ALL-CELLULOSE SHOE

Wood-Based Materials in Footwear

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ABSTRACT

The aim of the thesis was to test novel wood-based materials in footwear. The thesis was conducted within the Design Driven Value Chains in the World of Cellulose (DWoC) project funded by Tekes. DWoC is a multidisciplinary research project that aims on finding innovations from wood with the help of design. The client of thesis is VTT Technical Research Centre of Finland, where the author worked as research trainee during the project.

Cellulose has many good qualities, such as strength, abundancy, renewability and chemical tunability. Wood-based cellulose textiles have potential in replacing commonly used and often unecological textiles, such as cotton or oil-based textiles.

The main goal of thesis was to make a demo shoe, *an all-cellulose shoe*, from wood-based materials. The thesis was not aiming to develop a material that would be ready for commercial shoes, but to inspire companies and other stakeholders by the potential of cellulose in new applications. The research aimed to test and develop selected wood-based materials on footwear. Material development was design driven and done together with material researches. In order to compare the developed materials to commercial footwear materials, two standard tests for shoe uppers were carried out. The test results showed, that the materials were not ready to use in commercial footwear, mostly due to lack of strength.

The thesis resulted a pair of all-cellulose shoes. The materials lasted in shoe-making process, where the materials were doused in water, heated, glued, sewed and treated with heavy machines. Even though the materials are yet not strong enough to be used in commercial footwear, cellulosic materials turned out to be versatile and also proved to have potential in footwear.

Keywords Cellulose, Wood-Based Materials, Material Research, Ecological Footwear
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TIIVISTELMÄ

Muotoilun koulutusohjelma
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TIIVISTELMÄ

Opinnäytetyön tarkoituksena oli kokeilla uusia puupohjaisia materiaaleja jalkineeseen. Työ toteutettiin osana Design Driven Value Chains in the World of Cellulose (DWoC) -projektia, joka on Innovaatiorahoituskeskus Tekesin rahoittama tutkimushanke. DWoC on poikkitieteellinen tutkimusprojekti, joka pyrkii löytämään innovaatioita puusta designin avulla. Työnantaja on Teknologian tutkimuskeskus VTT, jossa työskentelin tutkimusharjoittelijana projektin ajan.

Selluloosalla on monia hyviä ominaisuuksia. Se on kestävä, uusiutuva ja yleinen materiaali, jota voi muokata moniin tarkoituksiin. Puupohjaisilla selluloosamateriaaleilla on potentiaalia korvata yleisesti käytettyjä, usein epäekologisia tekstiilejä, kuten puuvillaa tai öljypohjaisia tekstiilejä.

Työn päätarkoituksena oli tehdä demokenkä, selluloosakenkä, puupohjaisista materiaaleista. Työssä kokeiltiin ja kehitettiin valittuja puupohjaisia materiaaleja jalkineeseen. Materiaalitutkimus oli design-lähtöistä ja se tehtiin yhdessä materiaalitutkijoiden kanssa. Jotta kehitettyjä materiaaleja voitiin verrata kaupallisiin jalkinemateriaaleihin, jalkinepäällisille tehtiin kaksi standardikoetta. Tulokset osoittivat, että materiaalit eivät ole vielä valmiita käytettäväksi kaupallisessa jalkineessa, pääosin materiaalin kestävyyden takia.

Tutkimuksen tuloksena syntyi selluloosakenkäpari. Käytetyt materiaalit kestivät kengäntekoprosessin, jossa materiaaleja kasteltiin, kuumennettiin, ommeltiin ja käsiteltiin raskailla koneilla. Vaikka materiaalit eivät ole valmiita käytettäviksi kaupallisissa jalkineissa, selluloosamateriaalit osoittautuivat monikäyttöisiksi ja todistivat, että niillä voi olla potentiaalia myös jalkinemateriaalina.

Avainsanat Selluloosa, puupohjaiset materiaalit, materiaalitutkimus, ekologinen jalkine

Sivut 37 sivua

CONTENTS

1 INTRODUCTION

Great potential lies in Finnish forest, technology and design knowledge. For long, Finnish forest industry focused on producing paper and cardboard from wood pulp. Now politics, business and technology are widely focused on finding more value out of wood, the green gold that covers over 70 percent of the country. The purpose of this thesis is to take part to this conversation from the perspective of footwear design.

Design Driven Value Chains in the World of Cellulose (DWoC) is a multidisciplinary research project that aims on finding innovations from wood with the help of design. As a part of DWoC this thesis explores the possibilities of novel cellulose materials in shoe-making. The client of the thesis is VTT Technical Research Centre of Finland (later referred to as VTT), one of the four partners of DWoC.

Cellulose, the main constituent of plants, is the most abundant organic material in the world (O'Sullivan 1997, 173). Cellulose's good qualities, such as strength, abundancy, renewability and chemical tunability, makes it a potential super material of the future. Alongside the traditional wood and cellulose research, there is an increasing interest towards new innovative methods of using cellulose. (Cellulose From Finland n.d.) In this thesis these new, innovative wood-based cellulose materials are applied in shoe-making.

1.1 Objectives, Research Questions and Hypothesis

The aim of the thesis is to make a demo shoe, *an all-cellulose shoe*, from novel wood-based materials using a design driven research method. The materials are provided mainly by VTT and DWoC. The research aims to test and develop selected wood-based materials on footwear. Following research questions will be answered: (1) *How do wood-based materials work in shoe demos?* (2) *What is an all-cellulose shoe like?*

The thesis is not aiming to develop a material that would be ready for commercial shoes. The goal of the all-cellulose shoes is to inspire researchers, companies and other stakeholders and raise awareness about good qualities of cellulose.

The requirements of footwear materials are manifold. For example, the footwear upper needs to be strong and elastic in order to work properly. Hence, footwear can demonstrate the different properties of materials well. In this sense, the project aims to present many qualities of cellulose in one product.

The main focus is to find an upper material for shoes. Sole materials, heels and adhesives are also tested. Most of the materials used in the thesis are developed in the DWoC project or at VTT, some are commercial. The only material developed especially for this shoe demonstration is the upper.

It is hypothesized that (1) suitable materials are found and that demo shoes can be made from wood-based materials. It is further hypothesized that (2) the developed materials will not yet be suitable for industrial shoe making, mostly because of the lack of strength and water-resistance.

1.2 DWoC and VTT

This thesis is conducted at VTT, as part of the DWoC project. Design Driven Value Chains in the World of Cellulose (DWoC) is a multidisciplinary research collaboration project between VTT, Aalto University, Tampere University of Technology and the University of Vaasa. The project is funded by Tekes, the Finnish Funding Agency for Innovation. DWoC focuses on finding new and innovative applications for cellulosic materials by combining design-driven prototyping and technology development. The project takes place 1.4.2013–31.3.2018. (Cellulose From Finland n.d.)

The goal of DWoC is to make Finland a source of high-value cellulose products and business concepts. It also aims on changing “the current large-scale forest industry into a dynamic ecosystem for the bioeconomy containing both large and small-scale businesses”. In the DWoC project cellulose is used in highly refined products like textiles, clothing, health products and architecture. Close cooperation between designers, architects, business professionals and material researchers are in the centre of DWoC. (Cellulose From Finland n.d.)

The employer of the thesis, VTT, is a leading research and technology company in the Nordic countries. VTT provides services for both private and public sectors, domestically and internationally. It focuses on developing smart technologies and innovation services. VTT operates under the mandate of the Ministry of Economic Affairs and Employment and is part of Finland's innovation system (VTT n.d.). The author worked as a research trainee at VTT in the High Performance Fibre Products team for 6 months in spring 2017.

1.3 Structure and Research Methods

This thesis is an interdisciplinary research combining footwear design and material research. Figure 1. presents the structure of the thesis. The main focus is on the footwear upper material, which is developed in a design driven way. The essence of DWoC is to combine design and technology using a design driven approach, which is also used in this thesis. Taking design into material development in the early stages can improve and accelerate the research and result in a near ready-to-use product. Design-driven material research is presented in Chapter 3.

During the research, different demo shoes are made and materials are developed step by step based on the previous demo. The shoe upper material development is design driven and done together with VTT's material researchers. The chemical compositions of the other used shoe making materials will not be changed, though the author processes and moulds the materials for footwear purposes.

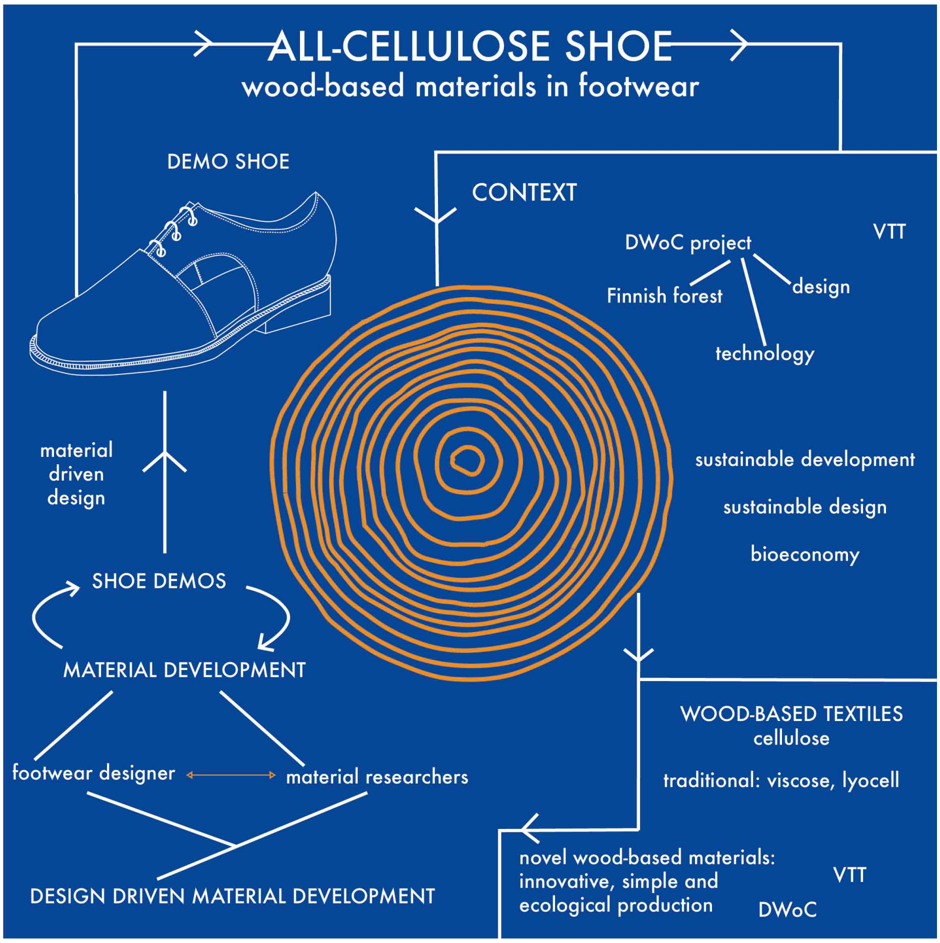

Figure 1. Structure of the thesis.

The research is conducted empirically. Different materials are tested with several footwear-making methods. The shoe design part is material driven (see definition in page 9), where each material is tested before the application. The materials used in the thesis have never been used in shoes before, hence all materials need to be trialled before using them on the final demo shoe. Upper materials are tested by sewing, gluing, shaping and lasting the material on a shoe last. Materials are also dyed, 3D printed and shaped with heat and moulds. These different methods of material shaping are presented in detail in chapter 5. After testing and trialling the materials, they are either developed further or discarded, in order to find suitable materials for the demo shoe.

Finally, in order to compare the upper material developed in the project to other shoe upper materials, the strength of upper materials is tested. Two different standard tests for shoe uppers are carried out. Information about the standard tests and the results are presented in Chapter 3 and 6.

1.4 **Context**

There is a need to find alternatives to commonly used footwear materials, such as chrome-tanned leather, oil-based synthetic materials or cotton[1], that too often are harmful to the environment. Ecological wood-based materials could be one solution.

In 2015, 23 billion pairs of shoes were produced worldwide. Almost 87 % of the world's shoes are produced in Asia (World Footwear Yearbook 2016, 3), where working conditions and environmental standards are not on an ideal level. The overall impact of the footwear industry to the environment is significant. The main environmental impacts of footwear come from the material processing and manufacturing phase (Cheah et al. 2013, 20). In addition, design process, transportation, consumption and recycling of shoes influence the environment.

Recycling shoes is far more difficult than recycling clothes. According to a study, "a single shoe can contain 65 discrete parts that require 360 processing steps for assembly" (Cheah et al. 2013, 18), hence this makes it also difficult to separate and recycle. Only a small amount of shoe waste is recycled (Better Shoes Foundation, A. n.d.). Commonly used footwear materials, such as chrome-tanned leather, cotton or oil-based materials, have major environmental impacts. There are many better alternatives for these materials, for example different plant-based textiles, such as Pinatex™, a nonwoven textile made from pineapple leaf fibres (Better

[1] On average, cultivating 1 kg of cotton takes 8000 litres of water. In addition, large quantities of fertilizers and pesticides are used. (Fletcher 2008, 7–8.)

Shoes Foundation, B, n.d.) This thesis focuses on wood-based material alternatives.

Using wood-based materials in shoes is not a new phenomenon. For example, during the Winter War, many shoes in Finland were made from paper fabric. Most of the available leather went to military purposes, which forced the footwear industry to create new materials. (Lehto, Lind & Palo-oja 2005, 81.) Paper and wood were popular substitutes. Soles were made of domestic wood such as birch, pine and spruce. Uppers were made of paper fabric (Lehto, Lind & Palo-oja 2005, 86) and other early cellulose materials, such as spun rayon[2]. Water and wear resistance of these materials were rather poor (Vaatturitietokanta 2017). The materials used in this thesis are novel, high performance, researched materials, though they are made from similar raw materials.

Figure 2. On the left, wartime women's shoes from 1943 made from paper fabric (Helsinki City Museum). On the right, a shoe from early 1940's. Paper fabric uppers are reinforced with lacquer. Soles are made of wood. (Museum Centre Vapriikki.)

1.5 Bioeconomy

In addition to the traditional forest industry and the production of bulk products, there is an increasing interest in developing higher value products from wood. One of the key concepts around this shift is bioeconomy.

Bioeconomy refers to a system that relies on the use of renewable resources to produce energy, products, food and services. It will reduce dependence on non-renewable resources, help preserve biodiversity and create economic growth based on sustainable development. One of the Finnish Bioeconomy Strategy's objectives is to generate new economic growth from high value products. (Ministry of Employment and the Economy 2014, 3.) This is also one of the main goals in the DWoC project.

[2] In Finnish *silla*.

One of the key projects of the Finnish government is to further bioeconomy to get “wood on the move and new products from forests”. In addition, one of the ten-year objectives of the government is that Finland would be pioneer in bioeconomy, circular economy and cleantech. (Prime Minister’s Office 2015, 24.) Replacing oil-based material with bio-based materials, such as cellulose materials, fits well with the idea of bioeconomy. Cellulose materials are common and renewable. (Kangas 2014, 7.)

2 CELLULOSE

Cellulose is the most abundant material in the world, and is considered as an almost inexhaustible source of raw material (Klemm et al. 2005, 3359, O'Sullivan 1997, 173). It is the main constituent of plants, also found in bacteria, fungi, algae and some marine animals. Cellulose helps plants to maintain their structure (O'Sullivan 1997, 173). Wood pulp is the most important raw material source for cellulose processing (Klemm et al. 2005, 3359). Among cellulose, the cell wall in plants consists of hemicellulose, lignin and pectin (Gibson 2012, 2749).

In this thesis, the main component of all used materials is wood-based cellulose. Also, other cellulosic materials are used. *Wood-based material* refers to a material, that can contain also other wood substances than cellulose, such as lignin. Both cellulosic and wood-based materials are used.

2.1 Ecological Cellulose Textiles

Material choices have a significant role in creating sustainable fashion. Materials have a direct impact on climate change, water pollution, biodiversity loss, use of unrenewable materials and waste. Production of all materials have ecological and social impacts but they vary depending on the fibre. (Fletcher & Grose 2012, 13.)

Man-made cellulose fibres have had an important role in the textile production for over 70 years. In the 1930s man-made cellulose fibres became one of the main fibres used in textiles and the production kept on growing. In the 1960s the production of synthetic oil-based fibres (polyethylene terephthalate, PET) expanded. Since then PET fibres, along with cotton, have been the main fibres used in textiles. These both are harmful to the environment. (Shen, Worrel & Patel 2010, 260–261.)

Viscose is a semi-synthetic cellulosic fibre that is formed from natural polymers. Commonly viscose is made from fast growing woods such as beech and more recently bamboo. The raw material for cellulosic fibres can be carbon neutral but the rest of the viscose process has serious environmental implications. The chemical processes behind viscose production generate emissions to air and water, which can create major environmental problems if discharged untreated. In addition, viscose manufacturing is also harmful to the workers. (Fletcher 2008, 14.)

Lyocell, a semi-synthetic cellulosic fibre developed in the 1980s, is considered as an environmentally better option for viscose. The fibre is not bleached and the use of chemicals, water and energy in dyeing is reduced. (Fletcher 2008, 32.)

Piñatex™, textile made of pineapple leaves and PLA fibres, is one example of ecological nonwoven cellulose material. Piñatex fibres are the by-product of the pineapple harvest. (Ananas Anam n.d.) The sustainable footwear company Po-Zu is one of the first companies who started using Piñatex in their products (see Figure 3).

Figure 3. Po-Zu's pineapple leaf shoes (Po-Zu n.d.).

There are several attempts in Finland to develop environment-friendly cellulose textiles. Spinnova, one of the spin-offs of DWoC, for example, is making wood-based yarn directly from wood fibres without using any extra chemical treatment (Spinnova n.d.). IONCELL-F is another innovative wood-based textile technology producing semi-synthetic cellulosic fibres, that can utilize e.g. recycled paper as raw material. Developed at Aalto University in collaboration with the University of Helsinki, this material requires no harmful chemicals in its production. (Aalto University n.d., see also Ma, Hummel, Määttänen, Särkilahti, Harlin & Sixta 2016.)

The upper material used in this thesis is also wood-based cellulose material, that requires no harmful chemicals. Instead of weaving the yarn into fabric, this textile is made by a process called foam forming. In this process fibres are mixed with aqueous foam first and then compressed with applied vacuum into nonwoven sheets. This technology is simple and requires only a small number of machines.

3 METHODS

The goal of this thesis is to create an all-cellulose shoe from novel wood-based materials. The upper material research is done together with the designer (author) and material researchers based on the designer's perceptions of the tested material.

This research is both design and material driven dialogue between the designer and researchers in DWoC and at VTT. It is an interdisciplinary discussion with chemists, material researchers and designers. The shoe design process is material driven, where the designer designs the shoe taking the characteristics of the material into account. The material development on the other hand is design driven, where before the material is made, the material researchers take into account the designer's ideas about the material. Both approaches go throughout the project.

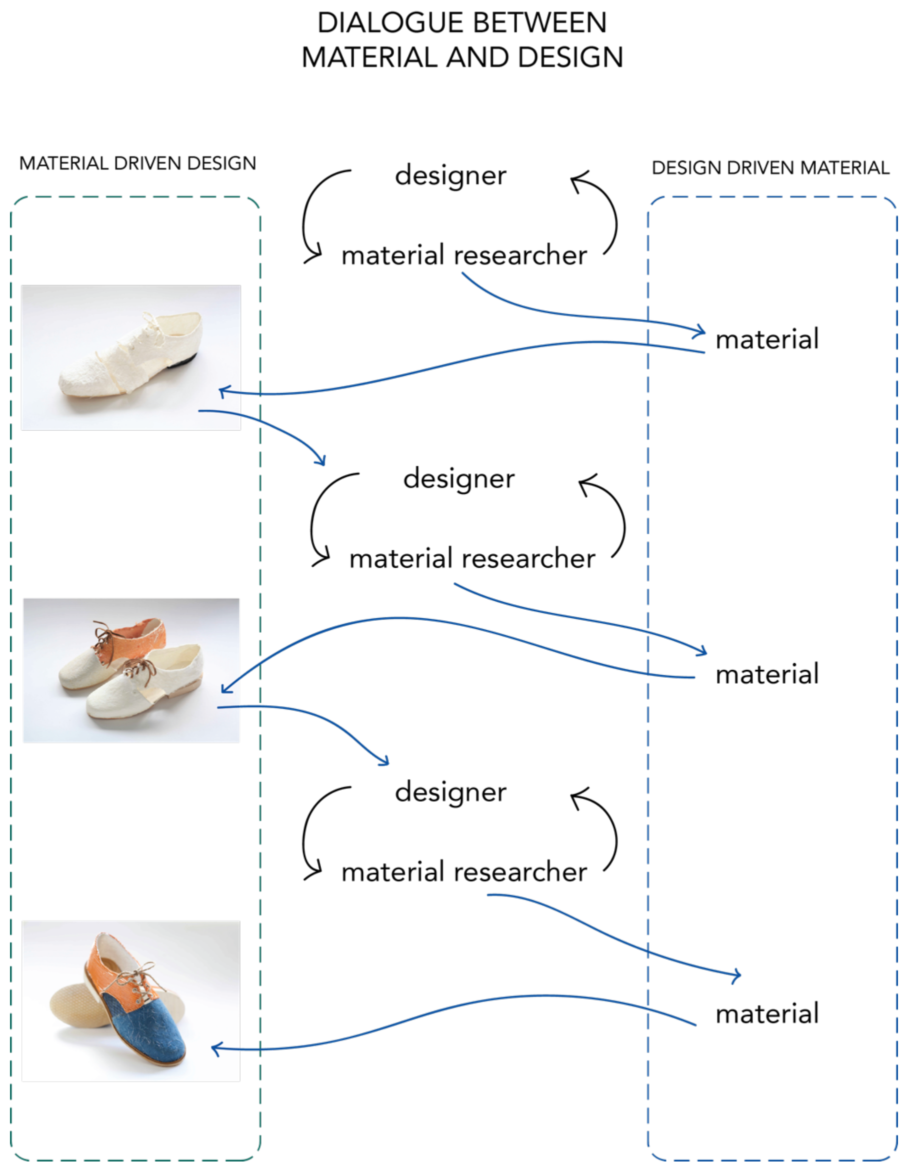

Figure 4. Dialogue between the material research and footwear design.

3.1 The importance of design in material research

The etymology of design comes from the Latin words *de* and *signare*, which means making something and distinguishing it with a sign and making it significant. As Krippendorff puts it, “design is making sense (of things)”. (Krippendorff 1989, 9.) Also in this thesis, it is the designer’s task to give meaning to the cellulose materials, to create a story around them.

Material research often focuses on the question *what is the material like*, whereas design is more interested in finding out *what the material does* or *what it expresses to us*. With the help of design, material can bend into applications. (Karana, Barati, Rognoli & van der Laan 2015, 35.)

Material research wants to offer novel, better alternatives, such as bio-based and smart materials. In addition to superior functionalities, the material should be meaningful in order to be commercially successful. Developed material should be meaningful and be ready to use in applications. (Karana, Barati, Rognoli & van der Laan 2015, 36.)

In material driven design, the designer should have a clear understanding of the characteristics of the materials; its limitations and possibilities. The designer should understand the material’s technical properties and as well how it can be shaped and turn into a product. It is also important to evaluate how the material is received by people before turning the material into application. In order to create a functional product accepted by end-users, it is important to know how people see the material, how does the material make people feel, what kind of emotions it awakens. (Karana, Barati, Rognoli & van der Laan 2015, 41–42.) The shoe demos made in this thesis are made by using a material driven approach, where the designer first evaluated and got to know the materials and only then started making the demos. The designer also got feedback from the material researchers after making each demo shoe.

On the other hand, the material development and research was design driven, when it comes to the development of the upper material. Here the designer tested each material by making a demo shoe and empirically observed how each tested material worked. Afterwards, the designer exchanged views with the material researches and the next material version was developed accordingly. Already in the beginning, the designer’s opinions were taken into account and the materials proposed were based on the designer’s views. The material researchers had an important role in suggesting different materials for the demo shoes. In addition, they were responsible for developing and making the materials, whereas the designer had limited knowledge of chemistry.

There are many advantages of involving a designer in scientific research. For example, designers can quickly make prototypes to test ideas, they can challenge scientists' views of their research, visualise scenarios of use and apply scientists' underlying theories. (see Driver, Peralta and Moultrie 2011, 19.)

3.2 Footwear standards

In order to compare the final developed material to commercial footwear materials, two different standard tests for shoe uppers will be carried out. The results of the standard tests will give more specific information about the material.

Standards are voluntary technical specifications that define requirements for products, production processes, services or test-methods. They are developed by industry and market actors based on some basic principles such as consensus, openness and transparency. The purpose of standards is to ensure interoperability and safety, reduce costs and facilitate the work of companies. (European Commission n.d.)

In this thesis two standard tests are carried out. The tested qualities measured from the developed upper material are tensile strength and elongation (EN 13522:2001) and abrasion resistance (EN 13520:2001). There are also other important tests that can be made for footwear uppers, such as tear and seam strength and water resistance tests. In this research, the material development only just started. It would take longer to develop the material for example to the level of leather in terms of strength. That is why it was decided to carry out two basic tests on the material. The footwear upper should be elastic and strong, hence tensile strength and elongation tests were carried out. Abrasion resistance is also important for footwear materials because the material should be able to endure under pressure. The test results are compared to the standard that defines requirements for footwear (CEN ISO/TR 20879:2007).

4 ALL-CELLULOSE SHOE

In total four different shoe demos were made. This chapter presents the design process behind the final shoe demo.

It was the employers wish that the shoe would be simple and be inspired by Finnish nature. As the materials come mainly from Finnish forests, it was natural to seek inspiration from there as well. The main focus on the shoes is on the materials. The model of the shoe is women's low heel summer footwear. The shoe construction type was chosen based on the designer's previous footwear making experience. Cemented shoe is a shoe construction type where the upper is lasted and attached to the lasting insole by gluing, then the sole is attached with adhesive (see Figure 5).

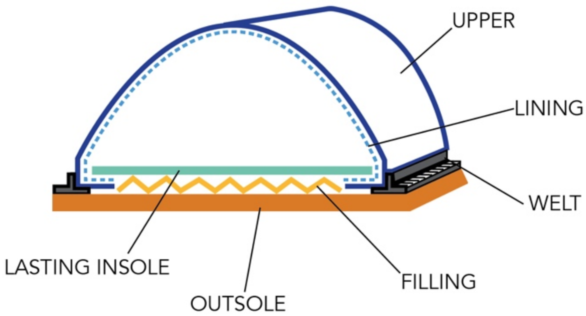

Figure 5. Cemented shoe construction.

The design process started by making a moodboard, where the designer collected inspiring pictures (see Figure 6). The main inspiration sources were Finnish nature: trees, pine and birch, as well as lakes and rocks. The visual focus was especially on different surfaces, such as tree bark.

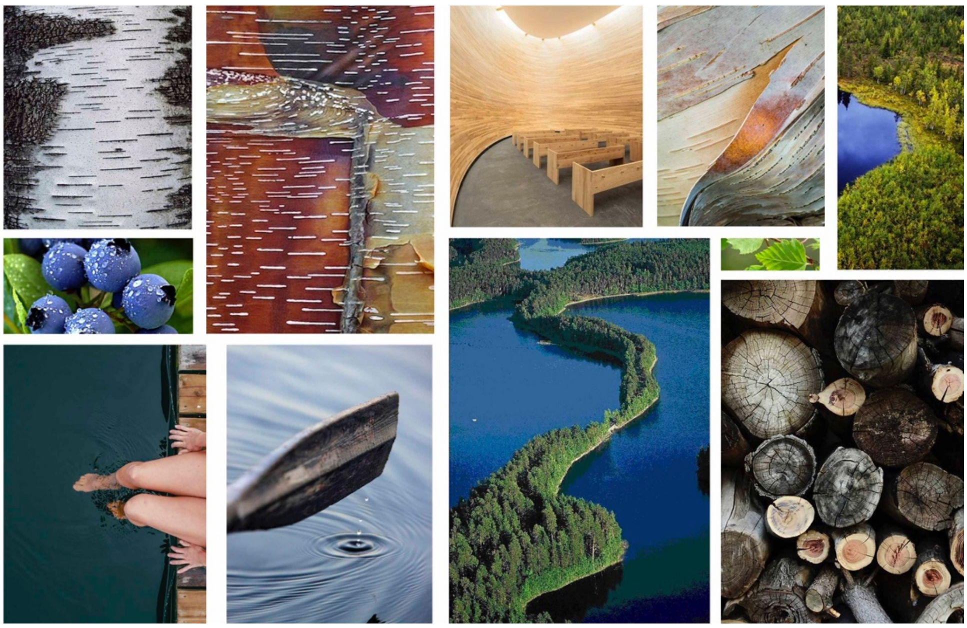

Figure 6. Moodboard. Inspiration from Finnish nature (Pinterest).

After making the moodboard, the designer made several sketches. In Figure 7, are the first three sketches. Inspiration sources, lakes, rocks and trees, are clearly visible. It was planned that several different materials would be used in the shoe. Hence a decision was made, to cut down colours to a minimum, so that the shoe would not be too mixed with colours and materials. After making the first sketches, more inspiration was sought.

Figure 7. First sketches.

Figure 8. Inspiration was sought from tree bark surfaces.

Figure 9. Clouds, lakes, reflections and surfaces.

Two main colours were selected for the final shoe, deep blue and orange. The orange colour resembles a pine tree in the summer, when the bark on the surface of the tree renews. In addition, the pattern on the quarter (back part of the shoe upper) was chosen on this basis. The vamp is deep blue, like a lake that has reflections of clouds on it.

The next sketches were simpler (see Figure 10). Chosen colours, blue and orange, were tested. At this point, the materials did not yet exist. Thus, the final model was not finalised until the materials were ready.

Figure 10. Sketches.

The final model (see Figure 11) was a simple derby shoe with lacing, that consisted of a vamp (the front part) and two quarters (the back part, two pieces sewed together). Inspiration sources, lakes and tree bark, are visible. The simplicity of the model gives space to the materials.

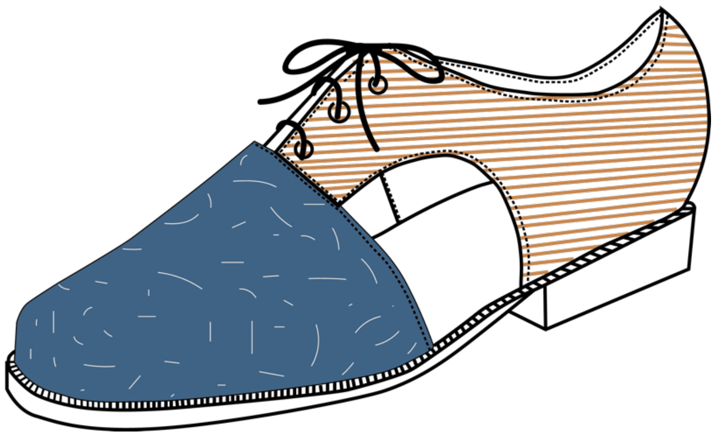

Figure 11. Technical drawing of the final model.

The design was material driven and material's qualities were taken into account. When the shoe is taken off from the shoe last, the shoe is fully bend and if the material is too weak, it can break at this point. This model was designed to be taken easily off from the shoe last, it has lacing and the quarter part is not attached to the vamp. The shape of the shoe last is rather round, this makes the lasting of the upper simpler. If the last has pointy toe part, it takes more time to get the wrinkles off, this also puts more strain on the material.

The materials are presented in the next chapter.

5 MATERIAL TRIALS AND DEVELOPMENT

The main goal of the thesis is to make an all-cellulose shoe from novel wood-based materials developed in the DWoC project and at VTT. In this chapter, each tested material is presented. The chapter is divided into five parts: 1) Adhesives and stiffeners, 2) Upper, 3) Outsole, 4) Heel and 5) Insole. In each part, the tested materials are briefly introduced.

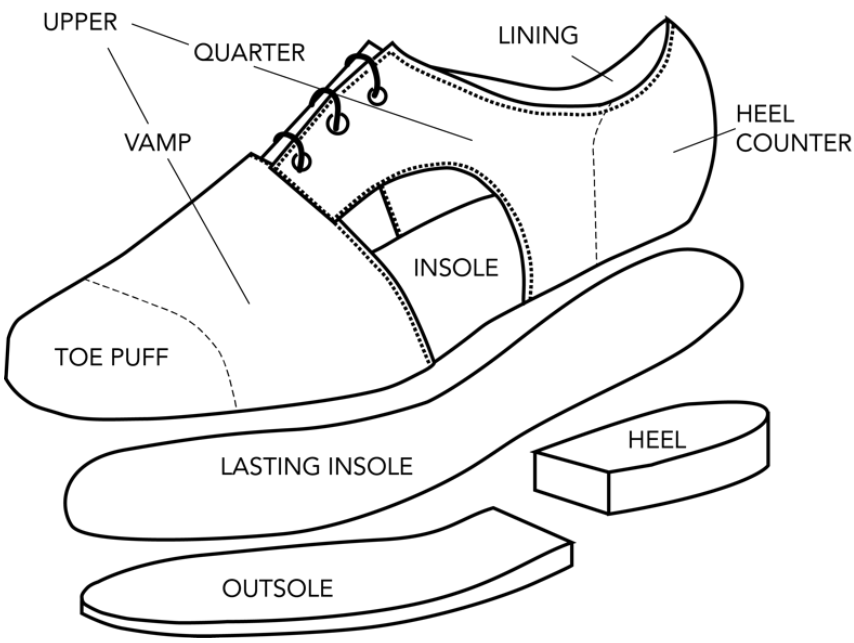

Figure 12. Shoe parts.

5.1 Adhesives and stiffeners

Traditionally the toe puff and heel counter of a shoe are made from leather or plastics (Saaristo 1989, 213 & Vass & Molnár 2013, 126). In this research, microfibrillated cellulose paste (MFC[3]) was used to reinforce the structure of the shoe. A small amount of MFC was applied between the lining and the upper, in the toe puff and the counter areas. MFC was also used as a glue in all demos.

The first demo was made from cardboard and MFC (see Figure 13). The MFC worked as an adhesive and stiffener in the shoe toe puff and heel

[3] Microfibrillated cellulose is a material derived from wood fibres by delaminating the fibres. Normally this is done by using high pressure homogenisers. (Kangas 2014.) In this work, the used MFC was produced by an enzymatic fibrillation process developed by VTT.

counter. At first, the cardboard was fully doused in water, then shaped over the last. MFC was applied on the top of the cardboard. Another layer of cardboard was then applied. Finally, the shoe was heated and dried. The material was too stiff to be used in the shoe as such but the MFC worked well as a stiffener in the toe puff and heel counter and was used in all the shoe demos.

Figure 13. Shoe demo 1 was made from cardboard and cellulose paste called MFC, which worked as an adhesive and stiffener.

5.2 Upper

The main focus was to find a suitable material for the footwear upper. The upper material should be strong, elastic, water- and heat-resistant and breathable (Saaristo 1989, 123 & Choklat 2012, 44). Material development started with a thin, easily breakable nonwoven foam formed[4] material, which was made from viscose, birch fibres and paper yarn. The material was not suitable for use as a footwear upper mostly due to lack of strength and elasticity. The upper material was developed in various ways. It was clear already at this point that the developed material would unlikely achieve all the qualities that a footwear upper should have. Therefore, a decision was made to concentrate on developing the strength and elasticity.

[4] Foam forming is a technology where fibre networks (similar to paper structures) are formed using foam as the carrier phase instead of water. In particular, the suitability of the foam forming technology to a broad range of fibre types, from cellulose nanofibres to long synthetic fibres, opens up a new avenue in material development. (Al-Qararah et al. 2015.) In this project, foam forming is used when making nonwoven textile. The fibres are first mixed with aqueous foam and then compressed with applied vacuum into nonwoven sheets.

Figure 14. Foam forming process.

Nonwoven foam formed fabrics were the most obvious choice for shoe uppers due to the fabric-like softness and visual looks. Already in the beginning of the process, it resembled cotton or some other fabric. However, the material was too weak and could be easily torn like paper.

Figure 15. Thin foam formed material.

The first further developed material used in the shoe demo was nonwoven foam formed material which consisted of birch fibres, viscose, paper yarn filaments and a small amount of latex. The use of latex was thought to increase elasticity. In addition, the thickness was increased. This material was used in demo 2 (see Figure 28). The material didn't break while sewing and it was also easy to mould on the shoe last. However, when taking the shoe off the last, the material was too weak and the shoe didn't maintain its shape well.

In the demo shoe 3 (see Figure 29) the uppers were made using the same ingredients as in the demo 2 but the cellulose textile was much thicker. The material for the vamp and the quarter were significantly thicker than in the second demo. When lasting the thicker material, it was hard to remove the wrinkles that formed in the toe area. In addition, the paper yarns in the quarter material came off easily. Otherwise the material worked well.

For the final demo (see Figure 30) the thickness was lowered a bit. Paper yarn was replaced with 4 cm long pulp filament yarn[5]. In former tests, the use of pulp filaments turned out to increase the strength of the material. Birch fibres were replaced with pine due to pine's longer fibres which aimed also to increase elasticity. The quarter area consisted of two materials, the upper and the lining. Use of lining made the structure stronger and visually cleaner.

Figure 16. Nonwoven thick material for the vamp.

5.2.1 3D printing the nonwoven textile with cellulose acetate

In order to make the material even stronger and to prevent the material from breaking when removing the shoe from the last, a special type of cellulose derivative[6], synthetized at VTT, was applied on the surface of the nonwoven material. The derivative was coloured with textile pigment and applied on the surface with a 3D printer[7]. During the shoe making process, it became clear that the printed layer strengthened the structure. When removing from the last, the printed side remained intact, and the non-layered side tore apart.

[5] Pulp filament, or more commonly DES (Deep Eutectic Solvent), refers to a pulp yarn process developed in DWoC project. The yarn production process utilises deep eutectic solvents. (Tenhunen et al. 2016.)
[6] Chemically modified form of cellulose (see, e.g. Alén 2011). Many derivatives made by adding side chains to cellulose are used as bulking and thickening agents in food and beverages, pharmaceuticals, and personal care products (Grand View Research n.d.)
[7] 3D printer prototype designed to print different pastes, Pyry Kärki and Ville Klar, Aalto university.

In the shoe demos 3 and 4, the wanted image was printed on the surface of the cellulose textile. The image was the pattern of the quarter in its original size. It was filled with an orange stripe pattern, resembling the surface of a pine tree. Printing the derivative straight to the original size, optimized the use of material and time (see Figure 17).

Cellulose derivative printing gave the material a leather-like texture. After printing, it took approximately two weeks for the material to dry in room temperature, as the acetate vaporized.

Figure 17. 3D printing cellulose derivative on the nonwoven textile. The printed shape is the pattern of the upper quarter part.

The material shaped well on the shoe last, in addition, it was easy to sew and work with. When removing shoe demo 3 from the last, the side with cellulose derivative stayed intact, whereas the other side and the other shoe fractured slightly. In the final demo, all quarters were layered with 3D printing, which supported the structure.

5.2.2 Reactive dyes

For the final demo, the vamp of the upper was dyed. This was made by dyeing pine fibres and viscose fibres separately before the foam forming process. A traditional reactive dyeing method was used, where the material is boiled in water with salt and sodium and reactive dyes. The colour was deep blue, like a Finnish lake. Also, the insole material was dyed in the same way.

Figure 18. Fibres and insole material were dyed with reactive dyes.

5.3 **Outsole**

Outsoles for the shoes were made from thermo-mouldable cellulose palmitate (MMCC[8]), a material developed at VTT. It was suitable material for shoe sole, due to its flexibility and strength. Five layers of the material were laminated together with heat. The outside of the sole was textured with a metal grid. The material is not porous, which made it hard to glue. Different solvent-free adhesives were tested. In order to make the surface more porous, it was treated with sandpaper. Afterwards the adhesive was applied and the sole attached to the shoe. The used adhesive was a commercial solvent-free adhesive.

[8] Molar mass controlled cellulose ester, also referred as cellulose palmitate (Willberg-Keyriläinen et al. 2016).

Figure 19. The outsole was made from a thermo-mouldable cellulose derivative.

5.4 **Heel**

Heels for the shoe were made of veneer, which had been glued together with CatLignin (see Wikberg, Leppävuori, Ohra-aho & Liitiä, 2017), a highly reactive lignin[9], developed at VTT. Heels were sawed and sanded with a grinder to the shape of the heel. After the shoes were taken off the last, the heels were attached with screws (see Figure 20).

Figure 20. Veneer and CatLignin worked as heel.

5.5 **Insole**

The insole was made from a nonwoven wood-based textile[10] (Suominen Nonwovens Ltd.) The material was dyed with reactive colours. Five layers of this thermo-mouldable material were laminated together with heat and shaped with a metal grid using the method developed earlier in the project by Aalto ARTS designers (see Härkäsalmi, Solala, Itälä & Tanttu 2015, 40). This treatment gave the material nice visual looks. Before shaping the material with a metal grid, a small amount of cellulose-based adhesive[11] was applied to the surface. This made the pattern on the surface more visual and helped the pattern stay intact longer. This material was used in

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[9] Lignin is one of main components in wood. Lignin fills the spaces in the cell wall between cellulose, hemicellulose and pectin component. (Lebo, Gargulak & McNally 2001.)
[10] composed of 35% biopolymer PLA (polylactid acid) and 65% wood-based viscose, fabric weight 40-55 g.
[11] Experimental cellulose mono acetate, 2017, Andreas Lindberg, Aalto university.

the insole of the shoe. It was glued on its place with the same cellulose-based glue as used in shaping.

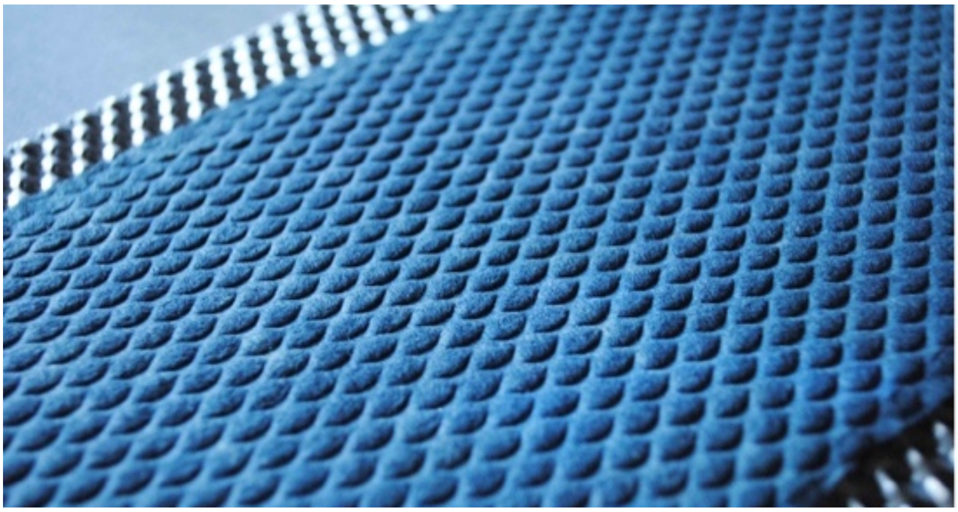

Figure 21. The insole material was dyed with reactive colours and moulded with heat.

Figure 22. The logo was laser cut on a thin veneer sheet. The blue material is the nonwoven textile developed for the shoe upper.

5.6 **Shoe-making process**

After finishing the materials, shoe-making started. Figure 23 presents some of the final materials for the shoe demo. The shoe making starts by making the uppers. The uppers were cut and sewed (Figure 24 and 26). The next step is to last the uppers on the shoe lasts. Before this, the uppers are normally doused in water, this helps the material to mould on the last. Final step is to attach the welt, the sole and the heel (Figure 27).

Figure 23. Materials for the final demo.

Figure 24. Uppers for the final demo.

Figure 25. Shoe-making. Most of the adhesives were cellulose-based.

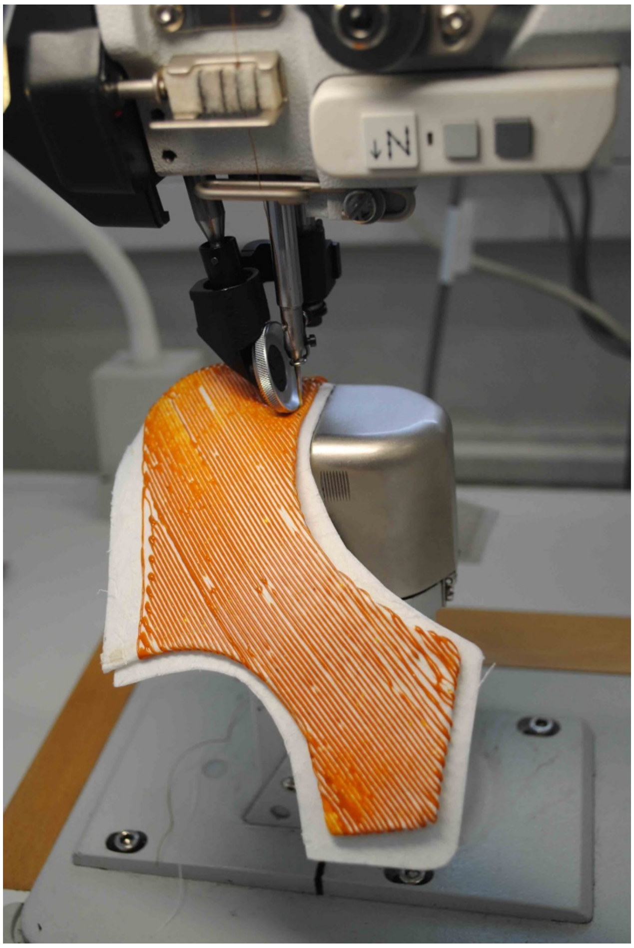

Figure 26. Sewing. Material did not break while sewing.

Figure 27. Wood-based materials were doused in water, heated and pressed with heavy machines.

6 RESULTS

In order to see how the novel wood-based upper materials would work in footwear three shoe demos were made. The first demo, made from foam formed material, was too weak and did not hold its form well (see Figure 28).

Figure 28. Demo 2 was made from thin foam formed material.

Figure 29. In the demos 3 A and B, the upper material was significantly thicker than in the demo 2.

The demos 3 A and B were already more advanced, mostly due to thicker material and a 3D printed cellulose derivative (see Figure 29). The thickness of the material resulted in wrinkles in the toe area, hence for the final demo (see Figure 30) the thickness of the material was lowered a bit.

To increase the strength and elongation, birch fibres were replaced with pine, due to its longer fibres. Also, cellulose derivative was 3D printed on the surface of the material. The materials used in the final demo worked well and they lasted during the shoe-making process where the uppers were fully doused in water, sewed, glued and lasted on shoe last.

Figure 30. The final shoe.

Figure 31. Side profile of the shoes.

Figure 32. Outsole and heel.

6.1 Standard tests for footwear uppers

Two standard tests for shoe uppers were carried out in order to find out whether the material could be used in commercial footwear[12]. It was clear already before the tests that the materials would not be strong enough but still the results would give some perspective of the strength of the material. With abrasion[13] and breaking strength[14] tests, it is possible to find out whether the upper material would be strong enough in use.

BREAKING STRENGTH AND ELONGATION	STRENGTH (N/mm)	ELONGATION (%)
3D PRINTED UPPER MATERIAL (160g/m²)	1.5	6.4
BLUE UPPER MATERIAL (320g/m²)		
ALONG	1.6	5.5
ACROSS	1.7	6.5
WHITE LINING MATERIAL (160g/m²)		
ALONG	1.5	5.2
ACROSS	1.4	5.7

Table 1. Breaking strength and elongation test results.

[12] Tensile strength and elongation tests were carried out at VTT, the abrasion resistance test at Tampere University of Technology.
[13] EN 13522:2001. Footwear. Test methods for uppers. Tensile strength and elongation.
[14] EN 13520:2001. Footwear. Test methods for uppers, lining and insocks. Abrasion resistance.

Based on these two tests, the materials are yet too weak for footwear. According to an international standard for performance requirements for footwear uppers[15], the breaking strength should be at least 8 N/mm, the elongation 15% (across) and 7% (along). The results show that the breaking strength in all measured materials is rather low. Depending on the material it is between 1.4 N/mm and 1.7 N/mm.

The elongation in all materials is also too low but significantly on better level than the breaking strength, when compared to standard requirements. With these materials, the elongation percent is between 5.2 and 6.5. The across elongation is weak but the along elongation is close to the 7 % minimum performance requirement. The 3D printed material seems to be slightly better with elongation when compared to the same material without the cellulose derivative 3D printing.

DRY ABRASION	degree of abrasion		
number of revolutions	3D PRINTED UPPER MATERIAL (160g/m²)	BLUE UPPER MATERIAL (320g/m²)	WHITE LINING MATERIAL (160g/m²)
1600	severe	moderate	moderate
3200	almost complete	severe	almost complete
6400	complete	complete	complete
12 600	–	–	–
WET ABRASION			
1600	complete	complete	complete
3200	–	–	–

Table 2. Abrasion test results.

The abrasion resistance on the other hand should be at least 12 800 (dry) and 6 400 (wet), while the abrasion degree should not be no worse than moderate with the mentioned revolutions. With the tested materials, the results in dry and wet abrasion resistance are rather poor. All materials were completely broken after 6 400 revolutions in dry abrasion. In the wet abrasion, the result was the same already after 1 600 revolutions. There was no difference with the 3D printed material.

6.2 Summary of the materials

The upper materials were visually versatile and easily mouldable on the shoe last. They were light and soft. The 3D printed cellulose derivative gave the shoe a leather-like texture. Overall, the uppers are still too weak for commercial footwear, though elasticity is rather good. The outsole

[15] Performance requirements for upper components for women's town footwear. In CEN ISO/TR 20879:2007. Footwear. Performance requirements for components for footwear. Uppers (ISO/DTR 20879:2006), p. 14.

material, cellulose palmitate, was flexible and strong and was suitable for shoe outsole. The material is thermo-mouldable and was moulded with metal grid. Patterning on the shoe sole increases traction in use. The heel, made from veneer and reactive lignin (CatLignin), was strong and suitable for shoe heel. The insole material, a nonwoven wood-based textile (Suominen Nonwovens Ltd.) was dyed and moulded with heat and metal grid. It was soft and the patterning gave the material interesting look. Microfibrillated cellulose paste worked as a stiffener in the heel counter and the toe puff. This helps the shoes to maintain their structure. Water resistance of the materials were not tested. Figure 33. summarises all used cellulose and wood-based materials in the final shoe.

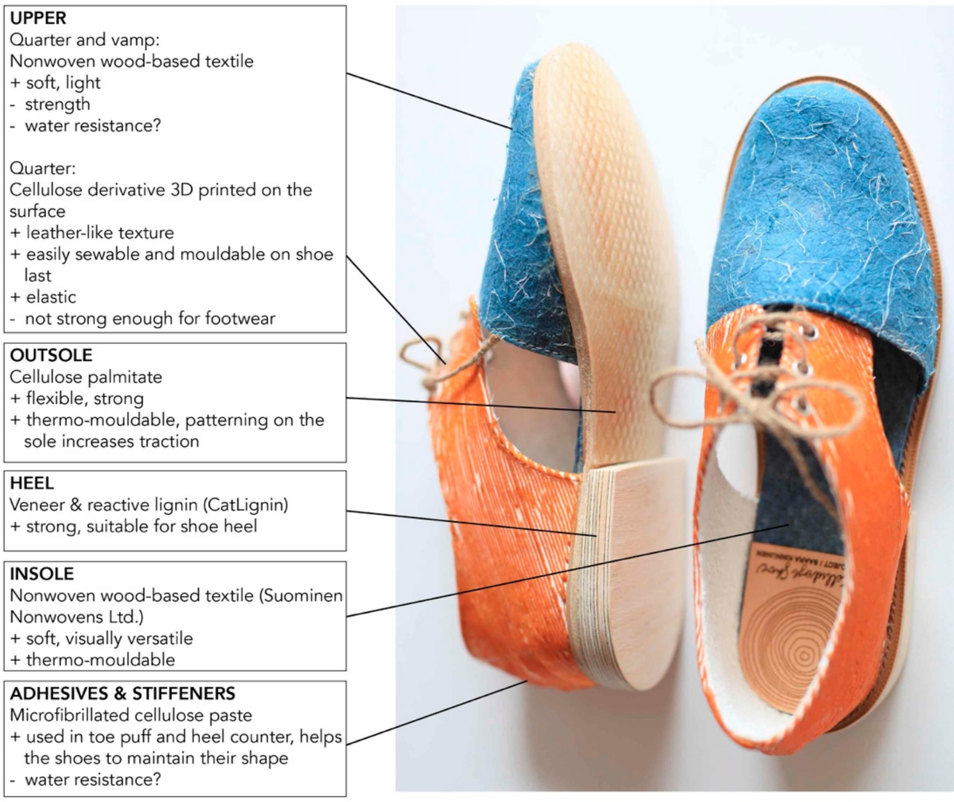

Figure 33. Summary of the used materials.

7 CONCLUSIONS

The aim of the thesis was to make an all-cellulose shoe from wood-based materials. During the project, a foam formed material made from pine fibres, viscose, pulp filament yarns and latex was developed. With different methods, it was possible to change the visual looks of the material. The cellulose derivative gave the material leather-like texture, whereas dyeing pine fibres and viscose changed the colour into deep blue, leaving the pulp filaments white.

Wood-based materials have several advantages. Wood is renewable and depending on the use of forests, also ecological. The use of wood-based materials could replace the use of oil-based materials and cotton. They are light and visually versatile. The materials used in this thesis alone varied a lot in terms of their visual appearance, some resembled leather and some cotton.

Figure 34. All shoe demos.

The project resulted in an all-cellulose shoe, which is an example of the endless possibilities of cellulose materials. The final demo is not yet suitable for footwear use. As the standard test results revealed, the upper material needs to be further developed. It should be even stronger, elastic and water-resistant. The commercial manufacturing of this type of material is yet not possible, the production process needs more research. As such, the material could be used in disposable footwear e.g. in slippers used in hospitals, hotels or airplanes. The material could be used also in other applications for example in different kinds of packaging or in disposable textiles. The durability of the material should be increased if used in other textile applications, such as in clothing or furniture. Further research and development would be needed to see if this material could be a footwear material in the future.

Other materials used in the project were also suitable for the shoe demos. Especially the outsole material, cellulose palmitate, worked well. It was easy to mould, in addition it was rather strong and flexible.

To sum up, the progress of the developed upper material was significant. In a short period of time, weak, non-elastic and thin material turned into durable material suitable for many possibilities. The goal was not to develop a material, which would be ready for commercial footwear rather than to demonstrate all the options that cellulose and wood-based materials can offer.

As the thesis shows, wood-based materials can bend into many shapes. In addition to being the traditional raw material for timber, paper and cardboard, Finnish wood could in the near future be a super material and provide endless possibilities for various industries.

Figure 35. All-cellulose shoes demonstrate endless possibilities of cellulose.

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Figure 6. Pictures collected from *Pinterest*.