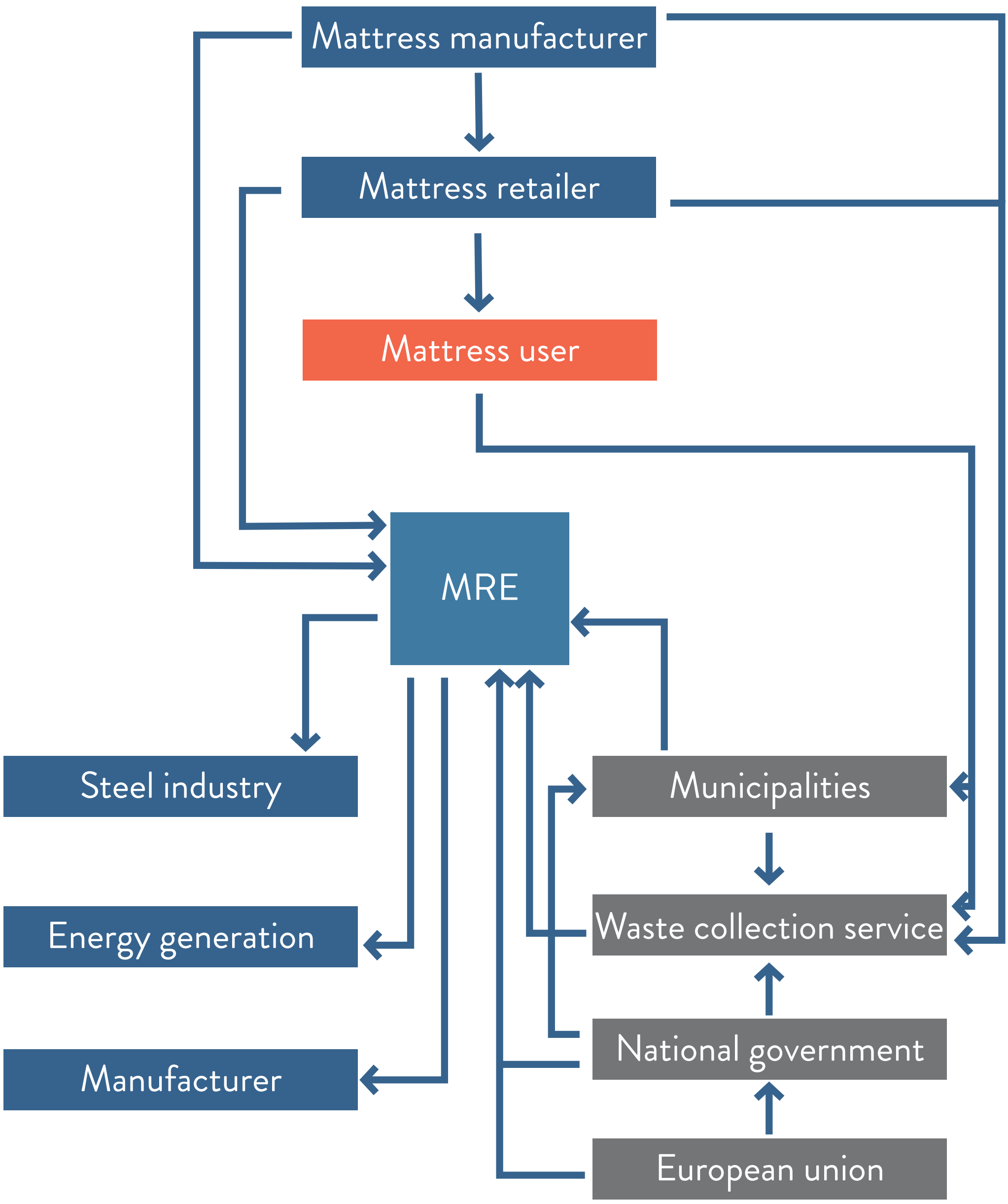


Figure 2: Stakeholder overview

2.2. Stakeholders

Next to the competitors there are several other stakeholders involved with MRE. Figure 2 displays an overview of the various stakeholders that are involved. Most information about the stakeholders was found in the graduation report of A. van den Dool. (Van den Dool, 2016)

The government plays a role in mattress recycling because she provides the guidelines and legislation for waste management. An envisioned circular system for mattress recycling was created based on a report from Narinx (Narinx, 2016). In the Netherlands the waste collection and disposal is regulated by the municipalities. The municipalities are in contact with waste management companies to dispose their household waste. Waste management companies are in contact with specialized companies, like MRE, to dispose of certain types of household waste.

At the moment of writing there is a bill to hold Mattress Manufacturers and Retail Businesses responsible for the correct disposal of their waste from 2019 onwards. The mattress manufacturers and retailers are therefore responsible for the disposal of their mattresses. Some businesses have a contract with MRE to collect their mattresses or deliver the mattresses themselves for recycling. Some other companies have a contract with a waste management company to dispose of mattresses.

The waste management company contacts the recycling companies to get rid of these mattresses. Matras Recycling Europe has connections with large companies, like IKEA and Beter Bed, in order to give recommendations to the manufacturers to make mattresses easier to recycle and disassemble.

At the end of life stakeholders can be found too. Recycled metal parts are processed by the steel industry. The foams that will come out of the core of mattresses are made into new products like cow mattresses. But the textiles are currently incinerated because there is no option for it to be re-used.

2.3. Mattresses

Generally, a mattress is constructed in three layers. These layers are the core, shell and tick.

The core is mostly made from polyether foam, latex foam or springs. Surrounding the core is the shell, which is commonly made from polyether foam, latex foam, horse and camel hair, coconut fibres, polyester (PET), cotton and/or wool.

The ticking, or outer cover, is mostly made from a polyester/cotton blend. This ticking cover can also exist out of multiple layers which are stitched together. Chapter 2.5 will describe examples of ticking found in the recycling hall of MRE.
These layers are stitched or glued together and therefore makes it more difficult to recycle the ticking.

Mattresses can be classified in five main groups. These main groups are: pocket springs, steel core, memory foam, latex, and PU foam. The mattresses with pocket springs and steel core have metal parts in them. These parts can be recycled by the metal industry since it is easy to separate and recycle them to create new metal parts.
The foams are recycled into gym mats, cow mattresses or underfloor panelling.

MRE commissioned Texperium to analyse the ticking material. The most common materials that are found in ticking are polyester and cotton (in combined form at 40% of the batch). In different kinds of mattresses horse hair or sheep wool could be found, among other materials.

Figure 3 displays the analysis of Texperium on what pieces of ticking can be reused.

When looking at the most common materials, polyester and cotton, the report of Van den Dool described the polyester as a thermoset. Which might be the first thing one thinks about, for example the polyester most boats are made from nowadays. These polyesters are resins which are cured by adding hardeners. However, when looking into polyesters there are various kinds. Most of them are thermoplastics. (Rosato, Rosato, & Rosato, 2004)

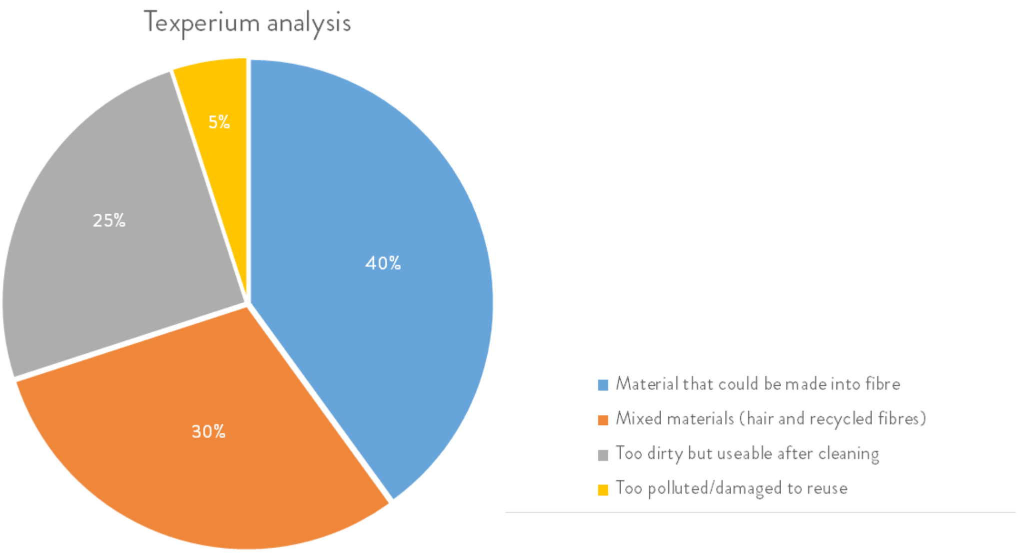


Figure 3: Texperium analysis of one ticking batch

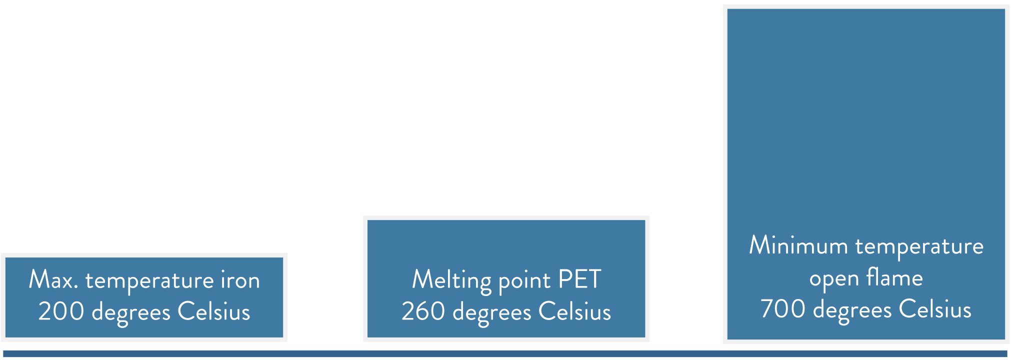


Figure 4: Temperature overview heating opportunities

As can be read in the next paragraph some different samples were created in the thesis of van den Dool by trying to iron them and by burning them. These temperatures however are either too cold or too hot for the polyester which is mostly used in textiles, namely Polyethylene terephthalate (PET). This plastic has a melting point of around 260 degrees Celsius. (CES Edupack, 2017, unfilled, semi-crystalline PET) The maximum temperature of a flatiron is around 200 degrees Celsius, and an open flame is mostly well above 700 degrees Celsius. (figure 4)
So the polymer bindings in the used PET samples did not melt enough to bind the ticking together with the flatiron. Or the melting occurred too fast to notice and burned the sample when using an open flame.

PET/Cotton blends
One of the challenges will be that the PET fibres in the textile are blended with cotton, also known as a composite material. Because of the different properties of the materials in composites they are more difficult to recycle. In this case the cotton has a lower ignition temperature than PET.

Separating the cotton and PET fibres is difficult. The fibres are intricately mixed with each other and cannot be separated physically or chemically. (Zou, Reddy, & Yang, 2011) Zou, Reddy and Yang mention that developing composites made from PET and cotton requires that the cotton fibres have minimal thermal degradation during the melting of PET. The production method that was used during this research was compression moulding, because of its low cost and simplicity. To prevent the cotton from degrading too much during the moulding plasticizers were used to lower the melting point of PET. However, the mechanical properties of the PET/cotton blend composite were better when using no plasticizers at all.

When comparing the mechanical properties of the PET/cotton blend composite from the research by Zou, Reddy and Yang research to other materials in the Cambridge Engineering Selector (CES, 2017) the graph in figure 5 was created.

The orange bubble is representing the PET/cotton composite. When looking at this graph the Young's

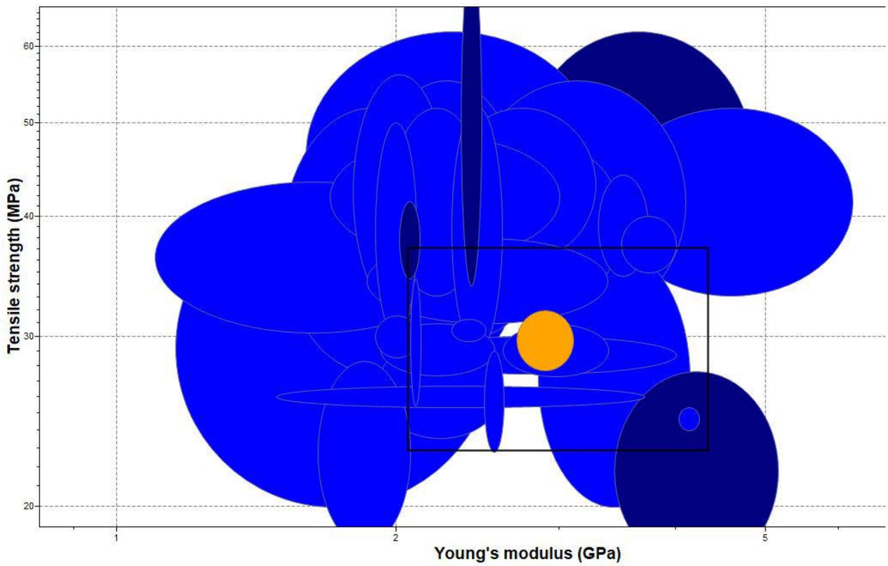


Figure 5: Comparison PET-blend to PP, PS,ABS, PC and PLA

Modulus and Tensile strength are comparable with some kinds of other plastics, namely PP, PS, ABS, PC and PLA among others. These comparable materials all have different additives.

The conclusion that can be drawn from this figure is that the properties of a PET/cotton blend can be similar to plastics. Although a PET/cotton blend might seem weak or too flexible there is a solution to fix it into a shape by pressing and heating.

2.4. TEPA

The current material that is made from waste ticking is called TEPA. A sample can be seen in figure 6.
TEPA is made by shredding and pressing the pieces into sheets by adding an adhesive.

The material is rather coarse. This is due to the current setting of the shredder. The difference between the materials used in ticking can be clearly felt. Harder and softer pieces can be identified in the sheet. The material is clearly heterogeneous.

The figure below that (figure 7) is a representation of the material van den Dool has made in her project. She eventually came up with and alteration of the material as it was provided to her.
After testing various techniques the final material that came out of the project of van den Dool was a sheet of shredded ticking which was used as a core in a sandwich panel. The outer layers were made of three thin layers of PP. This gave the shredded ticking sheet more stiffness and a smooth appearance. However, three layers were not enough to create an even surface without holes, so more or thicker layers of PP should have been added to create a smooth surface without holes. Eventually the PP would be replaced by PLA.

A remark that has to be made is that the addition of another material, bio-based (PLA) or not (PP), is not desirable in a circular economy because it makes it harder to recycle a second time. Also, more energy is put into the creation of the sheet by not only shredding the ticking but also in creating the material for the outer layers of the sandwich panel and fixing it on the shredded sheet of ticking.

Figure 6: Untreated TEPA sheet

Figure 7: TEPA sheet with PP outer layer

2.5. Ticking build up

This section describes different ticking materials that could be found in the hall of MRE. It shows how ticking is built up and how many layers there are. Also, it shows that there are some similarities between some ticking but differences too.

The figures show from top to bottom the inner layer to the outer layer. It also shows which materials are found in the ticking.

Ticking 1 - Bedderie

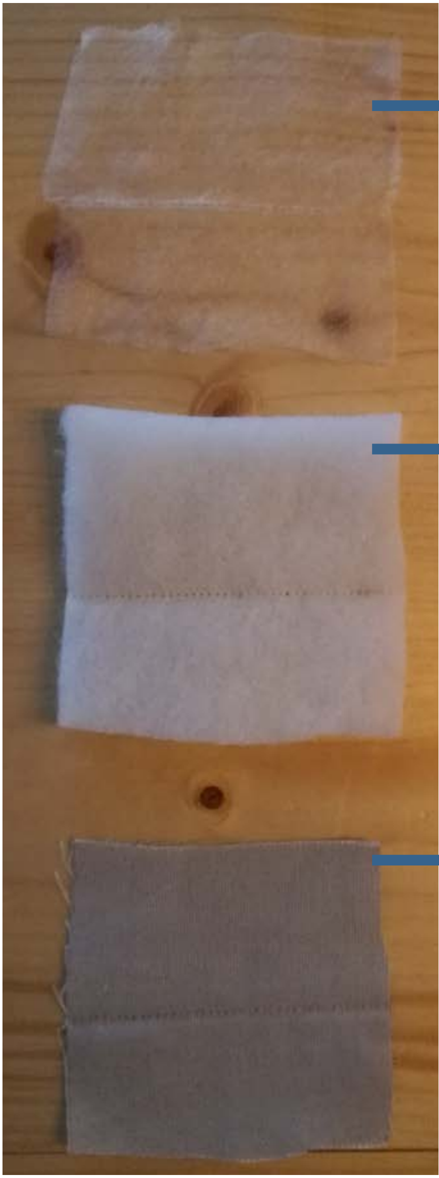
Inner layer
Thin protective piece of fabric

Middle layer
PU foam of about 8mm thick

Outer layer
Tightly woven fabric

Remarks
The vertical lines are made by the stitching that kept the different layers together.

Ticking 2 - IKEA



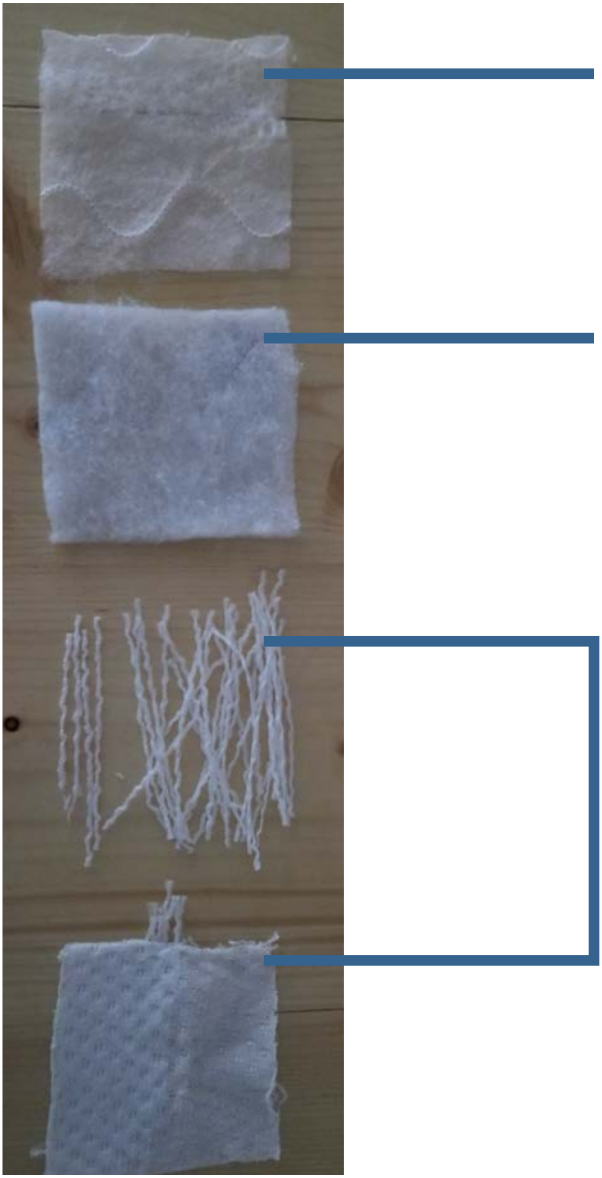
Inner layer
Thin protective layer

Middle layer
Felt like material from PET fibres

Outer layer
Tightly woven, stiff material

Remarks
The horizontal dotted line crossing the pieces of ticking is caused by stitching

Ticking 3 - Unknown manufacturer



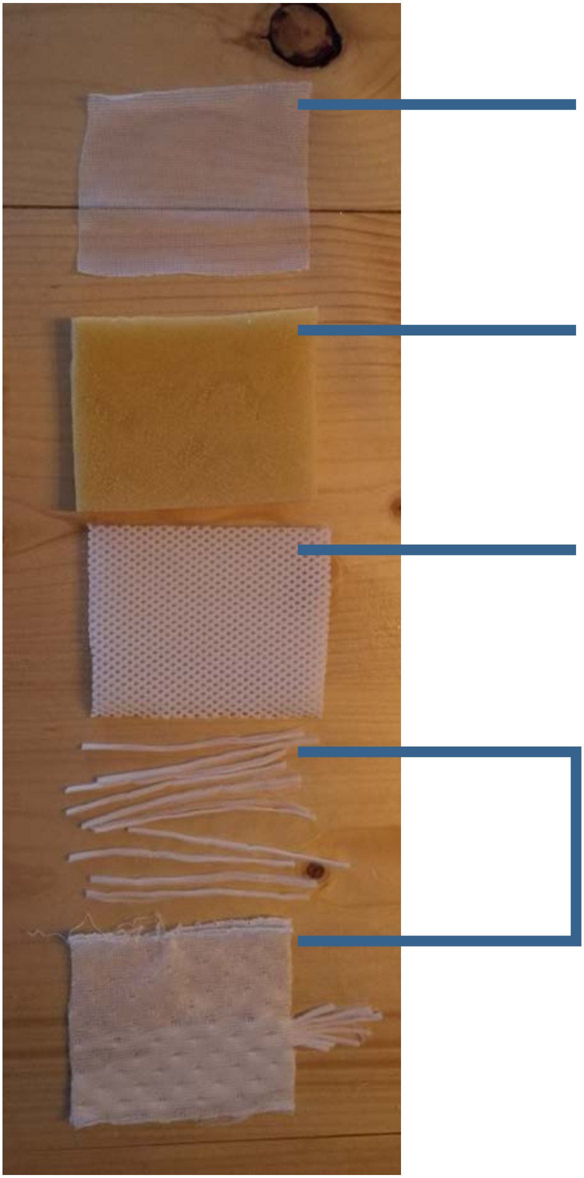
Inner layer
Thin protective layer.

Middle layer
Felt like material from PET fibres.
Thinner than the previous ticking.

Outer layer
The outer layer consists of two woven layers with strings of fabric in between.

Remarks
The wave line is made by stitching.
The outer layer is melted together to keep the strings in.

Ticking 4 - Auping



Inner layer
Gauze like, firm material

First middle layer
Foam

Second middle layer
Foam made from pulled fibres

Outer layer
The outer layer consists of two layers which are melted together with strings of fabric in between

Remark
The layers of this tick are only stitched together on the outside. This makes it easier to recycle.

2.5.1. Ticking results

As can be seen on the previous pages ticking is made up of materials like foams and fibres in different processed forms. The fibres are mostly made from PET which can be found in mixed form with hair or cotton.

It can also be seen that most of the ticking waste is stitched together, which makes it complex to recycle.

The last example is a ticking from Auping, which is one of few companies looking into what happens to mattresses at their end-of-life. This ticking was only stiched together on the outside to keep the layers together. By using stitching only on the outsides the ticking can be disassembled and recycled more easily.

Looking at the ticking examples it becomes clear how difficult it is to recycle the material. Therefore a solution for the current situation of ticking should be to be able to recycle all of the ticking waste.

2.6. Conclusion

Large amounts of mattresses are discarded every year in the Netherlands, namely 1,5 million. Of this amount of mattresses approximately half are recycled by Matras Recycling Europe (MRE) and their competitor. One of the reasons not all mattresses are recycled is the processing capacity which is not enough for the amount of discarded mattresses. Another reason is that not all materials in the mattresses have found a useful purpose yet.

Mattresses roughly consist of three layers. The core, shell and ticking. The materials from the core can be used in other products like cow mattresses or gym mats. Since MRE is only a disassembly company the materials taken from the mattresses are sent to other companies who can use the material as a raw material for other products.

The ticking is currently shredded and pressed into sheets, known as TEPA, to be used as insulation material in floors. TEPA is not yet sold well enough for it to be a useful purpose to recycle ticking. This is also a reason to try to find another solution other than insulation.

The ticking waste is mostly made from polyester (PET) and cotton. Other natural fibres and foams can also be found in ticking. This information about the materials in ticking can be of use when looking into existing recycling processes and what process might be best suited for ticking waste.

One research is done by Zou, Reddy and Yang into the recycling of PET/cotton blends from fabrics. This material was pressed into samples by applying heat and pressure. The result were samples which came close to the mechanical properties of other thermoplastics. This information is used later on in the report.

3
Literature review

3.1. Preceding project

In the graduation thesis of van den Dool (Van den Dool, 2016) this chapter was called 'tinkering'. According to the Cambridge dictionary to tinker means: 'to make small changes to something, especially in an attempt to repair or improve it'.

The last part in the definition of tinker, repair or improve it, forms a basis for various theories about waste management. These theories will be discussed in chapter 3.5 to 3.7.

Tinkering in preceding project

During the tinkering phase, van den Dool tried the following techniques in order to find a solution for the material.

- Unprocessed material: Some samples from different ticking material were selected and examined
- Shredding: Other samples were put in a shredder in order to create small pieces of material
- Spinning: Pieces of ticking were cut into strips to mimic yarn

- Felting: Only the filling of the ticking was used to create felt
- Pressing: By mimicking the process of paper recycling, the material was soaked in water and then pressed together
- Additives: Glue, plaster, wax and bleach were added to the ticking to try and create a composite material
- Resins: These were added to try and make a sheet of composite material.

The conclusions from this tinkering phase were:
- The materials are suitable to mix with fluid resins. However the drying time should be taken into consideration since this could take a lot of time in some cases.
- When using the non-shredded material it was found that in some cases the stitching of the ticking is still visible. This creates a soothing effect were the shredded material has a messy structure.
- When shredding the material a somewhat consistent material can be created. This could result in uniform samples

3.2. Experience of TEPA

One of the conclusions in this phase of the graduation thesis of van den Dool was that some of the participants were slightly disgusted by the material. A reason could be the irregularities and the colour of the material. Another reason might be that the material seemed dirty because of its texture or flexibility. An interesting outcome was that hygiene, in the sense of bacteria. was not mentioned by the attendants, neither was smell. This focus groups only consisted of four industrial design students, which does not represent a large group of Dutch people. These students are also trained in thinking of solutions for these kind of materials so they see other challenges than the average Dutch person. When showing pieces of ticking to other people than students hygiene issues where mentioned and these people were disgusted by the idea the ticking waste was once part of a mattress.

Another conclusion was that the samples with shredded material were not that interesting for the focus group. The samples with intact material were recognized and led to less confusion.

An interesting conclusion is that the students found it easier to come up with possible applications for the stiff materials rather than the flexible materials. This might be because they are used to designing with existing hard materials.

3.3. Material discussion in preceding project

Three material directions were chosen by van den Dool to look into further based on the outcomes of the focus group research. These directions are TEPA, coating and unprocessed ticking material.

TEPA solution
TEPA is made from waste ticking and is currently under development at Latexco in collaboration with MRE. This material is quite flaky. To prevent flaking a sandwich construction is made with ticking and sheets of PLA (Polylactic acid)

Coating
Wax is used to coat the material. Candle wax is currently a waste stream that is not separated in the Netherlands. However, in all of the Netherlands candle wax waste will not provide enough material to combine with all the ticking.
Also, from a recycling point of view the candlewax should be re-used as candlewax and not be combined with other materials.

Unprocessed material
The unprocessed material has an issue and that issue is hygiene. There might be some stains on the material. The ticking might also have a certain smell which can be perceived as unhygienic. Some further tinkering was done by weaving and stitching the ticking material.

3.4. Landelijk Afvalbeheer Plan

There are several international guidelines for waste management, and there are laws requiring the management of waste. In the Netherlands this law is 'Wet Milieubeheer', which is similar to the United Kingdoms 'Environmental Protection Act'. This plan has to cover a certain period of time. In the Netherlands this is called the Landelijk Afvalbeheer Plan or LAP for short (Landelijk afvalbeheerplan 2009-2021, 2014). The first LAP ran from 2003 to 2009 and was evaluated in 2007. After the evaluation some changes were made to the plan and in 2009 the LAP2 came into effect. In the meantime some corrections were made and at the fourth quarter of 2017 the plan known as LAP3 came into effect until 2023.

In these plans the goals for waste management in the Netherlands are explained. Seven streams of waste are defined in the LAP2. A few examples for these streams are paper, textiles, aluminium, and coarse domestic waste.

Mattresses are included in the coarse domestic waste. According to the LAP2 the most environmental benefit can be achieved by separate collection of various products defined as coarse domestic waste, like tapestry, mattresses or furniture. These separate groups of products should be re-used, recycled or eventually be used as secondary fuel.

Also, eco-design could play a large part in creating sustainable products. According to the Dutch government the change to a more sustainable way of life should be in giving products a longer life-span, which can be attained by repairing and refurbishing products where possibl. Furthermore, materials should be capable of efficient re-use and separation. And eco-design should be developed to design for a circular economy with attention to new business models.

3.5. Circular economy

The aim of the government in the Netherlands with the LAP is to halve the use of resources by 2030 and even become completely circular by 2050.
A circular economy is defined in a report from CBS (Delahaye & Baldé, 2016) and is described as follows:
'An economy which provides in need for necessary goods without unacceptable pressure on the environment and without depletion of natural resources.'

This is necessary because in the same report it is stated that the use of resources increased tenfold between 1990 and 2009 and is expected to rise further when no action is taken. This is not desirable because the recovery and processing of raw materials creates pressure on the environment and creates more emission of carbon dioxide.
Secondly it is not desirable to keep on using raw materials the way it is done now because the reserves of certain resources decrease significantly.

Linear economy
As of now the economy we live in is called a linear economy. This means that resources are used to create parts and products. These products are sold to the users and eventually the user disposes of these commodities. In this linear economy the use of raw materials is high and the waste streams are large. So, the pressure on the environment is high and the natural resources are depleted quickly.

Transfer to circular economy
When transferring to a circular economy the use of raw materials decreases, just like the waste streams. This is because the user has the choice to repair, re-use, refurbish or recycle their bought products. Expanding the life span of products this way has a lot less impact on the environment and reduces carbon dioxide emissions. And of course the depletion of raw materials is a lot less rapid.

This difference in linear and circular economy is visualized in figure 8 in which the linear economy is on the left. The circular economy is seen

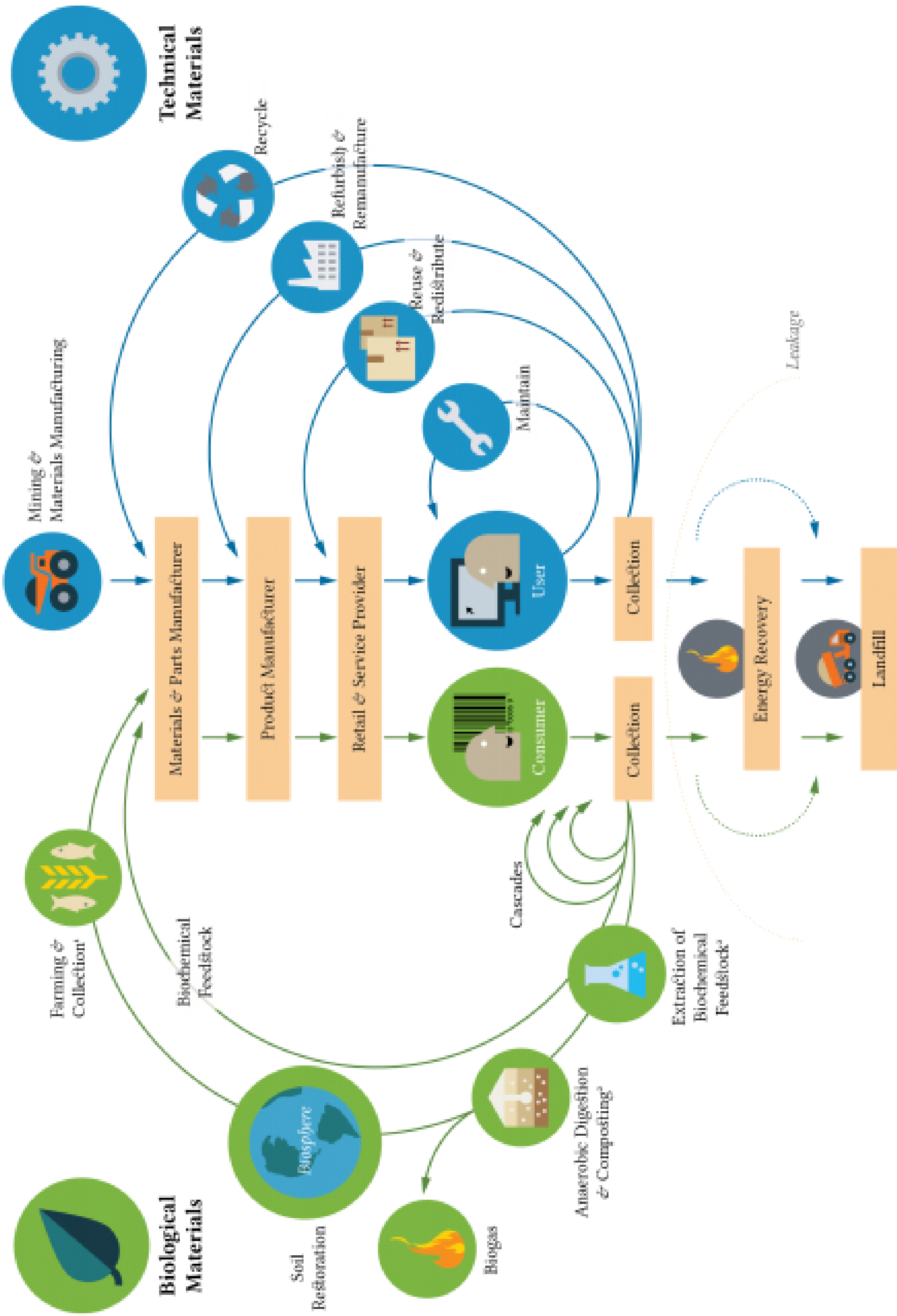


Figure 8: Overview of circular economy by the Ellen MacArthur Foundation

on the left of the figure. This figure is made by the Ellen MacArthur Foundation (EllenMacArthur, 2018).

3.6. Waste hierarchy by Lansink

The waste hierarchy, also known as the 'Ladder van Lansink' in Dutch, is devised by the Dutch politician Ad Lansink. This hierarchy is focussed on prioritizing the most environmentally friendly processing methods of waste. It is also a method on extending the life cycle of products and generating the least amount of waste. The method is illustrated in a pyramid most of the time. On top of the pyramid it shows the most favoured option, which is prevention of waste. The bottom of the pyramid shows the least favoured option, namely disposal of waste. The steps in between can be seen in figure 9.

Ticking waste in the waste hierarchy

The first step in this hierarchy is to re-use the material. This will be most sustainable because no virgin material is processed to create new mattress ticking. However, according to Chapman and Bartlett (Chapman & Bartlett, 2012) people are reluctant to re-use this material because of hygienic reasons. Even if the material is cleaned the idea that the material was used in a mattress is off-putting.

The second step is to recycle the ticking. This can be done by shredding the layers of ticking when they are still in combined form, or by using the separated parts of the ticking. The combined layers of the ticking are a multi material 'soup' of the various materials the ticking is made of. When separating the different layers, these layers can be recycled or re-used into other products.

The last resort would be to create energy from the waste by simply throwing it into the incinerator. This would be the least preferable way, especially if it is burned without energy recovery.

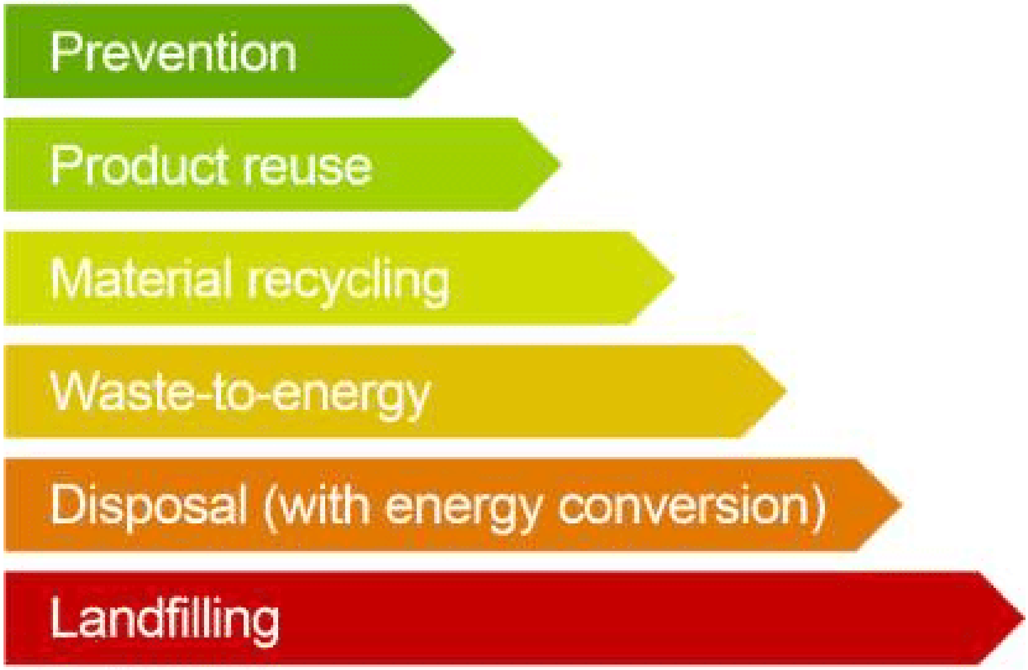


Figure 9: Waste hierarchy by Lansink

3.7. Inertia principle

Another theory on which the circular economy is based is the Inertia Principle of Walter Stahel. An illustration about this principle can be found in figure 10. These steps are mostly aimed at re-using products.
According to the first step, a product could be re-used directly when it is not broken. For the second step, a product can be re-used after a repair. So the components that are broken in the product can be repaired. The third step assumes that a product can be re-used after replacing an unrepairable part in the product. The final step is to only replace or treat the product in such a way that the product maintains its value.

According to M. den Hollander and C. Bakker (2017) the Inertia Principle is about product integrity. They defined product integrity as the extent to which a product remains identical to the product as it is manufactured. The goal of the Inertia Principle is thus to keep the product in its original state, or as close as possible to this state, in order to minimize environmental costs when performing interventions to preserve or restore the product's added economic value over time.

Den Hollander and Bakker mention that the Inertia Principle has an utopian goal. This goal is based on endlessly re-using and repairing products. Unfortunately people want to change products after a few years or do not want the hassle of repairing or second-hand selling of their possesions. So a part of products will eventually end up in a landfill or incinerator.

In the real world, moving down the hierarchy given in the Inertia Principle and the Ladder van Lansink, may be inevitable. In this case of recycling mattresses reasons why mattresses are not re-used in their original state will be given in chapter 4.1. This inadvertently leads to mattresses ending up in recycling and the materials coming from mattresses being reprocessed into other products.

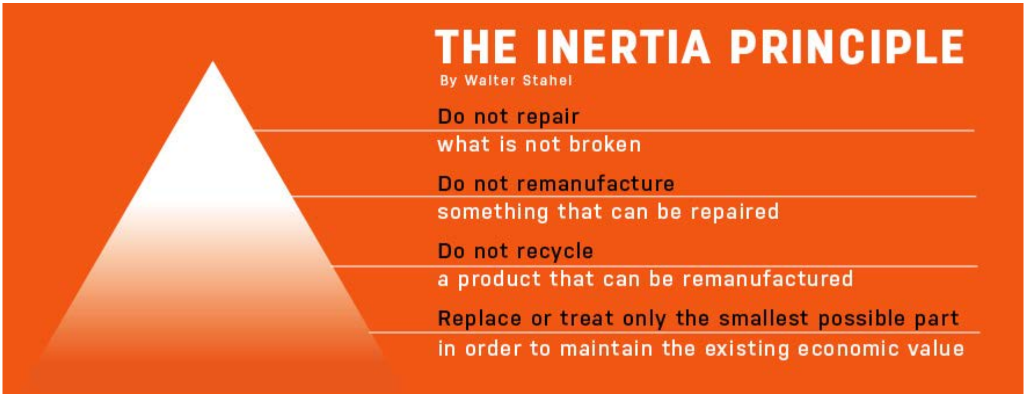


Figure 10: Inertia principle

3.8. Why recycle ticking?

The assignment for this thesis is to look into ticking waste of mattresses, but why not look into one of the other components? The assumption in this analysis is that mattresses consist roughly out of three components, namely the core, foam and ticking.

First of all, as mentioned, the foams are being re-used in other products. When becoming a circular economy re-using is one of the first solutions to look into. These foams can be in the core or the protective inner layer around a pocket spring core. The outer layer always consists of the ticking.

Springs
So why not look into the springs from the core? The first thing to mention is that most springs which are recycled in the Netherlands are pocket-springs. These springs are individually wrapped in a textile skin which makes it difficult and time consuming to separate the spring from its wrapping. The most straightforward solution is to put the whole pocket spring assembly into a shredder. After shredding the textile and steel can be easily sorted by blowing the textile, also known as fluff at this stage, from the mix.

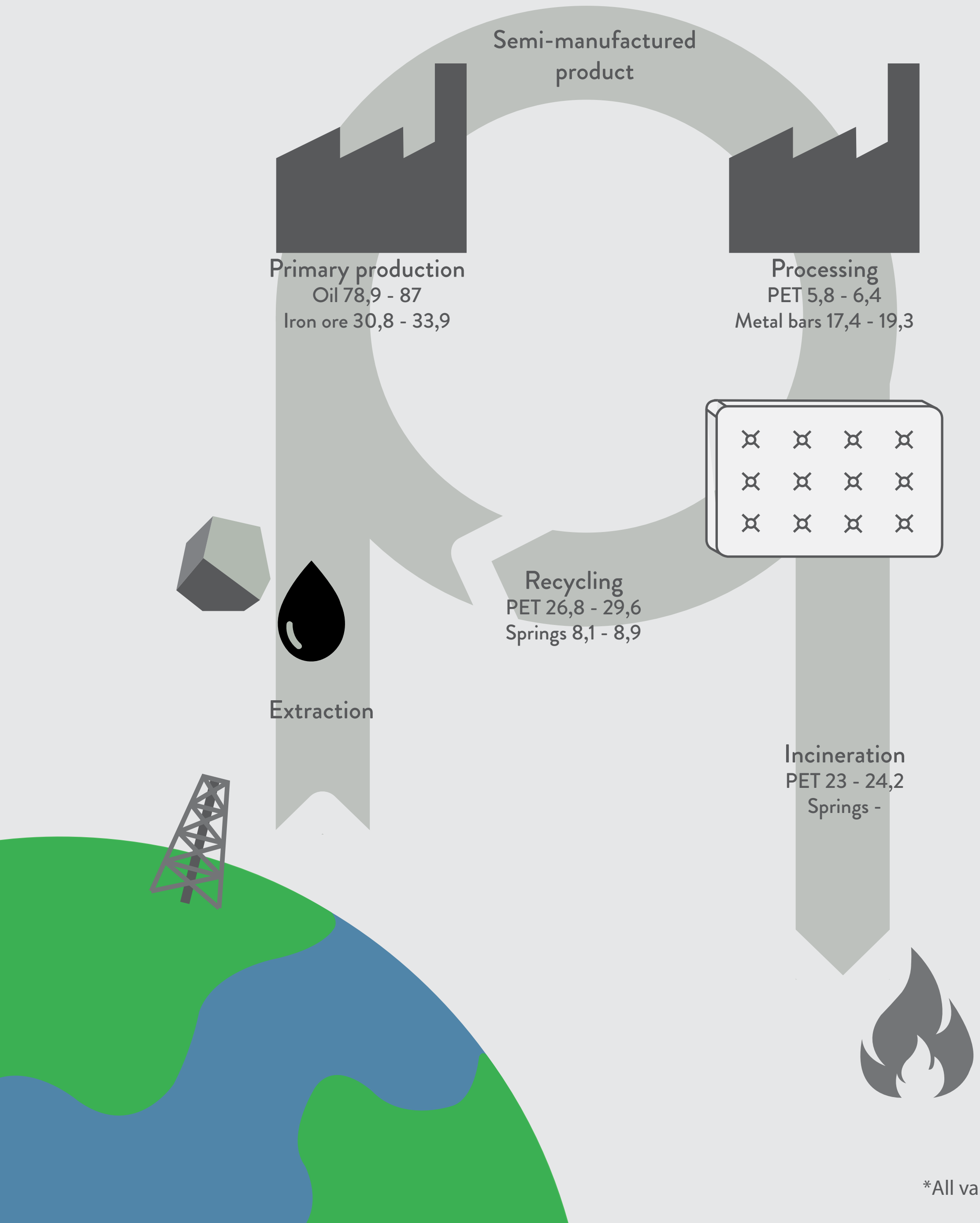
Another solution for the springs can be a machine developed by The Furniture Recycling Group (TFR Group). This machine is able to separate the spring and wrapping without shredding the spring. These springs can for example be re-used by mattress manufacturers.

The most important argument to choose to look into ticking over the springs is to look at the total of materials that are recycled by MRE. According to Ruud Kortink the weights of material for ticking and springs recycled is similar. But the volume of ticking is much higher than that of springs.

Embodied energy
In figure 11 the embodied energy for the various materials can be found.
The embodied energy includes all energy that is necessary to produce goods or services. Ticking can consist of different materials such as PET, cotton, polyurethane foam and other kinds of plastics. These materials

Figure 11: Embodied energy during life cycle of materials

Material cycle - Embodied energy



*All values in MJ/kg

have a mean of around 85 MJ/kg for production. The data provided in the table comes from the database from the Cambridge Engineering Selector ("CES Edupack 2017," 2017)

There is only information on PET for the embodied energy for recycling this material. The other materials are mostly incinerated for energy recovery.

As can be seen in figure 10 the amount of energy that has to be spent to produce and recycle the different parts is much higher for the ticking waste. The total energy used for the production of ticking in the mattress is approximately 91 MJ/kg. Whereas the energy to manufacture steel springs is about 50 MJ/kg.
The energy to recycle PET is however also higher than for steel. (About 28 MJ/kg and 8,5 MJ/kg respectively)
An important remark that has to be made is that the springs can already be recycled whereas ticking waste can not be recycled in a useful way.

It becomes even more difficult to recycle the combined parts of the ticking because they are joined together. Combining this with the information given before the need to find a solution for the ticking waste is higher than for the steel springs.

3.9. Conclusion

A previous project has taken a look into processing techniques to improve TEPA or reusing ticking waste. This preceding project concluded that the material is suitable for the use of resins or other material additions to improve the properties of ticking waste.
Adding material however is not desirable in a circular economy so another solution should preferably be found.
Also the preceding project has tried various processing techniques that do not have to be taken into in this thesis.
Another conclusion from the preceding project is that irregularities and colour differences are not desirable when designing with a sheet material.

One of the factors to take into account is the 'Landelijk Afvalbeheer Plan'. This describes the plan of the Dutch government for using and recycling waste material. Eventually, the economy in the Netherlands should change from a linear one to a circular one.

When looking into the theory of a circular economy products and its materials should be reused multiple times. The use of virgin material should be reduced to relieve pressure on the environment and because the material resources are going to be depleted eventually. Therefore it is not desirable to introduce other kinds of material in recycled ticking because it makes recycling hard and more expensive.
So the circular economy suggests that the ticking of mattresses should be reused first. It is recycled however because of hygienic concerns which still exist after cleaning.

So, to fit in the circular economy the ticking waste should be improved by adding no or as few as possible different materials.

4 Material processing

4.1. Current process of recycling ticking

The first question that rises when looking at mattress recycling is: why are mattresses discarded in the first place? The answer to this question is that plastics in general degrade over time. And because the foams in mattresses are a type of plastic, the foam degrades over time. The bonds in the polymer degrade during use of the product. The dynamic use of the mattress (sitting on the sides, lying down, and moving while asleep) causes these bonds to break. According to research done at the Oklahoma State University (Jacobson, Boolani, & Smith, 2009) mattresses lose firmness after five to six years. This causes dimpling or pit formation and eventually leads to loss of sleep and aching limbs.

The same research suggests that a new mattress increases the quality of sleep, reduces back discomfort, perceived stress, and other improvements in health from their test subjects.

So the support of the mattress decreases over time leading to loss of sleep and quality of health, which makes the direct re-use of most mattresses not likely. Why not refurbish a mattress then?

As mentioned in the previous paragraph, the foams in the core of the mattress degrade over time and are mostly unusable in mattresses in its recovered state. The foams are currently used in other industries like cow mattresses, furniture, and sporting equipment.

Some mattresses also have springs in their core. These springs are made of steel and can easily be reused as assembly, separate springs are recycled in the metal industry. There is a company in the United States of America, called Bedex, who refurbishes mattresses by only using the inner springs. A factory next to theirs puts the springs in the oven to release any stress that might be in the used springs. After that they sanitize and newly coat the assembly to be used in a new mattress. The recycled fibres and fillers of the old mattresses are made into air filters, industrial wipes, judo mats or carpet underlayment. Other patents in mattress recycling can be found in Appendix 8.

According to Chapman and Bartlett (Chapman & Bartlett, 2012) the main reason for not re-using the recovered mattresses or textiles is for hygienic and cleanliness concerns. Also according to that business case washing the textiles was not viewed as cost effective by recyclers because of the low value of the materials.

Some mattress manufacturers offer a take back service. For example the take back service that Auping is offering. When a consumer buys a new mattress from Auping, they have the option to let Auping collect their old mattress. When the old mattress is collected it is sent to a mattress recycler.

Mattress deconstrution process

So, recycling the mattress components is the most used practice to this day because of various reasons. The process used in the factory of MRE is as follows:

1. A mattress is placed on a workbench in order to be sliced open using a knife by manual labour. The manual labour provides more flexibility in deconstructing different kinds of mattresses.

2. The tick, core and shell are separated and processed individually. The core and shell materials are recycled into before mentioned solutions.
Most ticking consists of multiple layers. These layers are mostly stitched or otherwise connected to each other which makes it difficult and time consuming to separate. Therefore it makes separating the materials relatively expensive compared to the value of the baled textile. (Chapman & Bartlett, 2012) According to Chapman and Bartlett the textiles from the ticking and the shell will be collected together and will not be sorted further.

3. The ticking is sent to a company which shreds the textiles into pieces of about 2cm. These pieces are pressed into a bale using a method which is a trade secret. Sheets can be made from these bales to be made into packaging material or a subfloor. These solutions cannot be fitted into a circular economy because after this second use the material is again just discarded and/or incinerated.

4.2. Existing ideas in recycling

In this chapter research is done into recycled products .

De Vorm – Felt PET chair

Description
This is a chair made from recycled PET bottles by.

Processing method
PET bottles are collected, sorted, shredded, cleaned from residual drink and stickers, and put through an extruder to make tread. This thread can be made into fluff, which in its turn is used to make felt.
The felt is pressed into shape using a heated mould. In this case it is shaped into a seat for a chair, but other shapes are possible too.

Consideration
The first consideration is that the PET is put through an extensive process to create felt that uses dangerous chemicals. There might be other solutions that do not require the PET to be processed into fibres, but using it to manufacture sheets made of PET.

Figure 12: Felt chair made from recycled PET bottles

Dakine PET bottle collection backpacks

Desciption
This collection of backpacks made by Dakine is made from PET fibres.

Production process
The start of the production process is similar to the process used in the felt chair.
After the step of creating fluff however, the fluff is sent to another company that creates sheets of the polyester by carding it.
These sheets of polyester are made into thread. The threads are used to weave a sheet of textile.
The textile sheets are then used to cut shapes which are stitched together into a backpack.

Consideration
The consideration for this product is similar to the felt chair. This production process is even longer than that of the felt chair so more energy is put into making the material.

Figure 13: Backpack made from recycled PET bottles

Fossilized furniture

Desciption
Benches, tables and other kinds of furniture made from shredded paper

Production process
These products are made from shredded documents mixed with clear resin. By using a mould, the mix is made into objects like tables, benches or chairs.
An additional layer of polycarbonate can be added to get rigidity or create a flat surface.

Consideration
There are better solutions for recycling paper. For example, using recycled paper to make new paper.
The use and addition of clear resin makes the fossilized furniture harder to recycle after its use. This makes these objects not suitable for a circular economy. The objects are hard to recycle since a mixed material is created.

Figure 14: Bench made from paper and resin

Dear human’s recycled paper furnishings

Desciption
Art objects, chairs or lamp shades made from recycled paper pulp.

Production process
Waste paper is made into a pulp, which is a mix of small pieces of paper with water. This mixture is pressed into the shape of the product the creators have imagined.

Consideration
The creators working on this project consider their creations to be art. They claim the following: “While design considers the functional, aesthetic, economical and sociopolitical aspects of the object and its production, the creation of art is less hindered by such constraints.” This might be true, but using waste paper for these products might not be the right choice since the paper can be used to make new paper.

Figure 15: Recycled paper lamp shades

3D Printed planters

Desciption
As the name of these products suggests. These are 3D printed planters. The material that is used is wood.

Production process
By using a 3D printer, a lot of various design can be made without creating waste. The material consists of PLA wood filament. This filament is a mixture of cornstarch based bioplastic and recycled wood fibres.

Consideration
These planters can be made without creating more waste materials because of the use of a 3D printer.
The use of a wood mix makes the products smell like wood and keeps a natural feel.
The materials that are used are natural, this makes the claim that the planters are biodegradable very plausible.

Figure 16: 3D printed wood planters

Moving boxes

Desciption
A modular shelving system made from salvaged cardboard taken from recycling bins.

Production process
The cardboard that is taken from bins is cut into several shapes. These shapes will combine into stackable boxes that can be used as book or display shelves.

Consideration
One of the considerations for these bookshelves might be the durability in comparison to similar products. The durability for these cardboard boxes is lower than similar products made of wood.
It is however cheaper and lighter than its equivalents.
When looking at a circular economy the moving boxes might be re-used as moving boxes instead of cutting good pieces of cardboard up.

Figure 17: Recycled cardboard shelves

RECURF project

Description
This project is done at the Hogeschool van Amsterdam. Three companies collaborated in this, namely Starbucks, Ahrend and Sympany.
For each company a product was made by using their waste materials. The production processes are different for each product.

Production processes
Starbucks has waste material from jute bags in which their coffee beans are delivered. Fibres made from these bags are used as a replacement for glass fibre. The jute fibres were mixed with a partially biobased polyester resin. This mixture of resin and fibres was pressed into sheets. After the pressing, seating parts could be sawn from the sheets for the outside furniture at Starbucks stores.

Figure 18: Starbucks composite seating

The office furniture manufacturer Ahrend creates cutting waste from wool that is used in their chairs and other products.

This cutting waste is fibrillated and grinded into fibres with a length of about 1 mm. This powder was mixed with PLA and turned into granulate. Using an existing mould from Ahrend armrests were made.

The last company is Sympany. This is a used textile collector. Fibres from denim, jute and PLA thread were mixed. Non-woven mats were needled from this mix. These mats could be cold and hot pressed to create interior panels with sound dampening properties.

Consideration
The most important consideration in these projects is that the waste materials were mixed with other materials. This makes them more difficult to recycle when the new products are discarded.
The project with Starbucks also mixes a natural material with a partially technical material, respectively jute and partially biobased and polyester resin. This is also not a desirable solution.
Overall, there might have been other solutions for the waste materials.

Figure 19: Above, Ahrend arm rest
Figure 20: Below, Sympany interior panels

4.3. Ways of recycling textiles

Except for reclaiming fibres from used fabrics to make new clothing, or making cleaning rags from used clothing not much variable information can be found on recycling fabrics at the moment.

Another example of recycling fabrics was seen in the RECURF project when waste wool was used to create arm rests. However, this last example means adding new man-made material to natural waste material. In a circular economy this is not desirable because the natural material can be reclaimed by nature itself. The added resin cannot be reclaimed by nature.

Other than these examples, not much can be found on what recycling companies do with their fabric waste material.

The following paragraphs describe current fabric recycling possibilities.

4.3.1 Shredding

As described in chapter 4.4, the current process is to mix shredded ticking and press it into a bale. This is done to create a more homogenous material. When the same process in done with sheets of unprocessed ticking the different layers will create an unreliable material. When shredding the ticking all the various types of materials can be mixed and made into a more reliable, predictable material. Ideally, in order to create an even more predictable material, the size of the particles that come out of the shredder should be smaller than the current setting.

Figure 21: Textile shredder by Harden Machinery Ltd.

4.3.2 Unprocessed material

Another way of looking at the material is to consider it as a sheet. So why shred a sheet to create another sheet. One of the reasons is given in the previous paragraph, namely to create a more reliable material and as can be seen in chapter 2.5 not all ticking is made up of the same kind of materials. For example the yellowish foam than might be found is a thermoset that will not deform when heated.
One solution might be to fix it into place or shape by infusing it with resin for example. A reason to not use resin is because it adds another material to the foam which makes it harder to recycle once it reaches its end-of-life.

4.3.3 Separation

When looking at the ticking samples in chapter 2.5 the main problem in separating the layers is stitching. What if there was a way to remove the stitches from the ticking?
The sample of Auping is only stitched together on the outer edges of the ticking. So the layers will stay in place when only the outer edges of these layers are fixed together. One might argue that stitches in different patterns on ticking looks nice but currently in developed countries a bottom sheet is standard. This bottom sheet is laid on top of the mattress and might be a flat sheet that is folded around the mattress or a fitted sheet with an elastic band sewn into it. A bottom sheet is more easily washable and protects the mattress, extending its life-time.

So a recommendation for mattress manufacturers might be to get rid of the stitching because in homes it is just covered up with a sheet and it is not necessary to keep the layers together. When the stitching is removed, apart from the outer edges, recycling or disassembling ticking becomes easier.

4.3.4 Erase stitching

One of the possibilities of removing stitches is by using a tool called a seam ripper (figure 22). This tool is used by hand and is basically a small knife which is especially made for the purpose of getting under and cutting through stitches in clothing. This tool only cuts one loop in the stitching at the time, so to remove long lines of stitching a reasonable amount of time is needed to just remove this long stitch.

Figure 22: Seam ripper

When looking at amateur automated tools for removing stitches a tool was found that looked like an electric razor (figure 23). The piece of fabric of which the stitch needed removing was fixed on one side. While pulling the other side with one hand the razor was used to cut through the stitches. This makes the process a lot faster than with a seam ripper. However, there was no industrial equivalent found for removing stitching in clothing or ticking.

Figure 23: Automatic seam ripper

A solution might also be to use the thread that the company C-Tech innovation has developed. This thread is called Wear2 (figure 24) and can simply be torn apart after being microwaved for half a minute. When clothing or ticking would be stitched with this thread it can just be put in a microwave after which the layers or pieces of fabric can be separated.

Figure 24: Wear2 by CTech after microwaving

The previous solution however is only suitable for mattresses that will be newly manufactured. For existing mattresses another solution will have to be found.

In the textile industry laser cutting (figure 25) is already used to economically, meaning minimizing the amount of waste created, cut pieces of clothing out of a large sheet of fabric. Another machine that is used in the textile industry today is a machine that can recognize defects in new sheets of fabric. When combining these two pieces of equipment a machine could be made that could identify stitching in sheets of ticking and use a laser to cut the stitches. After this process the ticking can remove the different layers from each other. After this step the layers can be treated separately to manufacture new products.

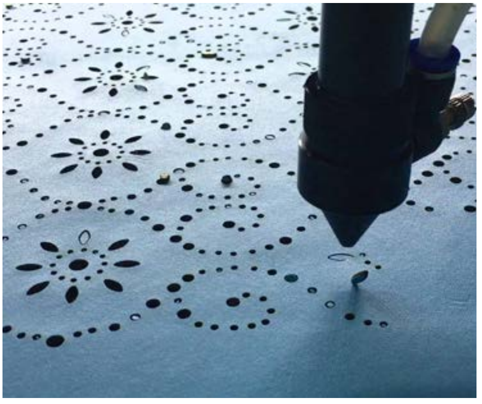


Figure 25: Laser cutting patterns in textiles

When a company wants to separate the materials even further there is a technique to separate polyester from cotton. This polyester/cotton blend is used in many pieces of clothing and also for ticking. The technique to separate the blend is to dissolve the cotton in an ionic liquid, which is salt in a liquid state. The cotton can be regenerated into fibres and the liquid salt can be recycled. The remaining polyester can be used as fibres or plastic. (IFAI, 2015)

Auping is also trying to make the mattress industry more circular. A new development is a collaboration between Auping and DSM-Niaga. Niaga has created a new type of glue that they have used in the carpet industry to keep the various layers together. (DSM-Niaga, 2017) They claim this new adhesive creates a 100% recyclable carpet. When collaborating Auping and DSM-Niaga hope to create a 100% recyclable mattress.

Another way to separate materials is to get the shredded material and use image recognition to identify specific materials which are not desirable to have in the new material. Just like in for example food industry, where image recognition is used to identify out of shape or discoloured items. These items are taken out of the production line using bursts of air. The computer that detects the unwanted item on the conveyor belt calculates where the item will be when reaching the end of the conveyor and activates a valve. A burst of air comes from this valve after which the unwanted item is collected in another storage container instead of ending up with the wanted items. This technique might also be used when selecting wanted and/or unwanted materials from the shredded ticking.

4.3.5 Processing methods

One of the processes that was not explored in the previous project is the use of heat at the right temperature of around 260 degrees Celsius. The only addition to the material when using heat is energy. No other kind of material is added so the material itself keeps its original composition.

The starting point is to first use sheets of ticking the way they are.

So, the sheets are only cut of the mattresses. The sides are cut off to create a flat ticking sheet. This sheet is then subjected to some processes.

The other starting point is to use shredded material and subject that to the same kind of treatments as the flat sheets. With the addition that the shredded material is easier to get rid of some pieces, like foam.
An addition following the previous paragraph is to use layers of material that were treated to dispose of the stitching and use those in different processing methods.

4.3.6 Conclusion

As can be read in the previous paragraph there are various methods of recycling textiles or get rid of stitches.

The first was to shred the material in order to create a more homogenous material.
Another option was to use unprocessed ticking. This will however not be an option according to the before mentioned research of Chapman and Bartlett.

To make the recycling of the ticking material easier it should be separated into its different materials. Therefore separation techniques were looked into. There are however no techniques for fabrics at the moment that are in use on a large scale. A few companies are looking into manufacturing possibilities to make separation easier such as Auping and DSM-Niaga.

The use of heat was not yet used in other projects that involved waste ticking. Preferably no other materials should be added to the waste ticking in order to not make it more of a mess of materials. This only makes the further recycling more difficult.

4.4. Samples

After analysing the different kinds of ticking some tinkering was done to some samples. The outcome of the samples is described in this chapter.
Only the most promising samples from the treatments are described. Other samples can be found in appendix 1.

The first treatment given to the waste material was to try to keep the appearance of the ticking while at the same time creating a stiffer sheet to work with.
A few samples were made by adding wallpaper paste between two layers. (Figure 26) One of the issues that appeared was that half of the samples were prone to mould. This might be because the samples were not clean.
The samples that were not mouldy resulted in a stiffer sheet. This sheet could also be easily bent. The foam in the samples kept its openness making this an option for example sound insulation boards.

Figure 26: Wallpaper paste sample

The second method to treat the ticking waste material was to verify that an open flame was indeed to hot for the material to melt. The result can be seen on the right (figure 27)
A piece of TEPA was used. A burner was held at about 10 cm distance. After a few seconds the sample caught fire. When the flame was removed the sample kept smouldering. The sample had to be extinguished resulting in the white top bit not being burnt. This means untreated ticking is flammable.

Figure 27: Open flame burnt sample

Because a burner was to hot to treat the waste, a paint burner was used for the second sample (figure 28). The temperature could be more controlled and only heat was added instead of heat and open flames.
The temperature however was still to high. The melting of the PET could not be controlled, therefore the material pulled open.

Figure 28: Pulled open material by heat

The thin outer layer of ticking of some samples did not react to heat and kept most of its original shape except for some burning on the edges. An example can be seen in

Figure 29: Molten inner layer, intact outer layer

figure 29. When adding heat with a paint burner at a bigger distance the melting could be more controlled. Figure 28 is formed by stacking four layers IKEA ticking. The foam parts melted but the tightly woven gray outer layer did not transform much.

The next sample (figure 30) was also made by adding heat to another piece of ticking. It was pressed between two pieces of metal while adding heat by a paint burner. This method resulted in a stiff but brittle piece of material.


Figure 30: Heated by paint burner between plates

Figure 31 displays two samples that were treated in an oven. The left sample was heated to 250 degrees Celsius. After heating is was pressed together.
The right sample was heated to 220 degrees Celsius and pressed. As can be seen in the figure the higher the temperature the more the white foam parts melt.
Other pieces of ticking where stacked and heated to various temperatures and pressed together. This treatment resulted in thick stiff sheets.

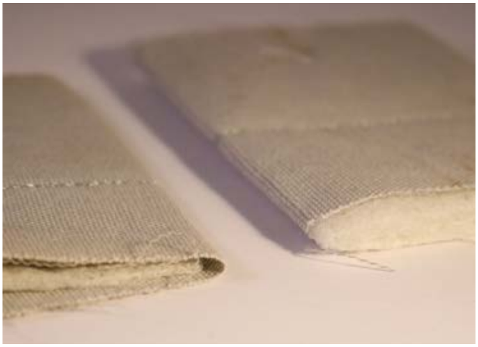


Figure 31: Oven heated samples

As seen in the samples applying heat makes the ticking waste melt into harder versions of the material.
It can also be seen that some layers of ticking deform in a different way by the applied heat. It was also seen that temperatures of around 600 degrees Celsius are not suitable for controlled melting of ticking since it shrinks rapidly.
Using temperatures lower than 250 degrees Celsius the ticking waste did not deform a lot.

It is also possible to add some sort of glue or resin to unprocessed sheets of ticking. This keeps the appearance of ticking but does not take away stains or tears in the ticking. Therefore it might be better to shred the ticking and create sheets from these pieces.

4.5. Processing techniques

As mentioned before, various processing techniques were analysed. First, an analysis was made of what the energy usage and cost would be for the current process and other processes that resulted from previous chapters. Including the current process there are seven processing techniques to recycle textiles. Most of the usual techniques for recycling textile are based on knowing rougly what materials are used in the textile. The range of different materials is therefore limited since it can be sorted on what material it is.
This is harder for ticking waste because over the years there are lots of materials used in different compositions. One of the criteria for the choice of processing technique is that it should be possible to recycle all the different kinds of ticking.

The seven techniques that were chosen for the analysis are listed below.

1. The first one is the current process of shredding, pressing and cutting.

2. The starting point of the second process is to separate the ticking that is stitched together. In order to do so, a guided laser cutter is used that can detect and cut the stiches.

3. The third process is quite simple. This process however assumes that the material that is most common in the ticking is polyester to melt all layers together. The ticking sheets are put in a heat press to bind several layers together creating a stronger and stiffer sheet.

4. This process is called rag tearing. Rag tearing is a form of mechanical recycling which pulls all fibres apart. The output of a rag tearing machine are small separate fibres.

5. The fifth process is creating filament from the fibres. This process can only have PET blends as input because it uses heat to create the filament. Other materials that might be found in ticking cannot be processed with this technique.

6. This sixth process is to create felt from the ticking. It is quite similar to process number four but has a different outcome. The felt that will come out of this process can be sold as felt or processed further like the felt chair from de VORM. (Chapter 4.2)

7. The final process is similar to the current method of recycling ticking. An addition to it is to create smaller pieces after the first shredding step. This process is similar to the process that the company Really uses to recycle wool and cotton into Solid Textile Board.

The three processes that were most promising after a cost and energy analysis are mentioned in the following paragraphs. The cost analysis and a description of the other techniques can be found respectively in appendix 2 and 3.

	Step 1 Decomposing	Step 2 Seperating	Step 3 Reprocessing
1. Current process	Shredder	Hydraulic press	Saw
2. Laser cutting	Guided laser cutter	Hand picking	Heated press
3. Heat press	Saw	Heated press	
4. Rag tearing	Shredder	Rag tearing	Heated press
5. Filament	Shredder	Filament roll	
6. Felt	Shredder	Rag tearing	Needle punching
7. Finer current	Shredder	Pulverizer	Heated press

Figure 32: Machinery needed for processes overview


Figure 33: TEPA

4.5.1. Current process

The process is visualized in figure 32. The picture on the left depicts a sheet of TEPA, which is the outcome of the current recycling process.

It starts with putting the material in a shredder. This makes it easier to mix the different kinds of materials that can be found in various ticking. Therefore, a more consistent material has been tried to be made.
After mixing all the different pieces of the ticking, a binder is added to create a block of material. This block of material is made in a press.
The last step in the current process is to use a saw to make sheets of the block of material.

Outcome
The current material is used as thermal and sound insulation. A suggestion was made in a preceding project to use the sheets in a composite sheet. (See also chapter 3)

Point of attention
The large pieces of material in the sheets make it a brittle and flexible material which makes is suitable for non-structural applications.

4.5.2. Rag tearing

Again, the process for this way of recycling is visualized in figure 32. Figure 34 resembles an example of the outcome of this way of recycling.

Before putting the ticking in a rag tearing machine is needs to be chopped into smaller pieces in order for the tearer to process the material.

The chopped up pieces can be fed into a rag tearing machine. This machine tears the fibres in textiles apart. The output of the machine are loose fibres.

Outcome
These loose fibres can be hot-pressed together into sheets or sold seperately as filling for furniture or insulation material. One company recycles waste from mattress manufacturers into filling for car chairs. This is not possible with used mattress waste because of hygiene concerns.

Point of attention
Not all ticking can be processed using this process. Sometimes, foams can be found in ticking which cannot be treated by the rag tearing machine.

Figure 34: Torn fibres


Figure 35: Solid Textile Board made by Really

4.5.3. Pulverizing

This last process is also visualized in figure 32. On the left, figure 35, a picture can be seen that resembles the outcome of this recycling process.

Again, the first step is to put the waste material into a shredder which transforms the ticking into a more manageable size.

To create a sheeting material with other properties than the current application the shredded pieces are put into a grinder which has even smaller pieces as output.

As was seen in the sample experimentation segment the ticking material melted when applying heat. The grinder output can be put into a hot-press to make a kind of board.

Outcome
A board like material

Point of attention
The board has to be made into products to give more value to the material. The board on itself cannot compete on price with MDF for example. (See also chapter 5.3)

4.5.4. Choice

As mentioned before a cost and energy usage analysis were done one the seven processing methods. The three that were most promising are explanained on the previous pages.

A representation of the cost and energy usage analysis can be found in figure 36. It now comes down to making a choice between the processing techniques.

Based on cost it would be most profitable for the company to stay with its current way of recycling. The TEPA however does not sell well enough to get rid of all the ticking waste MRE processes at the moment. For the company it might be wise to keep using its current way of recycling and combining it with one of the other processes.

When looking at the other two processes it can be seen that the rag tearing process might be most profitable for the company. It has to be stated that not all ticking can be recycled in this process because it only takes fibre like materials as input. The foam materials that are sometimes added in ticking cannot be processed by this machine.
The difference with the adjustment of the current process and the rag tearing is that the adjusted recycling technique is that all ticking materials can be processed.

The potential profits for the rag tearing process and ticking board are not far apart from eachother. This makes the choice harder.

Therefore, the potential for the recycled output is looked at. The rag tearing process has an output of fibres that could be used in new textile products.
The finer shredded material for the ticking board could be used in for example furniture or other applications for board.

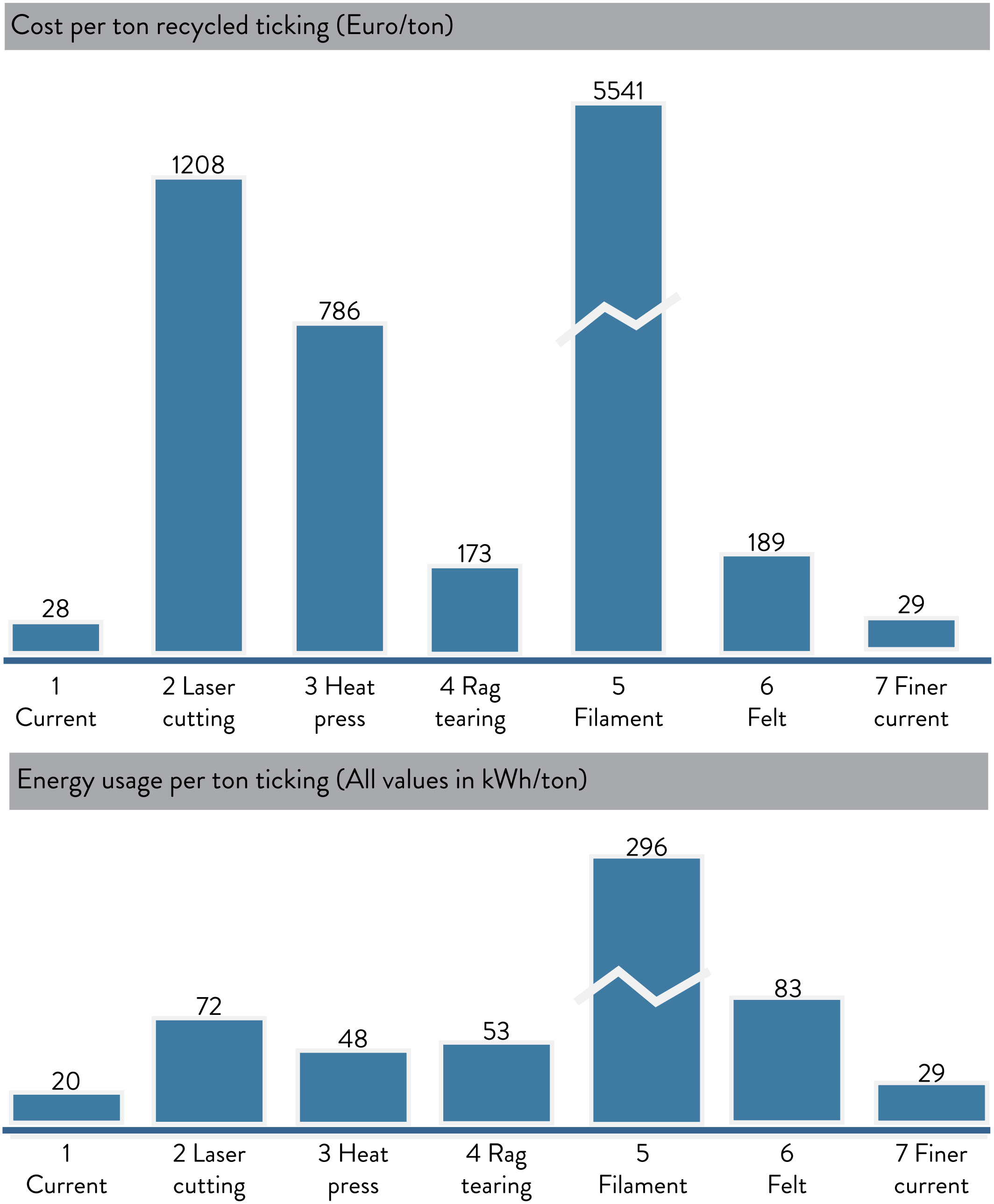


Figure 36: Cost and energy usage analysis

Weighted objectives

One of the ways to make a choice between the three solutions is to use the weighted objectives method. (Delft design guide, 2014) In the left column demands are set for the new application of ticking waste. These demands come from the previous chapters and the first price and energy comparison from which the three processes were selected.

Circularity
The first one is called circularity. This is one of the most important issues this project is based on. The term circularity, in the sense of this report, means how easy it is to reuse or recycle the outcome of the three beforementioned processes.
So the reuse of the rag tearing process is easier because it can be taken out of its container, like cushions, and put in another products.
The current process needs more effort because is has to be taken out of buildings. It might be deformed or not be a whole sheet so some of the material needs to be put through the shredding process to press whole sheets again.
The last process of ticking board needs to be put through the process again to be made into whole ticking board sheets again.

Investment
This is important for the company and the eventual cost of the final product. The more investments have to be made the more expensive the final products become and the more risk the company puts into the new product.

Applications
This is also important for the company. The more applications for the recycled products, the more chance of selling these products. For example the current process has a lot of competitors from existing products. For now the solution for TEPA has been insulation. The ticking board might be used for sound insulation or other applications sheeting material is used for.

Energy usage
This is an environmental issue. For now the energy that is used in recycling comes mostly from non-renewable sources. This might be different in the future. The KIVI in the Netherlands calculated that the

	Weight	TEPA Score	TEPA Total	Rag-tear Score	Rag-tear Total	Textile board Score	Textile board Total
Applications	20	6	120	7	140	9	180
Investments	20	10	200	4	80	7	140
Circularity	25	7	175	8	200	7	175
Energy usage	15	6	90	8	120	4	60
Appearance	10	5	50	7	70	8	80
Amount of recycling	5	8	40	6	30	8	40
Volume reduction	5	6	30	7	35	9	45
	100		705		675		720

Table 1: Weighted objective method comparison of chosen processing techniques

country could run on renewable energy in 2050. (De Ingenieur, 2018)

Appearance
How appealing is the appearance of products made from the material.

Amount of recycling
The amount of recycling means how much material the processing technique can process. The more material can be processed the cheaper the final product becomes because the costs can be divided over more material.

Volume reduction
Another point for making the final products cheaper is volume reduction. Because ticking consists of expanded materials it has a lot of air in it. The transport and storage of material with less air in it becomes cheaper because more weight of the material can be stored in the same space.
As can be seen in table 1 the textile board scored highest. This means textile board would be the best choice to continue with based on the selected criteria.

Benchmark

To get an idea about the competition and kind of applications for such a material a benchmark (Figure 36) is done. The textile board will be compared to the well-known MDF. A visualisation of the benchmark can be seen in figure 37. The grey bars represent MDF, the blue bars Ticking board.
The conclusion of the benchmark will be on what kind of characteristics the textile board is better than its wooden competitor.

One of the most important remarks when comparing the materials is durability in a circular economy. The biggest disadvantage of MDF is that it is legally required in the Netherlands to be burnt after its first life-cycle. This is because it might be chemically contaminated by for example glues. More information about this law can be found in the LAP2 mentioned in chapter 2.5.

So, from a circular economy point of view the textile board is a better choice since it can be recycled multiple times. (Recyclability in figure 37)

Other criteria in figure 36 that need explanation.

Availability
Currently MDF can be bought at every do-it-yourself market. The Ticking board is not yet available but might be processed into other products.

Temperature resistance
The temperature for the materials at which the properties will be affected.

Tensile strength
The strength of material in pulling direction.

Thermal conductivity
Is a measure of how well a material transfers heat. MDF conducts more heat than Ticking board (CES, 2016) So Ticking Board is better to be used as thermal insulation.

Acoustics
MDF gets a poor score on acoustics from Materia (Materia, 2018). The comparable Solid Textile Board gets a good on acoustics.

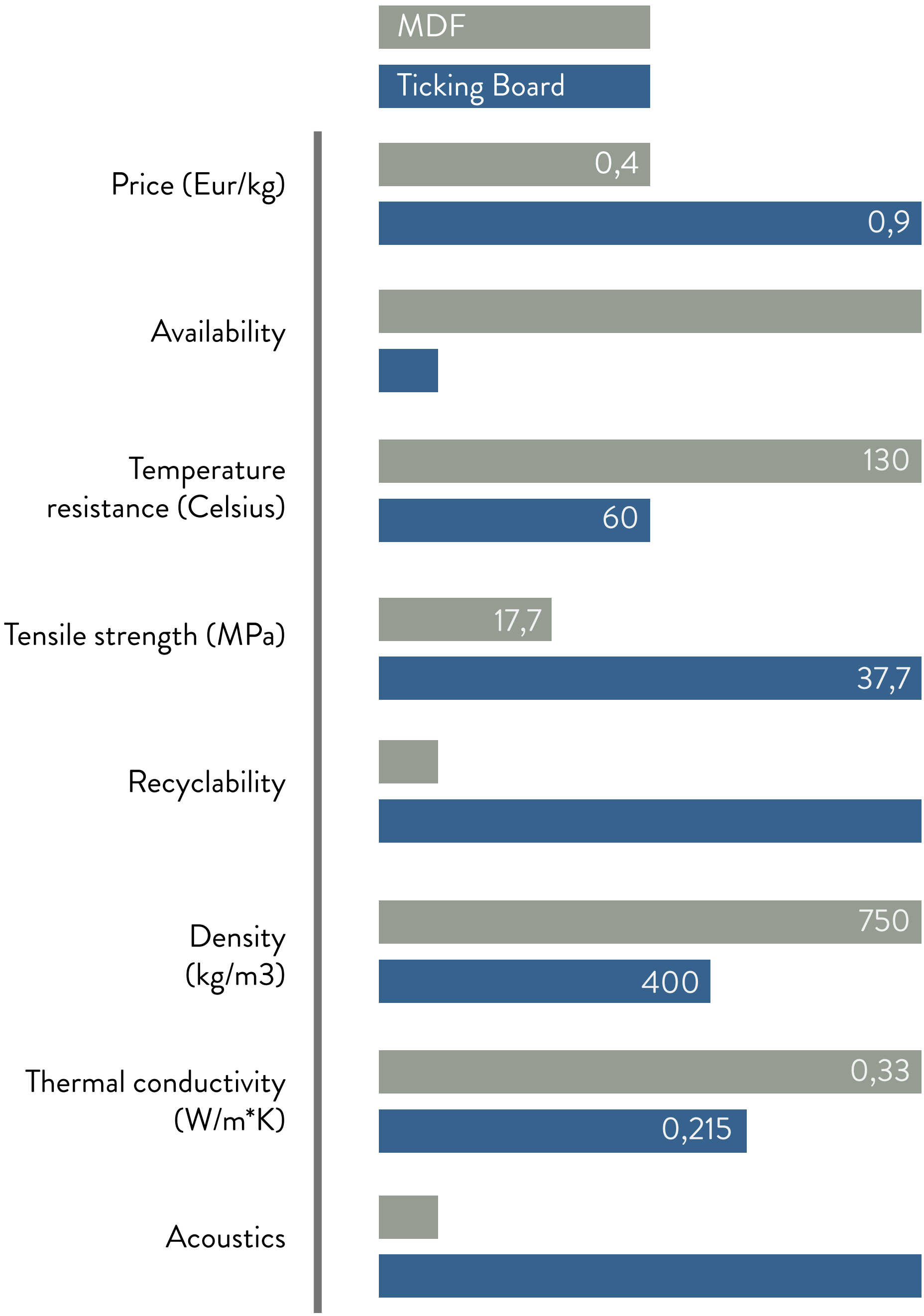


Figure 37: Material Benchmark

4.6. Conclusion

The first question in this chapter was why mattresses do not get refurbished at the moment. For the ticking this is mostly because of hygienic and cleanliness concerns but also because the material degrades over time.

To find a useful application for ticking waste the current ways or recycling fabrics were looked into. The recycling of fabrics is currently focussed on clothing. The difference between clothing and ticking is that clothing can be separated by hand into piles with comparable materials. Ticking should preferably be taken apart to separate the different kinds of material. At the moment this is hard and expensive to do because layers of ticking are stitched or glued together. This means that the best solution at the moment is to shred the waste material to turn it into an usable raw material.

Samples were also described in this chapter. These samples showed that all layers in ticking react differently to heat. So the layers of ticking have to be processed to mix smaller pieces of material to get a homogeneous material.

Existing products which are recycled are made by heat pressing or adding resins or glues. Because the ticking waste material should not be contaminated by other kinds of materials the addition of resin or glue is not desirable. Therefore heat pressing should be taken into consideration. Because heat pressing is already used at the moment a production line is set up quickly.

Other ways to process ticking waste are looked into and compared on cost, amount of material that can be processed and amount of energy these recycling processes use. The three most promising techniques are the current processing of ticking, rag tearing and heat pressing.

The current process has not yet yielded good results in sales. The machines used in rag tearing cannot process the foams that can be found in ticking. The last processing technique of heat pressing pulverised ticking waste can process all materials found in ticking and results into sheets of material that are made with just waste ticking. The pulverise heat pressing technique is chosen to develop a material that can be turned into a product in the next chapter.

Also looking at the rest of the benchmark, the thermal and acoustic properties of a sheet made of ticking waste are more useful than a MDF sheet. So a product might be made combining these properties which is recyclable multiple times.

5

Product design

Figure 38: First samples of Ticking Board

5.1. Heat pressed ticking

In the previous chapter the choice for a new way of recycling is made. Based on this choice, a few samples were made to get ideas on what to do with the material. (Figure 38)

The ideas for products made from the material can be found on the next pages.

First samples of Ticking Board
Production of the first samples were made using a press for t-shirts. This press has one side which was heated to 260 degrees Celsius. To get the sample heated properly it was turned a few times. The temperature was set at 260 degrees Celsius because the mats to protect the press were specified up to that temperature.
Also, the temperature to melt PET is around that temperature but should be ideally in the range of 270-290 degrees Celsius.

When heating the pulverized material steam came from the samples. This shows the material should be dried before putting it into the heated press. The water that has to evaporate from the pulverized material might change the properties while it is being pressed. Especially when the water cannot escape during production the end result of the Ticking board might be too weak to use.

When the samples came out of the press they were still weak. When they had a chance to cool down the PET could harden and the excess water was mostly evaporated. When the sample was pressed a second time, the material ended up being stiffer than the first time.

The issues of temperature and moist have to be taken into account during production of the final Ticking board.

5.2. Concepts

The next pages will describe a few concepts that were thought up.

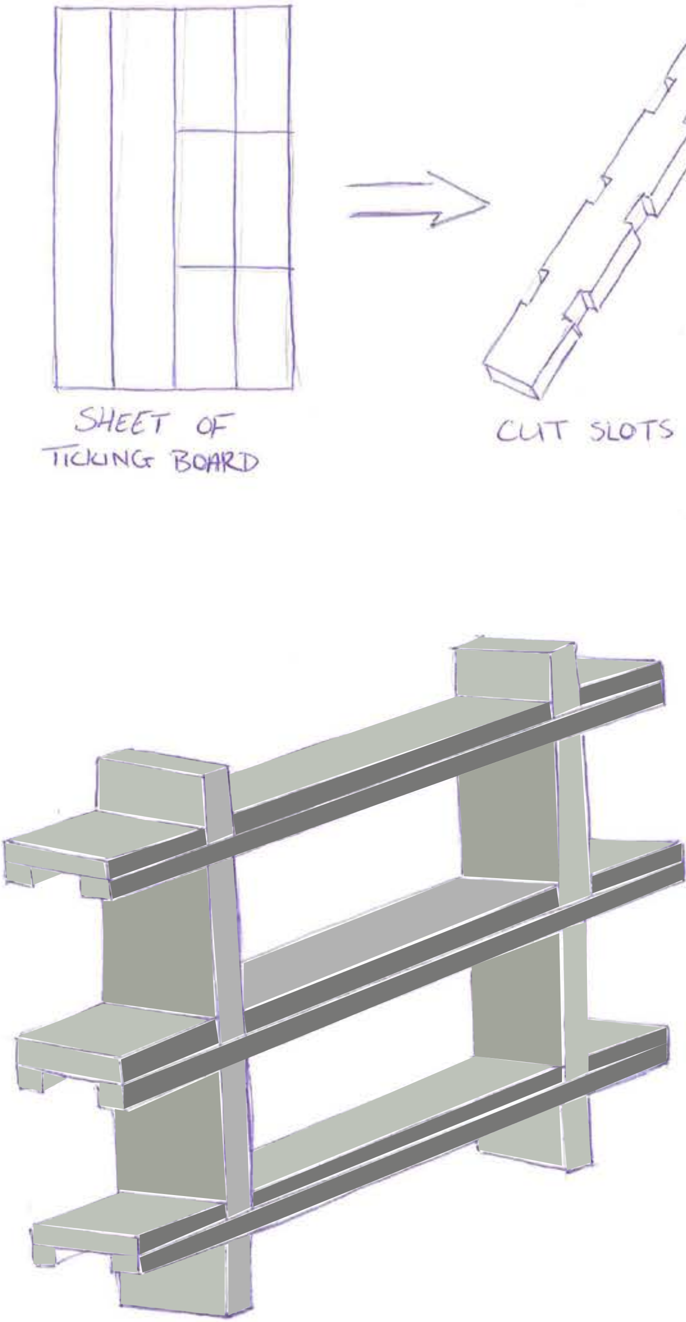


Figure 39: Closet from ticking board

5.2.1. Furniture

Because of the potential for the material to make panels suitable for construction purpose, like mdf, one of the ideas is to create furniture from it. Furniture is chosen because of the higher tensile strength than the compared material.

Manufacturing
The example in figure 39 shows a closet made from sheets of Ticking Board.
Because of the simple shape of the closet there are limited steps in production to come to the final product. When the sheets are pressed, the shapes for the closet panels can be cut by laser cutting or by using a saw.

Use
The closets that are made this way can be bought the same way it is offered as for example by IKEA in flat packs. The beams connecting the vertical parts have to be kept in place using screws or glue. This makes recycling a bit harder.
The closet might also be used as a roomdivider with sound absorbing properties.

Marketing
As mentioned, the closets can be offered for private use in homes at IKEA. This is also a way for IKEA to show they are recycling their own mattresses into new products.
Another market can be offices. To offer storage space and a degree of sound absorption.
Hotels could also be a market to show they are concerned for the environment and not only throwing their mattresses away but prolonging the life of materials used in their hotels.

Consideration
When looking at the first samples that were made using a t-shirt press, the strength of the material might not be high enough for use in furniture. The material could be improved in ways mentioned in paragraph 6.5.
As for circularity the furniture has to be collected separately in order to be processed into other products again. There might be a rental agreement for offices and hotels. After the rental period the materials are collected by the production company.
For private users, the material might be handed in at the store of purchase.

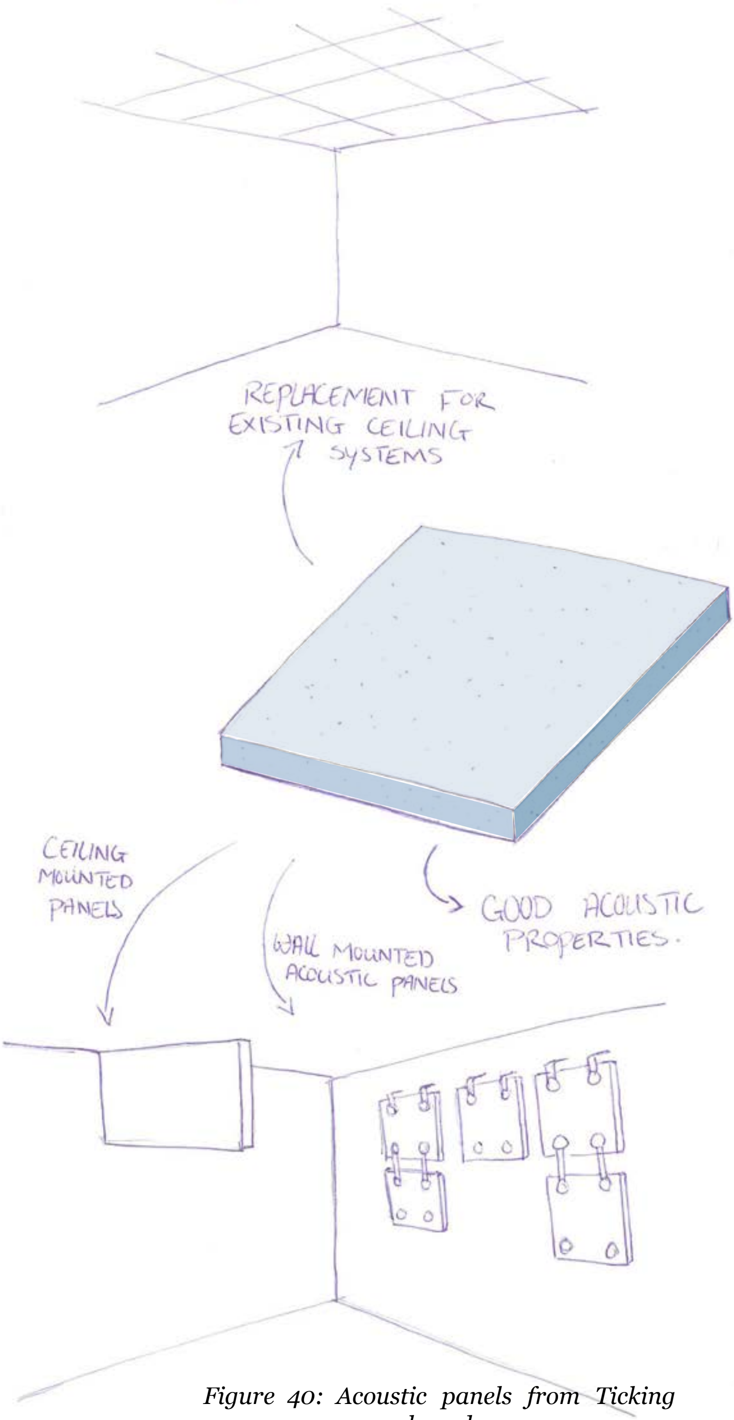


Figure 40: Acoustic panels from Ticking board

5.2.2. Acoustic panels

As the name suggests these panels can improve the acoustics in open spaces, for example offices.
Figure 40 shows an example of the panels.

Manufacturing
After the sheets of Ticking Board are pressed, the sheets are cut to the size which is specified for the intended use.
Holes have to be made into the sheets for the mounting system. The brackets to fasten the acoustic panels can be fixed to existing ceiling systems or screwed into the ceiling.
The material can be made into different densities. So the acoustic panels could be pressed into a more open structure in order to get good acoustic properties. The brackets could be made from a denser pressed material which has a higher tensile strength. This makes te brackets suitable for hanging the acoustic panels.

Use
The panels are fixed in place after installation. There is no need to move the panels when fixed in the ceiling.
When the panels have to be taken of or moved, the brackets allow for easy disassembly by just sliding them off. The brackets have to be screwed out of the ceiling.

Marketing
This system can be used in open spaces like offices or schools. The size of the panels can be fitted to the specifications of the intended use. There can be a system to hang more panels if necessary or change colour by adding a coloured sheets of PET or colouring with an environmentally friendly die.

Consideration
After removing the panels there can be an arrangement with the production company of the panels to take them back and recycle them into other products or use them in other spaces.

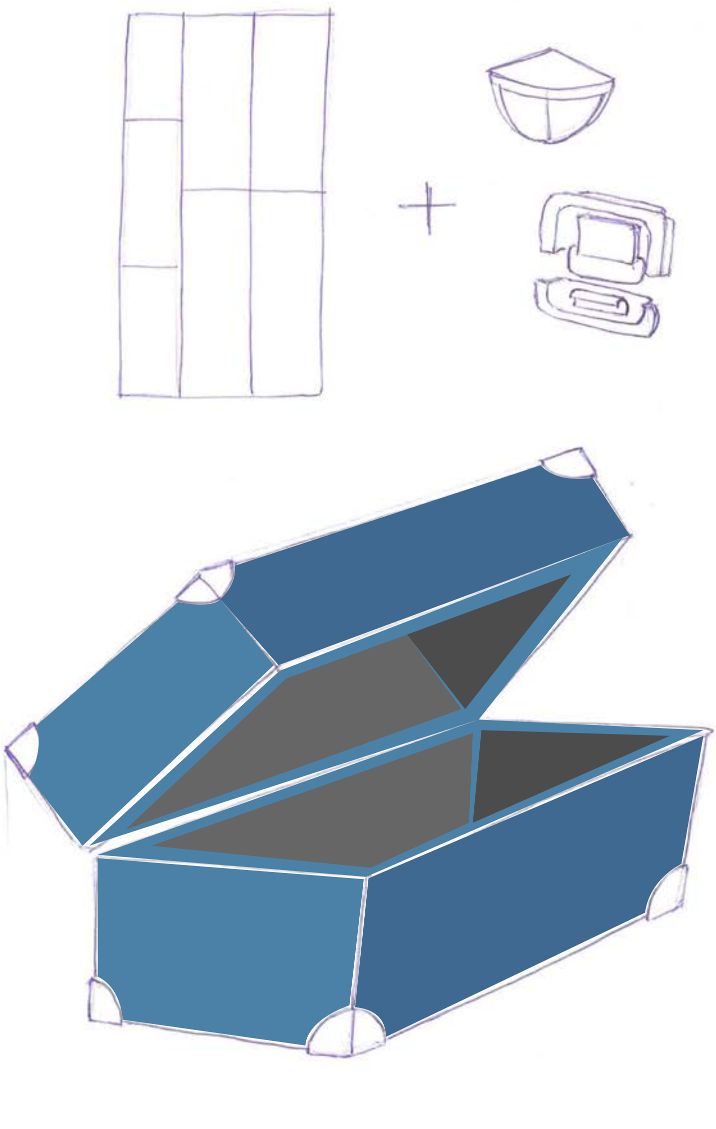


Figure 41: Flightcase from Ticking board

5.2.3. Flightcase for musical instruments

This idea came from the observation that flightcases for musical instruments are made from a wide variety of materials. (de Hoop, J., 2016)

Manufacturing
The sheets of Ticking board have to be pressed into the shape of the instrument to get a good fitting.
Another option for production is to keep flat sheets which are fitted at some points with some kind of profile. Foam has to be used in both cases to protect the instrument.
To provide more protection for the instrument the edges are generally reinforced by metal profiles.
These profiles can be attached to the Ticking board by using rivets.

Use
The flightcase are used to protect instruments during transport. Musicians tend to care for their instruments so proper protection has to be provided.

Marketing
There are approximately 2,5 million musicians in the Netherlands. Most of them only practice their hobby at home so the need for a flightcase is minimal. If this group already has a flightcase it is unlikely it will be replaced much. This also applies to the group of professional musicians (approximately 0,006% of the total musicians in the Netherlands which comes down to 15.000 people). The case might only be replaced when it is damaged.
There are also a lot of cases already on the market which makes it more difficult to get a lot of sales for this product.
Taking these things into account the market for flightcases is very small.

Consideration
The production of the flightcases takes another step of assembly and therefore energy and labour cost to manufacture the product.
In both manufacturing options the edges of the flightcase have to be reinforced by metal profiles which makes recycling the fligthcase more time consuming because of disassembly.

5.2.4. Idea choice

This paragraph describes the choice for which idea is developed further into a final product.

To make a choice between the ideas the considerations are compared. The benchmark comparison from the previous chapter will also be taken into account. A Harris profile is made (table 2) to make the concept choice visible.

The first criterium is if the concept makes use of its acoustic properties. The acoustic panels are designed as an acoustic solution so these get a higher score. The furniture can somewhat be used as an acoustic solution but is mostly used as a storage unit. the flightcase does not make use of acoustic properties since its function is just to carry and protect instruments.

Next, the thermal properties of the material are only used a bit by the acoustic panels since they are mounted on a wall acting as an extra thermal insulation layer on the wall. The other solutions do not have such a function.

Furniture uses the tensile strength properties best since its function is to store items. The higher tensile strength is to prevent the furniture from collapsing under the weight of these items. As a replacement for MDF it might be noticed that furniture made from ticking waste might be more expensive, but since the tensile strength is higher less material is needed in the furniture. This also reduces weight of the product and therefore also reduces for example the transport cost per product because more products can be transported in one container.

Acoustic panels are not used to carry a load so it does not use the tensile strength properties. Lastly, the flightcase is used to protect instruments so it is needed to make use of the tensile strength.

As mentioned before, the flightcase has a limited market. The other solutions have to compete with the current market of furniture and acoustic panels but have the advantage of being made from recycled material. Customers are

Concept	Furniture				Acoustic panels				Flightcase			
Score	-2	-1	1	2	-2	-1	1	2	-2	-1	1	2
Use of acoustic properties												
Use of thermal properties												
Use of tensile strength												
Market size												
Ease of recycling												
Multiple times of use												

Table 2: Harris profile concept choice

willing to pay more if products are made from recycled material.

The ease of recycling part is about the time it takes to disassemble the product. So since the flightcase needs strips for protection of edges it takes more time to disassemble. The acoustic panels and furniture are only screwed together so when these screws are removed the sheets of ticking waste can be recycled another time by sending them to the manufacturer.

Another point worth mentioning is that the acoustic panels can be used multiple times more easily since it does not have to bear loads like furniture and therefore keeps its original shape better. The flightcase can be used multiple times easily when the case is not too damaged.

Overall, acoustic panels make more use of the unique properties of the Ticking board, mainly the good acoustics. Its good thermal conductivity can also be used in the product proposal that will be described in the next paragraph.

5.3. Final product

The final product proposal is an acoustic improvement system for rooms.
Acoustic systems can be divided in ceiling and wall solutions. The ceiling solutions are for example the grey square office ceilings (figure 42) but can also be separate panels that are suspended from the ceiling (figure 43).
An example for acoustic wall solutions can be seen in figure 44.
A choice between these solutions is being made and a product proposal is done in this chapter.

Material

The material used for the acoustic panels is recycled ticking as discussed in the previous paragraph.
The sheets are shredded, pulverized and pressed into sheets for the acoustic ceiling or shapes for the wall coverings.

Parts

There are a few parts in this products, namely the acoustic panels themselves and the installation parts.

The acoustic ceiling panels can be a circular alternative for current panels. The dimensions of the tiles can be adjusted according to the specifications of the client.
The installation of these tiles can be done using frames that are used for existing ceiling tiles.

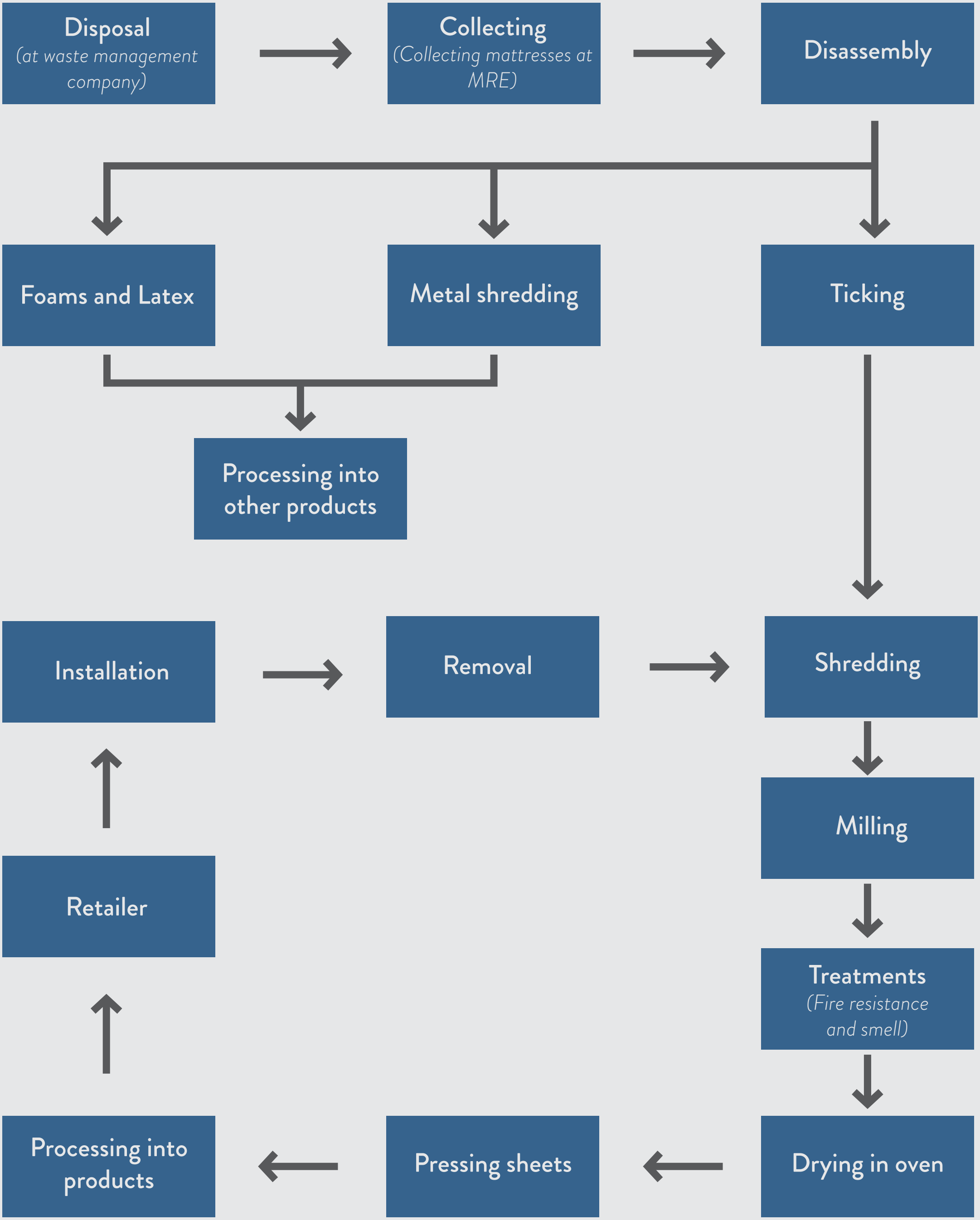
The acoustic wall covering is pressed into a predefined shape. The installation of similar products that can be bought at the moment is done using aluminium frames or glues.

Figure 42: Existing ceiling tiles

Figure 43: Existing suspended acoustic panels

Figure 44: Existing acoustic wall covering

General overview of producing Ticking Board



Production

For the production of the sheets various machines are needed. The first machine is a shredder to cut the sheets of ticking into smaller pieces. These smaller pieces can be processed in a pulverizer to create the base material for the acoustic panels.

As was seen during the first test of pressing the pulverized material, a lot of steam came of the sheets. Therefore the material should first be dried in order to get rid of excess moisture. An oven can dry the material and bring the temperature of the material up.

When the oven is used to raise the temperature of the material beforehand, the processing time of the sheets can be lowered since the material does not have to be heated by the press for a long time.
A press is used to create the final sheet of Ticking board for the acoustic panels.

Depending on the size of the bed of the press the Ticking board has to be cut a few times into standard sizes so a cutter has to be added to the production process.

A shape can also be pressed for use in acoustic wall solutions. A die is needed to press the shape. Since the shapes can be difficult to cut with a normal cutter a laser cutter can be added for cutting the final products from the pressed sheet. (Figure 45)

Figure 45: General overview of processing ticking board (page 102)

Installation

Installation of the ceiling tiles can be done by using existing systems and will not take any additional actions than other ceiling tiles.
The manhours for installing the ceiling tiles will therefore not be higher than current solutions.
As mentioned before the installation of existing wall panels is done using metal frames or glues. In this case a glue is not preferable since it can contaminate the material of the wall panel making it less suitable for further recycling. Therefore a rail is chosen to screw on the back of the acoustic wall panels. A similar rail is fixed to the wall itself. Due to the shape of the rail the wall panels can be hung onto the rail that is fastened to the wall.
An example of the proposed rail can be seen below in figure 46.

Figure 47 on the next page shows the installation process for acoustic panels.

The first step is to drill holes in the wall and screw a s-profile to the wall. Step number 2 is to mount the same profile to the acoustic panels.
The last step is to hang the acoustic panels on the profile which is screwed onto the wall.

Reversing the installation process results in the take-down of the acoustic panels.
So the panels are taken from the wall, the profiles are taken from the panels and the wall and all seperate components can be sent to its recycling companies.

Figure 46: Rail for mounting acoustic wall panels

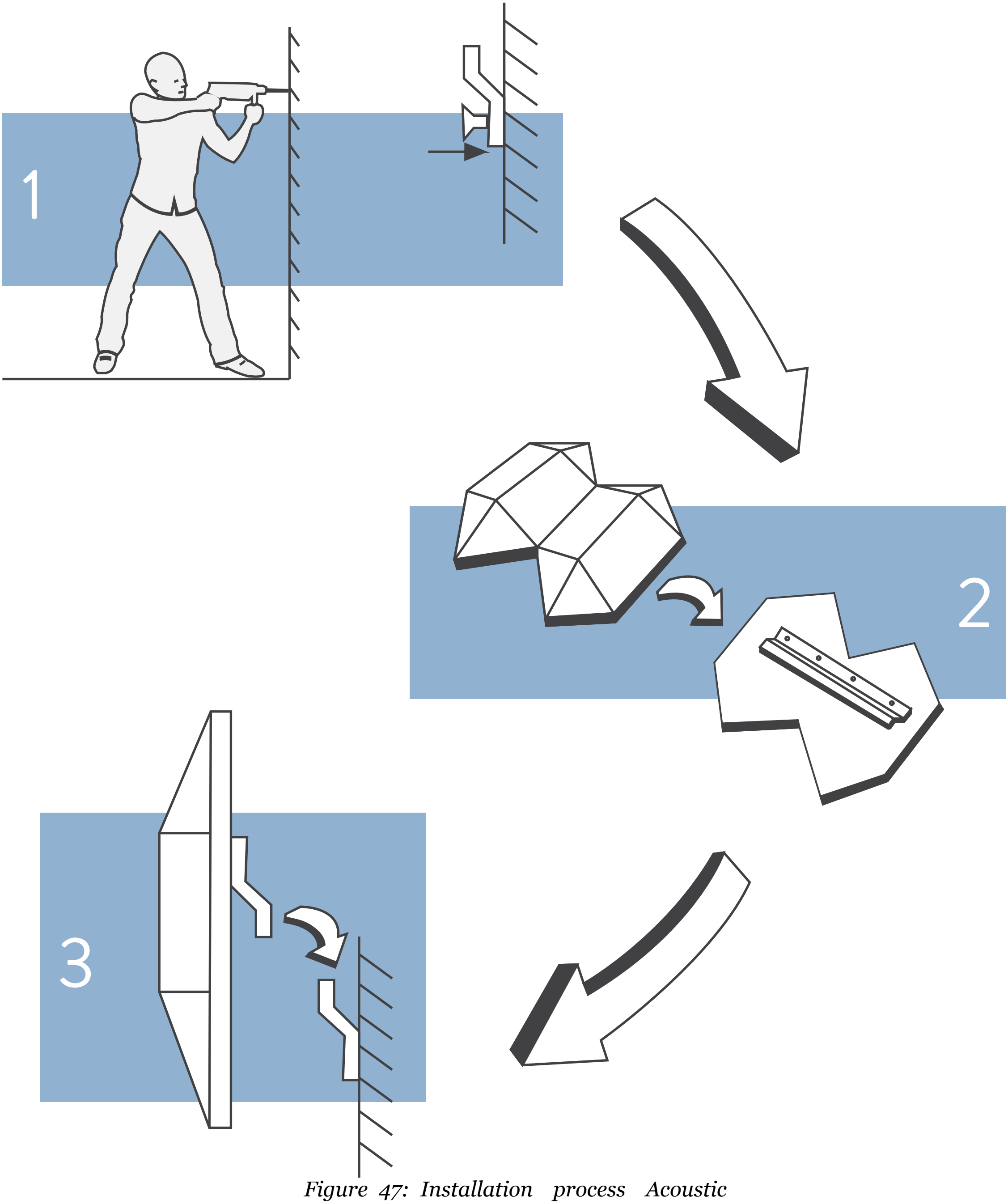


Figure 47: Installation process Acoustic Ticking

Price

The price of the ceiling tiles and the acoustic wall panels differ slightly from eachother because of differences in the production process. Therefore, two different prices are calculated. These prices can be found in figure 48. The model of Thomassen (2015) is used to make an estimation of the prices. A detailed sheet can be found in appendix 4.

The price for existing ceiling tiles ranges from 5 to 40 euros per square meter depending on its functionalities.
The price for acoustic wall paneling ranges from 100 to 350 euros per square meter depending on the materials and construction of the products.

As can be seen in figure 48 the prices are given per full flat sheet of acoustic ticking or per acoustic wall panel shape. After that the prices are calculated per square meter.
When looking at the prices and comparing these to existing solution it can be seen that the ceiling tiles will be in the top price range or even more expensive than its competitors. This means the ceiling tiles have a lot of competition from cheaper products.
Therefore it is wiser to choose to produce wall mounted acoustic panels since these are in the lower price range.

Selling price	**Sheets**	**Shapes**
Production cost	€ 4,1	€ 4,4
Overhead and profit factors	€ 2,1	€ 2,2
Retail margin	€ 9,3	€ 9,9
Taxes (BTW)	€ 3,2	€ 3,5
Selling price	**€ 14,8**	**€ 19,5**
Size of product (m^2)	0,54	0,12
Price per m^2	**€ 35**	**€ 163**

Figure 48: Selling price per sheet and shape

Comparison similar product

To get to know specific attention points for the Acoustic Ticking, figure 49 is made. It shows an overview of the properties of the first sample of Acoustic Ticking(in blue) and an Offecct Soundwave panel (grey).

Both are made from materials than can be recycled. The Offecct panel is made of polyester.
It shows the flammability of the Ticking Board panel needs to be improved.
The damping of soundwaves is also less for the Ticking Board. This depends however on the thickness and density of the material.
The price however is more interesting for the Ticking Board panel than the Offecct panel.

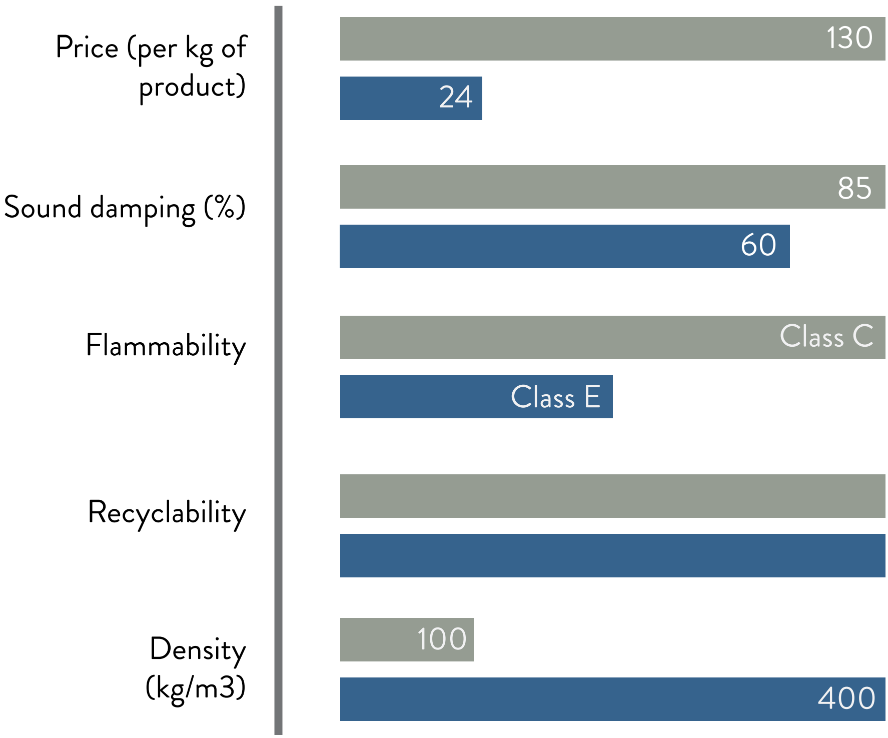


Figure 49: Comparison similar product

Specific attention points

There are some specific requirements to take into account when producing acoustic panels. Chapter 5.5 describes input from a company specialised in acoustic products on these topics.

Flammability

One of those is flammability. Unfortunately, the materials in ticking are quite flammable. A solution for this is to treat the panels with a substance to make them flame retardant. This substance is already used for curtains and other textile products.

When recycling the acoustic panels the substance stays in the material making the new products flame retardant. Of course, more research has to be done on the effect of the flame retardant solution in recycled acoustic panels.

Another requirement for use in buildings is that the production of smoke needs to be limited in case of fire. When the panels are treated with the flame retardant substance smoke is also limited when catching fire.

One of the considerations that needs to be taken into account is that the right fire retardant solution needs to be selected. There is no scientific consensus on the effects of current flame retardant substances but bromine based products should preferably be avoided. A non bromine based flame retardant substance is for example calcium silicate.

Particle size

One of the concerns that rose during the development of the acoustic panels is the particle size. Because the ticking waste is pulverizer into a dust-like material it is possible that small particles of the material might end up in the air.

The particle size is what makes asbestos hazardous. A lot of research is done on this subject. One source (Lemkowitz, S., 1996) mentions the specific sizes when asbestos particles are hazardous. According to this source especially the long fibres of over 20 microns with a diameter between 0,1 and 0,25 microns are a health hazard.

The diameter of polyester fibres lies usually between 12 and 25 microns.

A healthy human being has a system to get rid of particles with a diameter larger than 3 microns.
The natural fibres used in mattress ticking also have a larger diameter than 3 microns, namely between 11 and 50 microns depending on the kind of fibre.

Acoustic properties

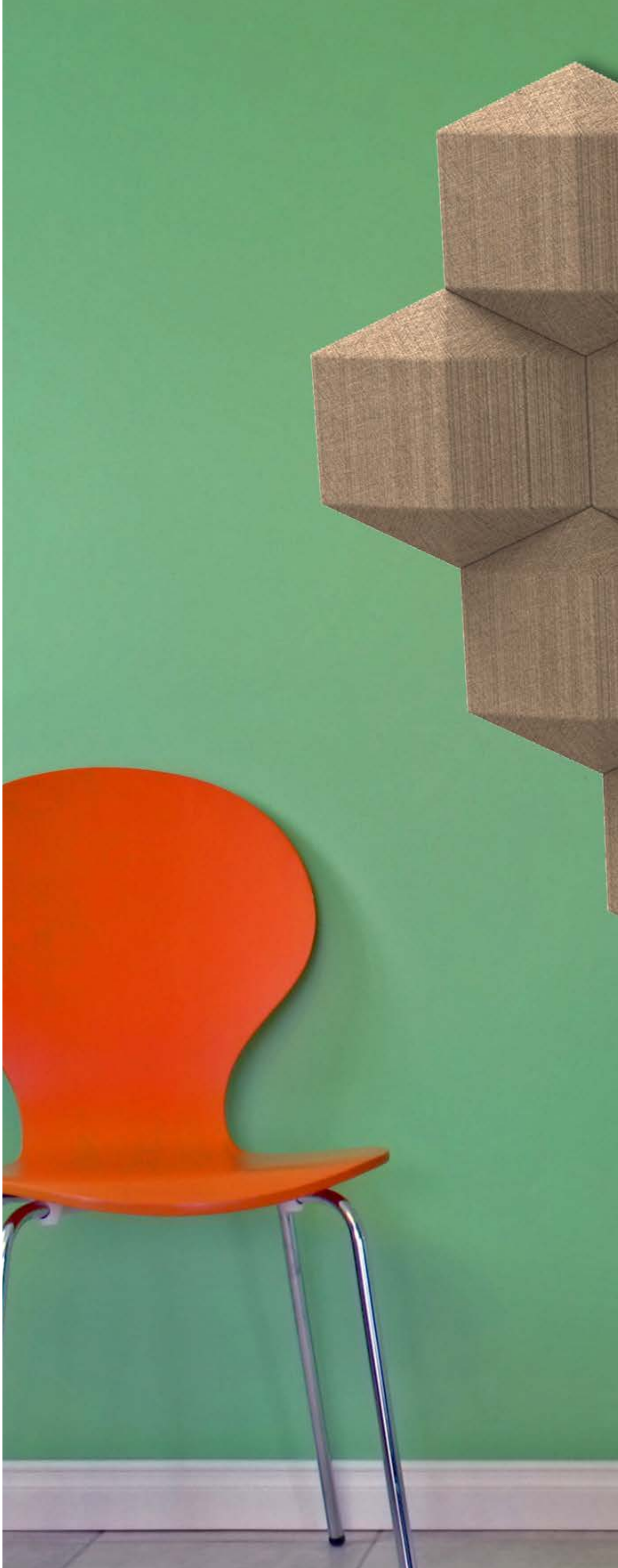
There are of course the acoustic properties of the panels. To be useful as an acoustic solution the panels have to have a certain damping of sound waves. As can be seen in the comparison in figure 49 the damping of sound is less than that of a compared panel. As mentioned this depends on the thickness of the panel. When the panel is thicker it can absorb a higher percentage of the soundwaves.

Sustainability

Because the Ticking board panels are only made from waste ticking they can be easily be recycled by putting it through the same process again. As mentioned in the particle size paragraph the diameter of fibres is key for health concerns. The diameter of the fibers will not change when pulverizing multiple times.

Ticking Board panels that have reached their end-of-life can be collected by the production company and processed with the same production process again and pressed into new sheets. Because the panels are installed in the open it is easier to collect and separate them during removal from the building.

As mentioned in chapter 2 a law proposal is sent to the Dutch government to take mandatory responsibility for products manufactured by mattress and furniture companies. This responsibility can be taken by collecting used ticking waste panels and recycle them as depicted in the general overview of the production process.



Acoustic Ticking

The picture on the left shows a render of the final product in an assembled form. The name of the product is Acoustic Ticking.

The rows of shapes are screwed onto a rail. A similar rail is mounted on the wall. The panels can be hung on the wall using these rails.

Removing the panels can be done by just lifting the rows from their rails and transport them to the manufacturer for recycling. (also figure 44)

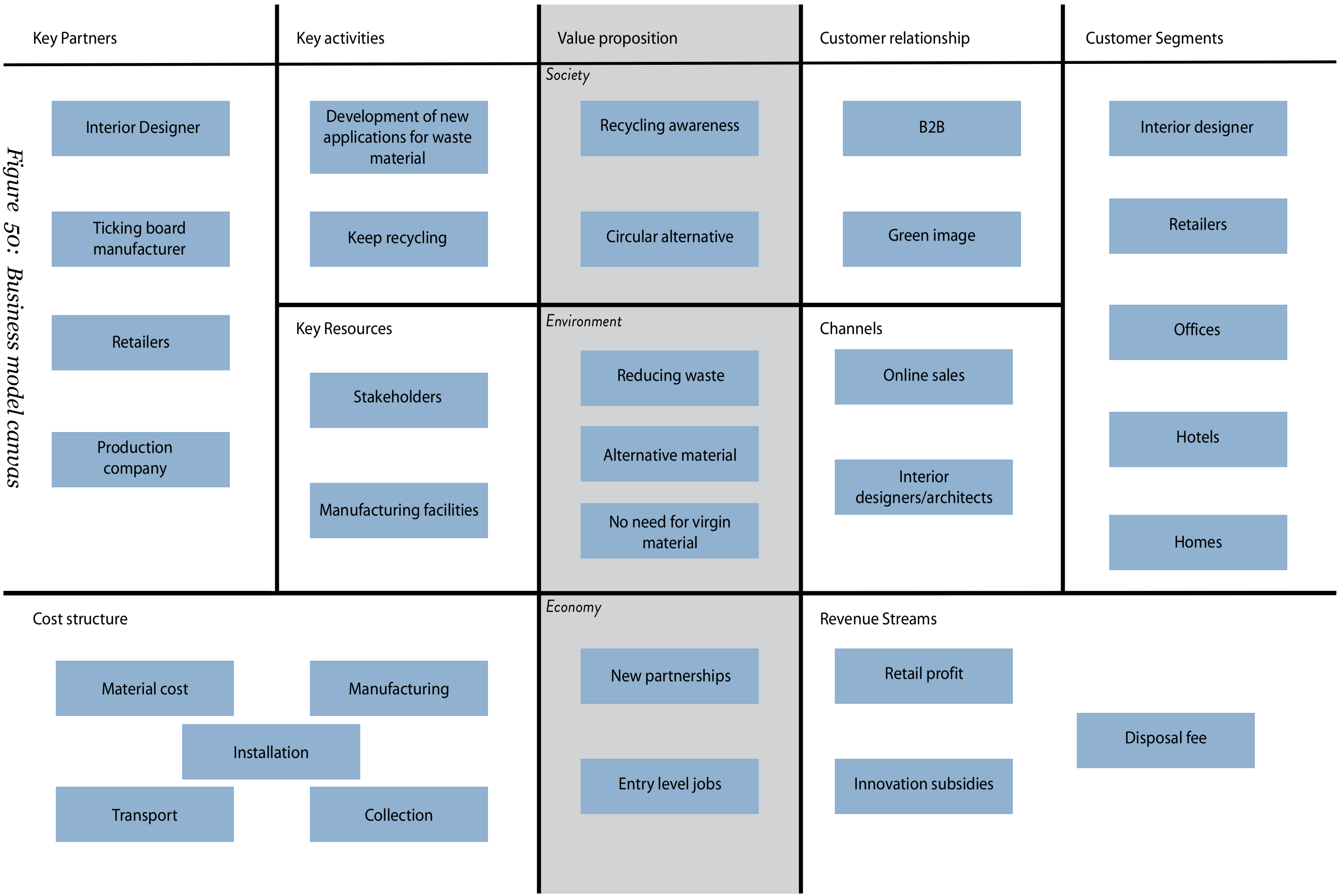


Figure 50: Business model canvas

5.4. Business model canvas

The business model canvas is used to create an overview of the new business model that comes with the new application of ticking waste. (Figure 50)
Because the classic Business model canvas does not take sustainability objectives into account an adaptation is used described by (Bocken, 2017). The difference with the classic version is the part of the value proposition. Commonly it only takes economic factors into account.
By using the adjusted version society and the environment are also taken into account.

Key partners

There are multiple stakeholders included in the production of Ticking Board. There is of course MRE which collects and separates the ticking material.
After separation the material is sent to the manufacturing company which makes the sheets of Ticking Board by shredding, pulverizing and heat pressing the waste material. During shredding or pulverizing the ticking an odour reducing agent has to be added.
After pressing the sheets they have to be treated to reduce flammability.
When the sheets are done they have to be transported to a company, like Merford, which produces and sells the final product. Chapter 5.5 describes input from Merford on the Acoustic Ticking.

Key activities

MRE is in this case involved in developing a new application for ticking waste. The end-of-life of ticking material will be prolonged by doing so.
The acoustic panels can be a first application for the ticking waste. After perfecting the manufacturing process other products made from ticking waste may follow.

Key resources

As MRE is not interested in manufacturing the final product themselves other stakeholders have to be included in the business model. These stakeholders have different skillsets to create a viable business case. For example, one stakeholder has the manufacturing knowledge and another has customer knowledge.

Another resource may be a start-up like REALLY on which the Ticking Board idea is based. This start-up will take on a leading role in the process.

Value proposition

As mentioned before the value proposition is divided into three subjects, namely society, environment and economics.

The value for the society is to make people aware of recycling and how seemingly non-recyclable material can be reused in other applications.
By using these other applications the amount of waste is reduced and a new valuable material is created that can be used in a circular economy. Also, no virgin material has to be used except for some additions to enhance the performance of the material (mostly in regards to reducing flammability). This addition however comes back into the material cycle when the acoustic panels are taken back to reuse the material.

Cost structure

The cost as can be seen in chapter 6.3 is based on estimations of production, material and manufacturing cost. When all the costs and margins are put together the selling price would be around 160 euros per square meter for the proposed product (figure 47, chapter 5.3). This puts the acoustic panels in the lower to middle range of similar products.

Revenue streams

The revenue streams will consist of margins for all stakeholders that are also taken into account in the selling price.
Another way of creating revenue is to apply for innovation subsidies or even the possibility of creating a crowd funded campaign.

Customer segment and relationships

The main customers will be businesses. These business have open spaces in which they want to improve the acoustics. These open spaces can be offices, retail spaces or churches for example.

Channels

The acoustic panelling is a product proposal to make the mattress industry fit in a circular economy. Since the mattress manufacturers will have to take responsibility for their materials this product can be one of the product proposals to show they will take this responsibility. This product will be sold by one or more partners. Most of the companies that sell acoustic panels have the possibility of online orders. The business that orders such an acoustic panel can do this directly from one of the sales partners. Another possibility is that an interior designer or architect functions as a channel since they can order acoustic panels from the partner as an intermediary.

5.5. Prototyping

This paragraph describes the prototyping stage of the acoustic panels.

Production of prototype

First ticking waste was pulverized using a Fritsch knife mill. (figure 51) After the pulverizing step, a t-shirt press (figure 53) was used to heat and press pulverized ticking waste at 260 degrees Celsius (figure 52).

The pulverized material had to be heated for at least ten minutes at 260 degrees Celsius in order to let the heat creep into the whole sheet. The difference with the suggested production process for ticking board is that the t-shirt press only has a top plate that is heated. This makes it more difficult to heat the ticking waste evenly.

Also because the material is heated and pressed at the same time the outer layer hardens before the inner material has a chance to be heated enough to melt together. This results

Figure 51: Fritsch knife mill

Figure 52: Pulverized ticking waste

Figure 53: T-shirt press

Figure 54: First sample of Acoustic Ticking

in a flaky inner layer (figure 55)
The density for this first sample was about 400 kg/m^3.

Figure 56 shows a sample made from pulverized waste using a larger sieve in the knife mill. This was done to see if it was possible to create a more open structure in the acoustic panel in order to improve the sound absorbing properties. As can be seen in the figure the density for this sample is lower which is desirable for an acoustic panel (see also the 'Evaluation of samples' at page 120)

The last sample which can be seen in figure 57 was made to see if it was possible to recycle the acoustic panel itself. The first samples were pulverized a second time using the knife mill with a small sieve (3 mm). Again the pulverized material is pressed using the t-shirt press at 260 degrees Celsius.
The resulting sample is weaker than the first sample. This might be because the material is finer than the first step of pulverizing.

A recommendation would be to use a large sieve in the knife mill or pulverizer to keep the material as


Figure 55: Flaky inner layer


Figure 56: Sample from longer fibres


Figure 57: Ticking waste recycled second time

coarse as possible. Especially in the second and further steps in recycling the acoustic panels.

Evaluation of samples

For this part of the prototyping stage the company Merford was contacted to get input on the developed material. A sample was taken to an interview with this company.
An interview guide and the questions asked in this interview can be found in appendix 5 and 6.

Merford is a large player on the market of acoustic panels in the Netherlands.
In general Merford was quite enthousiastic about the sample. They are interested in recycled materials since they get questions from their customers if they sell such a material. The one material they sell which is recycled is made from old jeans and is called Metisse.

Interview results

Having seen some products made from ticking before the most

important point for Merford is to be able to guarantee that the acoustic panels made from ticking waste do not contain pathogens.
Since the acoustic panels are heated in a oven at around 260 degrees Celsius it is unlikely the waste material will still contain bacteria or other live material.
Another thing that was pointed out in the interview is that the material is quite flaky. This is not desirable because it produces lots of dust. A suggestion made by Merford is to cover it using a piece of cloth or textile.

Furthermore, the density for an acoustic panel should be as low as possible to be able to absorb sound waves. To get a good absorption of soundwaves Merford suggests a density of 50 to 60 kg/m^3. So the density from the first sample (400 kg/m^3) is too high. The density from the second sample (figure 55) comes closer to a working acoustic panel at about 160 kg/m^3. This second sample was made using the larger sieve (figure 58) in the knife mill and then heating it at 260 degrees Celsius with low pressure.

The last remark that was made by Merford was about flammability. They were not overly concerned since it is already possible to add flame retardants to materials. As is also described in the paragraph about production.

The outcome of the interview has yielded suggestions for future improvements on the material and will be listed in the recommendations in chapter 7.

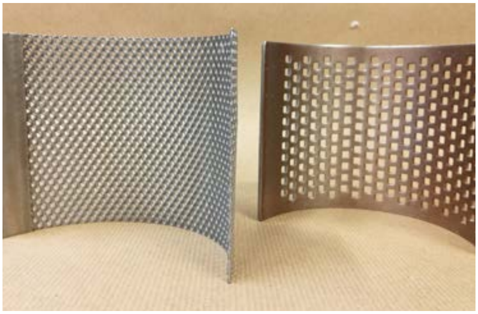


Figure 58: Small and large sieve for knife mill

5.6. Conclusion

This chapter has described the development of the final product.

Starting with three concepts the best solution, based on information from previous chapters, is an acoustic panel.

When looking at acoustic panels there are several options. A price comparison is made between these several options.

The comparison takes into account the process of making a base material and manufacturing the final product. The comparison is between ceiling tiles and acoustic wall panels. Based on the calculated prices and comparing these with existing acoustic solutions the most competitive one is chosen, namely acoustic wall panels.

The start for the acoustic wall panel is shredding, pulverizing and drying the waste ticking in an oven at 260 degrees Celsius. The heated ticking can be put in a press to create various shapes of panels.

There are however some important requirements to take into account. When using the material in buildings the flammability should be a low as possible. Therefore a solution should be applied to the ticking waste to reduce its flammability.

An interview is done with a company specialised in acoustic products. This company is called Merford. The interviewee was not overly concerned with flammability since there are solutions to overcome that. The most important issue he mentioned was that of pathogen concerns. When selling an acoustic panel made from ticking it has to be guaranteed non pathogenic.
Most biological pathogens however are eradicated during the heating part of the production process.

Other recommendations found during the research part of this thesis, comments made by Merford and how to proceed with the Acoustic Ticking can be found in chapter 7.

After the interview with Merford input about the density that is recommended for acoustic panels another sample is made as seen in chapter 5.5. This shows it is possible to reduce the density of the panels towards the recommended values.

Overall the suggested solution is viable as a product according to Merford, after the changes that are suggested in chapter 7.

This chapter discusses the review questions that are stated in the starting chapter of this thesis. The second part gives an overall conclusion of the thesis.

6 Conclusion

6.1 Review research questions

This paragraph dicusses in brief the research questions that were set up in the beginning of the project.

1. How can the material be used in a circular economy.

For the material to be used in a circular economy the lifespan of the material has to be prolonged. The TEPA solution is used in buildings as (sound) insulation in concrete floors and will only be accessible for recycling after demolishing the building. The material needs to be separated from the concrete rubble at the building site or recycling plant after which the material is sent to another recycler. When using the material in interior design it can be easily taken out of a building and separated at the building site after which it can be sent directly to the recycler.

2. Why choose mattress ticking to recycle instead of other parts of a mattress.

The most important argument for this question is that it takes almost three times the amount of energy to produce virgin polyesters than for example steel. Recycling of PET also costs 2-3 times less energy that the energy used to make virgin PET. (See also chapter 3.8)

3. How can recycled mattress ticking be improved to be usable.

After looking into other projects and tinkering with the material usable production processes are chosen and compared to come to a usable material. (Chapter 4) The final solution is to use the properties of the polyester (PET) that is used in ticking. At a certain temperature (270-290 degrees Celsius) PET will melt and encapsulate the other materials used in ticking. This principle is used to make sheets which can be used as acoustic panelling.

4. What improvements can be used to create value to the material?

To create value to the material the

material needs to have a solution which can eventually 'pay the bills'. In other words the material needs to be sold for a higher price than the production, transport and other costs. When looking at the price of competitors the acoustic panelling can be sold for the same price and still have a good margin.

5. What are the properties of the improved material?

The properties of the material differ for the different pressure options during pressing. The higher the pressure, the better the mechanical properties like yield strength. Due to its high natural fibre content the improved material is best to use in an acoustic solution. (Yahya & Chin, 2017) It is also possible to press sheets with a higher density by increasing the pressure during production of the sheets. These higher density sheets could be used in some kind of construction solution or for example furniture. The properties of the improved material in comparison to existing materials can be found in chapter 4.5.

6. Can the improvements be implemented in a circular economy?

The addition of an anti-flammability solution or any addition of substances is not desirable in a circular economy. However, to create a material that can be used as acoustic panelling there are certain requirements it has to fulfil. But when the material is collected to be processed into other products these additions will stay in the cycle of material. So the material can still be implemented in a circular economy.

7. How can the material be improved by adding as few additions as possible.

Looking at other projects other materials are added to create a useable material (see also chapter 4). For example the RECURF project uses waste wool or jute. In this project resins are added to create products. This makes it harder to recycle these new products since the material is mixed.
The final material in this project only needs a treatment against smell and

flame resistance which do not have a big influence on the mechanical properties of the material like in projects where resin is used. These substances will be mixed with ticking waste during production and will stay present during recycling.
Other than the smell and flame retardant treatment the material gets its properties from the waste material without the addition of resins or other (waste) plastics.

8. What are the unique properties of the different materials?

The unique property of the material is that by regulating the pressure a different material can be made. With less pressure an acoustic panel can be made. By increasing the pressure the sheet will get better mechanical properties and can be used in for example furniture as replacement for MDF. MDF is now the most used material in furniture because of its availability and price. It is not however a good material for use in a circular economy since it has to be burned after its end-of-life. (Source: LAP2)

9. What do current recycled products look like and are these products suitable for use in a circular economy

Current products that are recycled are mostly made from a single material. At the moment it is difficult to separate combined materials. Other projects about recycling can be found in chapter 4. Many of these projects use an adhesive or other addition that makes the next step of recycling more difficult or almost impossible. Therefore most of these projects are not suitable for use in a circular economy.

10. How can the current shredding and pressing method be improved to create different properties.

The current process can be improved by adding a pulveriser after the shredder. This pulveriser creates smaller pieces of material that will make a more homogenous material. When having a more homogenous material the properties in the product will be similar throughout the product and the view of the

product will be more soothing than the messy TEPA for example.
By using a heat press no other material or glue has to be added to the waste material which makes it possible to keep the original waste material without additions.

11. Can the material be treated with heat to create an improved material compared to TEPA?

As can be seen in this report the material can be treated with heat. The pieces of material in the TEPA however had to be made smaller in order to create a more homogenous material. This eventually resulted in the Ticking Board.

12. How can the shredded material be improved to not be perceived as 'confusing, messy or disgusting'.

According to the graduation project of Anne van den Dool people thought of the material as confusing, messy or disgusting. During her research she found that her subjects did not have this feeling with untreated pieces of ticking. The texture and the plain colour of untreated ticking waste made sure of that. The treatment of ticking waste is therefore adjusted to make a more even material. This is achieved by pulverizing the shredded material. The small blended pieces of pulverized material produce an even colour and feeling. This is different from TEPA because in TEPA harder and softer pieces of material can be felt. These differences in material are also not desirable for a large sheet in terms of properties. By pulverizing the material the material properties will be similar across the whole sheet/product.

13. What is the role of hygiene while using this material?

When showing the material to people they are surprised it is made from used mattresses. The idea however of it being made from mattresses disgusts some people because of the concern that there might be traces of urine, sweat, fecal matter or pathogens. After mentioning the production method (heat treatment) these concerns are taken away. Only positive amazement is left that such

a sheet can be made from the waste mattress ticking.
One thing that was mentioned was the smell of the material. Therefore a smell treating substance needs to be added to the production process.

14. What materials are used in mattress ticking?

There are a lot of materials used in ticking. The most common materials that can be found however are polyester and cotton. Other materials used in ticking can be horse hair or wool. See also chapter 2.3.
All these different materials in the textile are difficult to separate at the moment since the fibres are all combined. Ticking also consists of different layers of textile or foam that are glued or stitched together. This makes separating the different layers very expensive and time consuming.

6.2. Conclusion

The main goal of the project was to find a new application for ticking waste material. Because the Dutch government wants to create a circular economy in the Netherlands regulations for waste treatment are set up. At the 29th of June 2018 a letter was sent to the Dutch government about a law for manufacturers of mattresses and furniture who have to take responsibility for their products from 2019 on. (CBM, 2018)

This project takes a step into the direction of recycling existing mattresses, or ticking in particular.
In order to make the mattress industry circular the manufacturers have to modify their products. When mattresses are more standard in size and exist out of the same materials and/or structure, the disassembly will become easier. When the disassembly is easier the recycling will also become easier. The largest challenge in this project was to create a homogenous material which can be useful in one way or another. When ticking would have existed from less different materials the challenge would have been easier to overcome. The final product is still a mess of materials because it is too difficult and expensive at the moment to separate the various materials. The suggested solution in this project should be a temporary solution to prolong the lifecycle of the materials found in ticking instead of burning it. There are still a lot of mattresses in the Netherlands, but also all over the globe, which exist from mixes of materials. Some manufacturers are taking steps into more circular products because of new laws that will take effect in the coming years.

In this chapter recommendations for various parties are given that were found during this thesis. The last part will be a project and personal evaluation.

7

Recommendations and Evaluation

7.1. Recommendations

There are recommendations for mattress manufacturers which were found during the project. But there are also recommendations for further development of the material.

Mattress Manufacturers

- Use less different materials in mattresses. Some companies already implement this in their mattresses. For example IKEA produces ticking for most of their mattresses that only consists of cotton.
- Use one layer of ticking or use less stitches/connection points for the different layers in ticking. For example the ticking example of Auping that can be seen in chapter 2.5.
- The stitches can also be made from a material that disintegrates in a microwave. The company C-Tech innovation has such a yarn used for stitches called Wear2.

Development

- The shaping of the material could be looked into. Other heat press/already pressed into shape instead of pressing sheet and then shaping
- There might be some parts of the process that can be optimised for sustainability. This should be looked into further

Material

- There might be other textile manufacturers that have similar waste that could be used in the product.
- Brown/burnt colour of the material. Maybe colouring or change in heat treatment process?
- The amount of sagging of the sheets when hanging vertically should be looked into.
- Shrinkage and other technical properties for different batches of material should be tested.
- Exact acoustic properties should be tested.
- The influence of the flame retardant substance needs to be looked into further.
- Because the material of ticking differs in every batch a sample needs to be taken every time to check the material properties.

- The input from the interview with Merford about the flaky material should be looked at.
- Also the density might be improved on the make the acoustic properties of the material better.
- Are there any pathogens left after the production process?

Design

- The connection to the wall should be looked into further. It might for example be made from Ticking Board which is pressed harder. This stiff sheet can be cut into shapes that can be fixed to the wall to hang acoustic panels on.
- Various shapes or connection points might be made to expand the range of possibilities to use the acoustic panels in.
- The Ticking Board can be pressed into a denser material that might be used in furniture or construction applications.
- During pressing the sheets might get protrusions in a certain pattern for aesthetics and better acoustic properties.

7.2 Project evaluation

Process

The first few chapters in this thesis and the subjects treated in these chapters were quite structured since it was clear what I had to research. However the structure and order of the subject was changed a few times to keep the report readable and logical.
When coming to the specific making of choices the process could have been sped up. The tinkering part took a lot of time. One of the initial research questions was if the waste material could be heat treated to improve it in some way. When tinkering with the material a lot of experiments could have been thought of. These experiments could have been going on until now because there are always small factors to change in the process. The research question was answered already after one or two tests. I have done a lot more tests which were actually not necessary to do since the heat treatment question was already answered. It also did not yield any more interesting results.

After eventually abandoning the tinkering and moving on to another method the result of the project became clearer. Production methods were looked at that made it clearer in which direction to go with the project. These production methods pushed the project forward. In other words when getting stuck another method and speaking to people can help improve the project.
The other methods used of getting to a useful application in the end of the project helped formulating the final product. These methods where looking into properties of other sheet material and getting to know the unique properties. The final method was to look at comparable acoustic panelling and what kind of acoustic panel should be produced from the ticking waste material.

Personal

This project was the first project to do and manage alone. The process did not come easy to me. Starting the project with literature research and looking into other projects for example was the easy part of the process and gave a good basis for understanding the context of the project. However, I would have still been looking into literature if I did not have people around me who said to make a choice on what information to use and to make choices.
Half way through the project I was trying to do the whole project completely alone without the help of other people. This of course did not help to speed up the project. Because this project was a lot different than working in teams, which I was used to at IDE, I struggled a lot with getting people on board and involved in the project.
Also, because I tried to do everything myself I eventually got stuck and was too hesitant in contacting people who might be able to help me. This is also due to being too perfectionistic. Everything had to be perfect before showing the results to others which is of course very counterproductive.

So for myself I can conclude that I have to keep everyone involved in the loop by meeting regularly. This will help to improve the coming projects faster and more efficient.
The communication between parties can also be largely improved from my side. Besides the outcome of the project this might be one of the most important parts of the project. Everyone involved can be put on the same track and discussions about the project will also improve the efficiency of the project since choices can be made faster. When my stakeholder management was better throughout the project the outcome would have been faster and might have included more aspects about the final product.

The conclusion about the process and personal part of the project can be summarized as follows: always keep the process structured and make sure to speak to stakeholders frequently. This makes the project come together faster and more efficient. The structure can for example be done by making the diverging and converging stages more clear.

8
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9
Appendix

Appendix 1: Samples

This appendix shows samples that are not included in the main report.

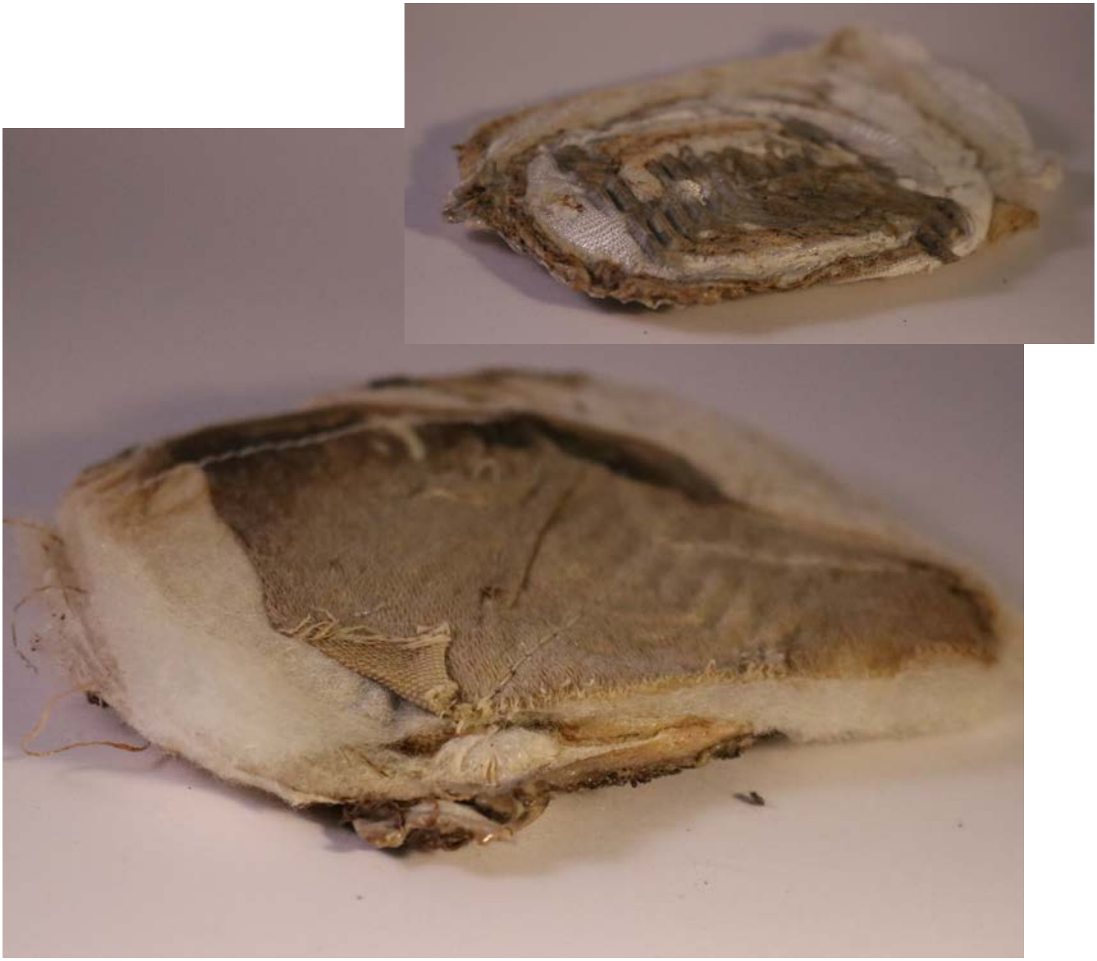
This first sample is a piece of TEPA which was heated by a paint burner set at around 600 degrees Celsius. The TEPA shrunk a bit but this did not yield a useful result.

The picture above shows ticking that was infused with wallpaper glue. Because the ticking was not cleaned it developed mold after a few days.

The picture above shows a pillow made from waste ticking. A clean piece of ticking is used for the outside. The pillow is filled with ticking that is cut into pieces of about 50mm x 20mm.

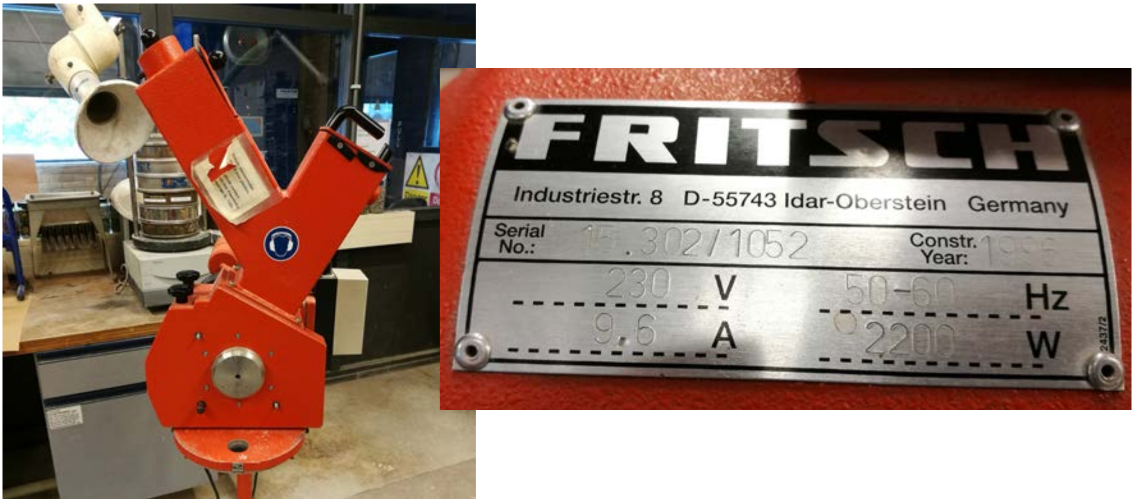
For the sample above, a piece of ticking is wrapped around a tube. It was heated by a paint burner set at 600 degrees Celsius. As can be seen the foam parts shrunk fast and created an uneven surface. As can also be seen in the sample on the left of this page.

The sample above is made by moulding shredded pieces of ticking (pieces of about 20mm x 20mm) into homemade PLA. The recipe used was 1 tablespoon cornstarch, 1 teaspoon of vinegar, 1 teaspoon glycerine and 4 tablespoons of water. This sample is not suitable for a circular economy because other material is added to the ticking



These samples are made by putting pieces of ticking, of about 10cm x 10cm, in an oven at 290 degrees Celsius. After heating the ticking it is pressed together with a weight of 80kg. As can be seen the top textile layers do not deform but burns at the edges. Furthermore the felt inside becomes a hard material.

Cut ticking before pulverizing



Fritsch knife mill used for pulverizing

Ticking after pulverizing

Ticking after pressing in a t-shirt press and cut into hexagons. Used during the interview with Merford.

Ticking before and after a second time of pulverizing

Ticking waste after the second time of pulverizing and pressing. The sample was a bit more brittle than the first sample. This might be because the fibres in this second sample are shorter in length.

To check if the proposed installation method could work a screw is put into a piece of pressed pulverized ticking waste. As can be seen this works so the installation method is possible.

When using the t-shirt press the sample on top is made by just touching the pulverized material. So that sample is made by just heating the material. In this way the density is around 160 kg/m^3.
The sample in the middle of the page is made by pressing the pulverized material as hard as possible with the press. The density is around 400 kg/m^3

Appendix 2: Cost analysis of processing technologies

To make an early estimation on the processing cost of the seven chosen processing techniques the table on page 148 is made.

In this table the machine, tooling and energy cost are summed up for each step in a processing technique. For example the first technique is the current processing of ticking waste. All cost for shredding, pressing and cutting are summed up.

These machines have a certain processing capacity of how much waste they can treat. This is taken into account under processing weight.

To make a better estimation on the processing cost an employee is needed for every machine. This is taken into account too.

At the bottom for each processing technique there are two prices given per ton ticking. The first one is without employee cost and the second one the employee cost are taken into account.

In the current processing technique for example, the processing price per ton ticking is 5,65 euros. With employee cost the processing price increases to 28 euros.

Machine cost	1. Semi-manufactured product				2. Laser cutting machine			
	Step 1: Shredding			People	Step 1: Laser cutting			People
	Fixed (45760 kWh)	Shredder	€ 1.400	€ 30.420	20280 kWh	Laser cutter	€ 6.000	€ 30.420
	Variable	Tooling cost	€ 8.000			Tooling cost	€ 5.000	
		Energy cost	€ 5.000			Energy cost	€ 1.500	
	Step 2: Pressing + binding				Step 2: Separation NIR			
	Fixed (15454 kWh)	Press	€ 1.200	€ 30.420	9091 kWh	Spectroscope	€ 1.000	€ 30.420
	Variable	Tooling cost	€ 1.000			Conveyor	€ 1.500	
		Energy cost	€ 1.700			Energy cost	€ 1.000	
	Step 3: Cutting				Step 3: Pressing			
	Fixed (22880 kWh)	Cutting machine	€ 1.200	€ 30.420	15454 kWh	Press	€ 1.200	€ 30.420
	Variable	Tooling cost	€ 1.500			Tooling cost	€ 1.000	
		Energy cost	€ 2.500			Energy cost	€ 1.700	
Total			€ 23.500	€ 114.760			€ 19.900	€ 107.660
Total without energy cost			€ 14.300	€ 105.560			€ 15.700	€ 104.460
Total kWh			42047				22412,5	
kg CO2			27289				14546	
Processing weight								
Weight (kg) of ticking/hour			1000				150	
Working days per year			260				260	
Working hours per day			8				8	
Total weight (kg) ticking per year			2080000				312000	
Cost per kg ticking			€ 0,006	€ 0,028			€ 0,223	€ 1,208
Cost per kg ticking without energy cost			€ 0,003	€ 0,025			€ 0,176	€ 1,172
Cost per ton ticking			€ 5,65	€ 28			€ 223,24	€ 1.208

Machine cost	3. Hot press				4. Rag tearing				5. Filament			
	Step 1: Cutting into sheets			People	Step 1: Cutter			People	Step 1: Shredder			People
	11440 kWh	Cutter	€ 800	€ 30.420	11440 kWh	Cutter	€ 800	€ 30.420	45760 kWh	Shredder	€ 1.400	€ 30.420
		Tooling cost	€ 3.000			Tooling cost	€ 3.000			Tooling cost	€ 8.000	
		Energy cost	€ 1.250			Energy cost	€ 1.250			Energy cost	€ 5.000	
	Step 2: Hot press				Step 2: Rag tearing				Step 2: Extruder			
	18720 kWh	Press	€ 400	€ 30.420	36400kWh	Rag tearer	€ 450	€ 30.420	31200 kWh	Extruder	€ 3.500	€ 30.420
		Tooling cost	€ 1.500			Tooling cost	€ 3.000			Tooling cost	€ 2.500	
		Energy cost	€ 2.250			Energy cost	€ 4.000			Energy cost	€ 3.500	
					Step 3: Hot press							
					18720 kWh	Press	€ 400	€ 30.420				
						Tooling cost	€ 1.500					
						Energy cost	€ 2.250					
Total			€ 9.200	€ 70.040			€ 16.650	€ 107.910			€ 23.900	€ 84.740
Total without energy cost			€ 5.700	€ 66.540			€ 9.150	€ 100.410			€ 15.400	€ 76.240
Total kWh			15080				33280				38480	
kg CO2			9787				21599				24974	
Processing weight												
Weight (kg) of ticking/hour			150				300				500	
Working days per year			260				260				260	
Working hours per day			8				8				8	
Total weight (kg) ticking per year			312000				624000				130000	
Cost per kg ticking			€ 0,103	€ 0,786			€ 0,027	€ 0,173			€ 1,563	€ 5,541
Cost per kg ticking without energy cost			€ 0,064	€ 0,746			€ 0,015	€ 0,161			€ 1,007	€ 4,985
Cost per ton ticking				€ 786				€ 173				€ 5.541

Machine cost	6. Needle punching				7. Fine semi-manufactured product			
	Step 1: Cutter			People	Step 1: Shredding			People
	11440 kWh	Cutter	€ 800	€ 30.420	Fixed (45760 kWh)	Shredder	€ 1.400	€ 30.420
		Tooling cost	€ 3.000		Variable	Tooling cost	€ 8.000	
		Energy cost	€ 1.250			Energy cost	€ 5.000	
	Step 2: Rag tearing				Step 2: Pulverizer			
	36400 kWh	Extruder	€ 450	€ 30.420	Fixed (57720 kWh)	Pulverizer	€ 940	€ 30.420
		Tooling cost	€ 3.000		Variable	Tooling cost	€ 3.000	
		Energy cost	€ 4.000			Energy cost	€ 6.350	
	Step 3: Needle punch	Puncher	€ 400	€ 30.420	Step 3: Pressing + binding			
	55120 kWh	Tooling cost	€ 8.000		Fixed (15454 kWh)	Press	€ 1.200	€ 30.420
		Energy cost	€ 6.000	€ 760	Variable	Tooling cost	€ 1.000	
						Energy cost	€ 1.700	
Total			€ 26.900	€ 118.160			€ 28.590	€ 119.850
Total without energy cost			€ 15.650	€ 106.910			€ 15.540	€ 106.800
Total kWh			51480				59467	
kg CO2			33411				38594	
	non continuous operation		€ 21.660	€ 112.920				
Processing weight								
Weight (kg) of ticking/hour			300				1000	
Working days per year			260				260	
Working hours per day			8				8	
Total weight (kg) ticking per year			624000				2080000	
Cost per kg ticking			€ 0,043	€ 0,189			€ 0,007	€ 0,029
Cost per kg ticking without energy cost			€ 0,025	€ 0,171			€ 0,004	€ 0,026
Cost per ton ticking				€ 189				€ 29
	non continous operation		€ 0,035	€ 0,181				

Appendix 3: Description other processing techniques

This appendix describes the remaining processing techniques that are not specified in chapter 4.5.

Laser cutting

Process description
The idea for this process comes from trying to separate the layers of ticking. To cut the stitches that can be found in ticking a laser cutter is used.
Because the stitches do not have a similar pattern the laser has to be guided. Since there is an existing technique to detect faults in textiles a similar camera recognition system could be used to detect the stitches.

After that the materials can be sorted using infrared. The infrared is used to detect the type of material the cut pieces are.
These separated materials can be processed according to existing recycling techniques used for the various materials.

Outcome
Separate pieces of textiles and foams sorted according to the type of material the pieces are made of.

Point of attention
The separate pieces have to be processed into products again after sorting. The energy this takes might make the new products too expensive.
This processing technique is too expensive at the moment.

Heat pressing

Process description
This process does not involve cutting ticking into small pieces, it is only cut to create standard size sheets. The layers are simply melted together by a heated press. This process however assumes that all ticking has a certain amount of PET in them.
However there are also foams that can be found in ticking. These foams do not transform when heated.

A cutter is used to cut standard size sheets. These standard size sheets are melted together using a heated press creating a stiff sheet

Outcome
Stiff sheets of ticking that might be used as a construction material.

Point of attention
Not all material can be processed using this material. Or when foams are left in the processed ticking a sandwich panel might be constructed. The foams however do not transform or melt using heat.

Filament

Process description
This process can only process PET blends since it uses heat to create filament. Other materials that might be found in ticking cannot be processed with this technique.

First a shredder is needed to reduce the size of ticking in order to fit in the filament extruder.

The filament extruder takes the small pieces of ticking and melts and extrudes the PET blend into filament.

Outcome
Rolls of filament that can be used in 3D printers.

Point of attention
Not all ticking can be processed using this technique.

Needle punching

Process description
This process is to create felt from the ticking. It is quite similar to the rag tearing process but has a different outcome. The felt that will come out of this process can be sold as felt or processed further like the felt chair from de VORM. (Chapter 3.2)

A cutter will take the ticking and cut it into smaller pieces. These smaller pieces are taken to a rag tearing machine which will pull the ticking apart into separate fibres.

These fibres are taken to a needle punching machine which will create felt.

Outcome
The outcome of this process can be used as felt itself or processed further into other products.

Point of attention
The foams that can be found in some ticking cannot be processed using this technique.

Appendix 4: Cost calculation of final product

The cost calculation for the final product includes two prices. Except for the cost calculation of the final product it is also to calculate the production price for acoustic sheets.

In chapter 5 a choice had to be made if the final product would be acoustic sheets or acoustic wall panelling. The choice is based on the calculation found in this appendix.

This cost calculation is based on Thomassen (2015) ‘Samenvatting - Kostprijsopbouw Berekening’.
The values are taken from sources found in the document from Thomassen.

Machines	Cost (€)	Write-off years		Machine cost per year	Energy cost	Maintenance	Investment hourly	Tooling cost
Shredder	140000	10		14000	16800	8400	12	8000
Pulverizer	225000	10		22500	27000	13500	15	6000

Machines	Capacity (kg/hr)	Machinehours	Machine/hour rate	Machinecost	
Shredder	1000	1200	39	47212	
Pulverizer	800	1500	46	69015	
				Total machinecost	**116227**

Personel		Personel hours	Personel cost/hr	Personel cost	
Shredder	1	1200	15	18000	
Pulverizer	1	1500	15	22500	
				Total personel cost	**40500**
				Total cost processing	**156727**
				kg ticking processed	**1200000**
				Cost processings/ kg	**0,1**

Machines	Cost (€)	Write-off years		Machine cost per year	Energy cost	Maintenance	Investment hourly	Tooling cost
Oven	150000	10		15000	18000	9000	10	1000
Press Sheet	50000	10		5000	6000	3000	0,38	10000
Press Shapes				7500	6000	3000	0,29	200000

Machines	Capacity (kg/hr)	Machine hours	Machine/hour rate	Machine cost	
Oven (2x)	800	1500	29	43010	
Press Sheet	90	13333	1,80	24000	
Press Shapes	130	17143	12,63	216500	
			Sheet	**Total machinecost**	**67010**
			Shapes	**Total machinecost**	**259510**

Personel		Personel hours	Personel cost/hr	Personel cost	
Oven	1	1500	15	22500	
Press Sheet	1	13333	15	199995	
Press Shapes	1	17143	15	257145	

Sheet	Total personel cost (€)	222495		Shapes	Total personel cost (€)	279645
	Total productioncost (€)	289505			Total productioncost (€)	539155
	Total # sheets	160000			Total # sheets	160000
	Price per sheet (€)	1,8			Price per shape (€)	3,4
	Price per kg ticking (€)	0,2			Price per kg ticking (€)	0,2
	Weight (kg) per sheet	7,4			Weight (kg) per shape	0,8
	Sub total production price per sheet (€)	3,3			Sub total price production price per sheet with shapes (€)	3,5
	Failure + Overhead factor	16%			Failure + Overhead factor	16%
	Total productioncost/sheet (€)	3,8			Total productioncost/sheet with shape (€)	4,1

Machines	Cost (€)	Write-off years	Machine cost per year	Energy cost	Maintenanc	Investment hourly	Tooling cost
Cutter	50000	10	10000	6000	3000	3,75	5000
Laser cutter	500000	10	100000	45000	30000	12,5	12000

Machines	Capacity (sheet/hr)	Machinehours	Machine/hour rate	Machinecost
Cutter	60	2667	9	24004
Laser cutter	20	8000	23	187013

Personel		Personel hours	Personel cost/hr	Personel cost
Cutter	1	2667	15	40005
Laser cutter	1	8000	15	120000

Total cost cutter	64009		Total cost laser cutter	307013
# of sheets	480060		# of shapes	1920000
Cost per sheet	0,13		Cost per shape	0,16
Final production price per sheet	**3,9**			**4,3**

Selling price		**Sheets**	**Shapes**
		€ 3,9	€ 4,3
Overhead company	15%		
Overhead selling cost	5%		
Profit factor	25%		
Total factors	50,90%	€ 2,0	€ 2,2
Selling price at manufacturer		€ 6,0	€ 6,4
Retail margin	150%	€ 8,9	€ 9,6
Retail + Selling price		€ 14,9	€ 16,0
Taxes	21%	€ 3,1	€ 3,4
Final selling price		**€ 18,0**	**€ 19,4**
Size of product (m^2)		0,54	0,12
Price per (m^2)		**€ 33**	**€ 159**

Appendix 5: Interview guide/results and questions

User research
The purpose of this user research is to validate the material properties of the acoustic panel, to validate the design and to get to know the opinion of the users of the panels. This paragraph will describe the setup for the user research and the results of the interview. The results from this interview will give input for future development of the material and/or product. Another result can be ideas for other kinds of products.

1.1 Setup

During the interview several topics will be discussed. After general introductions the first topic are the properties of the material and in what way they could be improved. Also specific requirements that might be applicable are discussed.
The second topic will be about business aspects. For example what information the company needs when selling the panels and who will produce the products.
Other topics will be about recycling, sustainability and partnerships. Two of the companies that were interviewed were visited, another interview was done over the telephone. A sample of the material was sent to the company were the interview was done over the phone.

1.2 Results

The results will be discussed here. First the company is described briefly and a conclusion will be given for the recommendations made by the company. The detailed interview can be found in appendix 6.

Merford
Merford was contacted to get input on the developed material. A sample was taken to an interview with an employee of this company. The employee with whom the interview was conducted is Kaj Tyszka.

Merford is one of two large players on the market of acoustic panels in the Netherlands. They also have other activities like bulletproof and acoustic doors or control cabins on large cranes in the Rotterdam harbour for example
In general Merford was quite enthusiastic about the sample. They are interested in recycled materials since they get questions from their customers if they sell such a material. The one material they sell which is recycled is made from old jeans and is called Metisse.

Interview results

Having seen some products made from ticking before the most important point for Merford is to be able to guarantee that the acoustic panels made from ticking waste do not contain pathogens.
Since the acoustic panels are heated in a oven at around 260 degrees Celsius it is unlikely the waste material will still contain bacteria or other live material.
Another thing that was pointed out in the interview is that the material is quite flaky. This is not desirable because it produces lots of dust. A suggestion made by Merford is to cover it using a piece of cloth or textile.

Furthermore, the density for an acoustic panel should be as low as possible to be able to absorb sound waves. To get a good absorption of soundwaves Merford suggests a density of 50 to 60 kg/m^3. So the density from the first sample (400 kg/m^3) is too high. The density from the second sample comes closer to a working acoustic panel at about 160 kg/m^3. This second sample was made using the larger sieve in the knife mill and then heating it at 260 degrees Celsius with low pressure.

The last remark that was made by Merford was about flammability. They were not overly concerned since it is already possible to add flame retardants to materials. As is also described in the paragraph about production.

The outcome of the interview has yielded suggestions for future improvements on the material and is listed in the recommendations in chapter 7.

Interview akoestische panelen

Introductie

- Wie zijn jullie?
- Wat doen jullie? Wat zijn jullie werkzaamheden?
- Hoe lang zitten jullie al in dit vakgebied?

- Wie ben ik?
- Uitleg over het project. (Opmerking: Voor het gemak noemen we dit een (akoestisch) paneel)
- Er zijn een aantal punten waarover ik het wil hebben tijdens dit interview. (Doel, eigenschappen, zakelijke aspecten, afsluitende vragen)

Doel van het interview

- Wat jullie mening is over dit paneel.
- Of er verbeteringen nodig zijn aan het paneel.
- (Erachter komen of dit paneel voor alle partijen interessant is te verkopen)

Eigenschappen

1. Wat is jullie eerste gedachte als jullie dit paneel zien?
2. Wat vinden jullie van de kleur?
3. Zijn er verbeteringen door te voeren voor de kleur?
   a. Zo ja, waarom?
   b. Zo ja, welke verbeteringen? (Iets met meerdere kleuren?)
4. Wat vinden jullie van de geur?
5. Zijn er verbeteringen door te voeren voor de geur?
   a. Zo ja, waarom?
   b. Zo ja, welke verbeteringen?
6. Hoe worden jullie huidige producten gerecycled?
7. Welke afmetingen moeten de panelen hebben?
8. Van welke maximale dikte gaan jullie uit bij jullie producten? I.v.m. bestaande installatie systemen?
9. Wanneer mag een paneel een akoestisch paneel worden genoemd?
10. Aan welke eigenschappen moet een akoestisch paneel voldoen?
   a. Zijn er bepaalde richtlijnen waar een akoestisch paneel aan moet voldoen?
   b. Waar laten jullie de metingen doen wat betreft de akoestische eigenschappen?

Zakelijke aspecten

1. Hoe komen jullie nu aan akoestische panelen?
2. Hoe werkt de productie bij jullie? Doen jullie dit zelf of een andere partij waarbij jullie de verkoper zijn?
3. Hoe ziet jullie bestaande zakelijke samenwerking met partners/andere bedrijven eruit?
4. Op welke manier staan jullie open voor een nieuwe samenwerking?
5. Hoe zien jullie deze nieuwe samenwerking?
6. Hoe staan jullie tegenover duurzaamheid/circulaire economie?
7. In hoeverre worden jullie producten gerecycled?
8. In hoeverre zijn er bestaande oplossingen waarbij de gebruikte producten door jullie (of andere partij) opgehaald en gerecycled worden?
9. Welke informatie hebben jullie nodig voor de verkoop van dit paneel of akoestische panelen?
10. Voor welke prijs kopen jullie vergelijkbare materialen in?

a. Indicatie van de kosten voor de panelen

b. Wat is een paneel waard? (Monetair gezien in relatie tot circulairiteit)

Afsluitende vragen

1. Wat vinden jullie van dit paneel?
2. Zouden jullie geïteresseerd zijn wanneer dit op de markt zou komen?

a. Waarom wel/niet?

b. Wat zou het nog nodig hebben om wel interessant voor jullie te zijn?

3. Mag MRE contact met jullie opnemen in de toekomst?
4. Weten jullie misschien andere bedrijven die eventueel geïnteresseerd zijn?

Appendix 6: Interviews

Introduction

Merford is a company which produces acoustic panels among other sound proofing solutions and other specialist products like bulletproof doors and control cabins for cranes. The acoustic department started as acoustic insulation of industrial exhaust systems on buildings. The department for acoustic panels split from the industrial part a decade back to focus on the other kind of solution they had to provide.

Properties

1. What is your first thought about the panel?

The first thing that comes to mind is that you have to be able to guarantee that there are no pathogens left in the mattress material. This is the most important point in my opinion to not make people ill from our products.
Also the material is quite flaky so this has to be looked at. It might be covered with a piece of textile for example.

2. What do you think of the colour?

The colour is not the first concern. The colour can be changed after the acoustic panels are done. It can be painted or covered by a piece of textile.

3. What improvements have to be made to the colour?

At the moment this is not the first concern

4. What do you think about the smell?

The smell is not very pleasant but also not very notable from a distance.

5. What improvements have to be made to the smell?

At the moment the smell is not the mayor concern and not very notable.

6. How are your products recycled at the moment?

At the moment our products are not recycled.

7. What dimensions do the panels have to have?
We deliver custom panels so the factory makes the panels at the right dimensions.

8. What maximum thickness do you take into account for your current panels? (For existing installation solutions)
As mentioned we deliver custom panels so there is no maximum thickness. All is made on demand.

9. When is an acoustic panel called an acoustic panel?
In general an acoustic panel should have a somewhat absorbing property. A good acoustic panel should have a bit of an open structure and have a density of about 50-60 kg/m^3.

10. What properties does an acoustic panel have to have?
This is mentioned in the previous question. This is the most important for an acoustic panel.

Business aspects
1. How do you get your acoustic materials now?
We buy our acoustic materials from other companies. Our factory uses these foams etcetera to create the products for customers.

2. How does you production work? Do you do this yourselves or are you just the selling company?
The materials are bought and then made into the products we sell

3. How is your existing collaboration with other companies?
They are only suppliers of materials.

4. In what way are you open to new collaborations?
The selling of acoustic materials can be done by us. As mentioned we only tool materials into shape and then sell them. The acoustic material from ticking waste should be produced by another company.

5. What is your opinion on sustainability/circular economy?
It is a good thing but our company does not really take it into account yet.

6. How are your products recycled?
Our products are not recycled but discarded by the user.

7. Are there solutions where your used products are collected and recycled by your company?
We are not aware. This is not the case for us at least.

8. What information do you need for selling the acoustic panels?
The density of the material and the acoustic properties of the material. Also the flammability.

9. What do you think of the price of the acoustic panels?
In comparison to existing acoustic materials it is quite expensive, but in comparison with recycled products it is a good price.

Closing questions

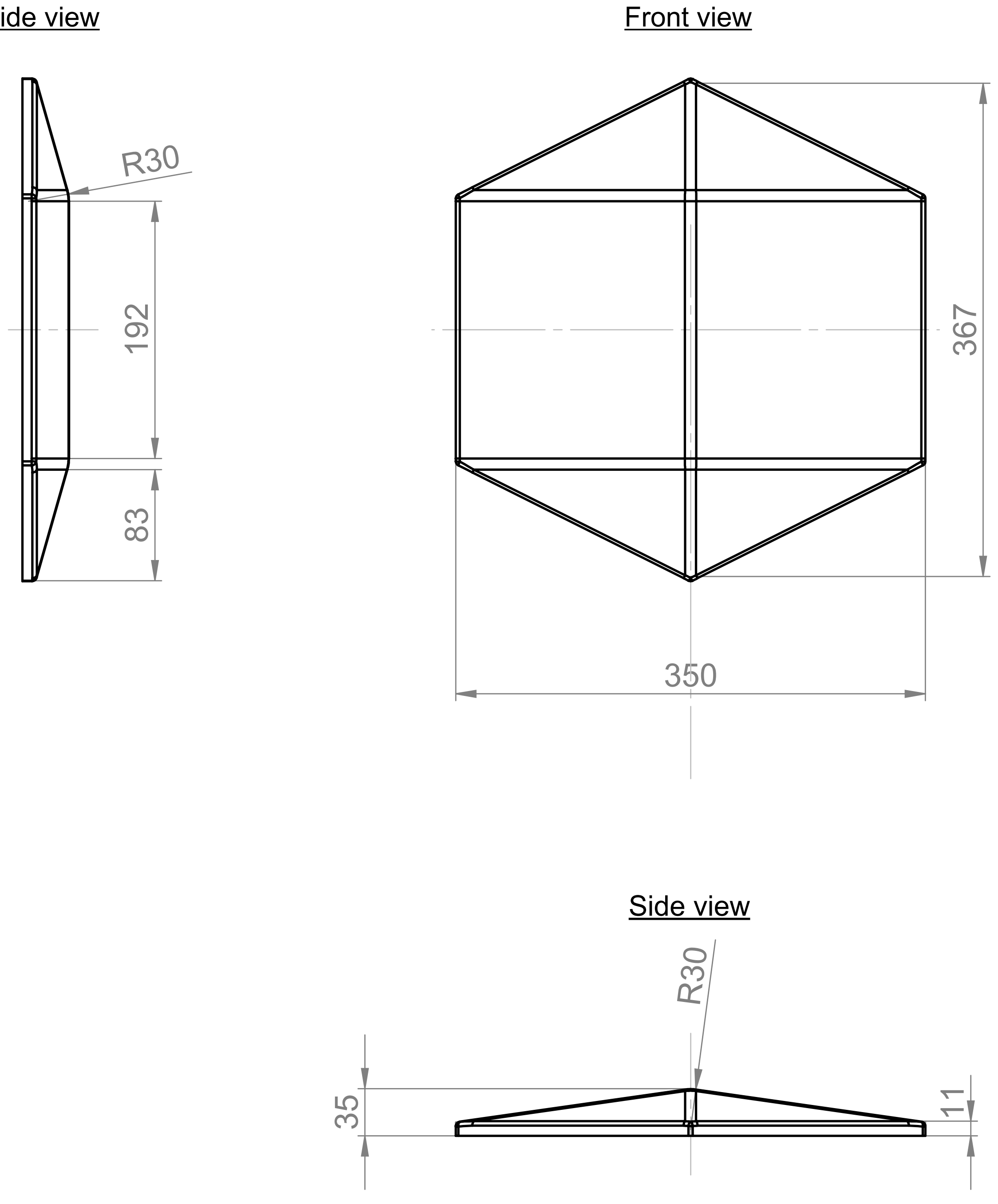
1. What do you think of the panel?
It is an interesting solution for ticking. I have seen products made from ticking but not as far in development as this one. There are some things to take into account. As mentioned the pathogens that have to be eradicated and the flaky appearance of the material should be looked into. Also the density of this first sample is too high for an acoustic panel. The flammability is not a great concern since there are already solutions that can be applied to reduce the flammability.

2. Would you be interested in the acoustic panels when they are ready for sale?
When the points of concern are overcome we are interested in the panels to sell them. There are customers who ask for recycled products in acoustic solutions. They are also willing to pay more for these recycled products than non-recycled products.

3. Can MRE contact you in the future?
Yes.

4. Do you know other companies who might be interested?
Except for EASYnoisecontrol, who is our greatest competitor, there are not much companies selling acoustic solutions as we do.

Appendix 7: Technical drawing final product



Material: Pulverized waste mattress ticking
All roundings are 3,5mm
if not otherwise indicated

benaming: Acoustic Ticking			maateenh. mm
		formaat A4	tekeningnummer 1
TU Delft Industrial Design Engineering	schaal 1:1	datum 11 september 2018	
	getekend Tjerk Alewijn		Graduation

Appendix 8: Patents

This paragraph sums up four patents that were found on Google Patents in relation to the reuse or recycling of mattresses.

Methods and apparatus for refurbishing bedding mattresses (2001, US 6263532 B1).
This patent describes a separate upper, lower and border panel which creates an enclosure for an existing mattress construction.

Process for producing a new improved mattress from a used mattress (2000, US 6101718 A).
The title suggests that a whole mattress is being refurbished. The patent however describes how to only use the inner spring assembly in a new mattress. The foams are not refurbished in this patent.

Modular mattress structure (1976, US 3950800 A).
Faulty components of the mattress could be easily replaced with this idea. All components can be exchanged by the user when they are defective. This way the life span of the mattress is extended before it has to be sent to a renovator or recycling facility.

Separating Components of a Pocket Sprung Mattress Sub-Assembly (2017, US 20170216980 A1).
In this patent a method is described on how to separate a pocket spring assembly. This assembly consists of a packet of individually wrapped springs. The method in this patent is to tear this packet apart to get the individually wrapped springs using a set of rollers. A next series of rollers will tear the textile pocket in which the springs are retained and separate the metal spring and textile remainder.