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LASER CUTTING TECHNOLOGY IN THE PRODUCT DEVELOPMENT PROCESS OF A SPORTS JACKET

LASERLÕIKUSTEHNOLÓGIA KASUTAMINE SPORDIJAKI TOOTEARENÐUSPROTSESSIS

MASTER THESIS

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2. Research key factors for development of sportswear.
3. Explore how laser cutting technology can change the properties and quality of textile materials.
4. Develop a sports jacket, including examples of laser cutting technology applications.

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List of abbreviations and symbols

EA - elastane

PA - polyamide

PES - polyester

PU - polyurethane

TPU – thermoplastic polyurethane

INTRODUCTION

The laser cutting technology has been available from the 1960s. Thanks to technological advancements laser cutting technology has become more accessible to manufacturers, small-businesses and schools or even hobbyists with a 3D printer, which is convertible into a laser cutter. In the garment and textile industry first examples of this technology were seen in high-end couture products, where laser cutters were used for making intricate details, resulting in highly aesthetic garments and accessories. At the moment, examples of applications can be seen in everyday garments from companies such as Nike, Forever21, Lululemon Athletica and Victoria's Secret. In technical textiles laser cutters are used not only for producing aesthetic designs, but also to add function to the products. Although, there exist many examples of applications, there have been few studies published about this.

Laser cutting technology results are largely dependent on the properties of cut materials, including composition, weight and structure. There is a large variety of textile materials available. So, when cut with a laser beam they can give very different results. This is mainly visible in the quality of the cut edge but can also be seen in any defects around the edge due to the chemical reaction between the material and laser. Unfortunately, cutting parameters for textiles are not so widely available and researched as, for example, parameters for cutting wood, plastics and metals.

Taking all the previous into consideration, the aim of the thesis is to study how laser cutting technology can change the properties and quality of textile materials and be implemented in product development. The topic is studied in the example of sportswear – a product group that has high functional requirements – to examine how the garment functions could be enhanced. Also, the opportunities of laser cutting technology in one athletic garment are studied to see whether it can be used for several applications.

The first chapter of the thesis gives an overview of laser cutting technology regarding history, working principle, comparison to contemporary cutting tools and its uses in the textile and garment industry. The second chapter gives an overview of sportswear and focuses on the key principles that are important in product development. The third chapter joins the two topics together and explores laser cutting technology opportunities among sportswear, including presenting examples of products on the market.

Based on the literature overview the practical part studies laser cutting technology in the product development process of a sports jacket. The first part includes testing different

textiles with a laser cutter to suggest suitable cutting parameters and determining unsuitable sportswear textiles for laser cutting. The suggested parameters and samples can be used as reference for future projects in the Laboratory of Polymers and Textile Technology. The second part involves testing textile properties that are altered during the cutting process of woven fabrics, including permeability and abrasion resistance to surface fuzzing and pilling. The third part consists of developing a sports jacket and sewing two prototypes. The technology is finally analysed and compared to conventional tools and methods.

The practical part is conducted in the Laboratory of Polymers and Textile Technology. For developing patterns Lectra Modaris V8 is used and for technical drawings Lectra Kaledo Style V4 software is used. The laser cutter files are made in Adobe Illustrator CC19 and files for cutting are prepared in RDWorks V8.

1. LASER CUTTING TECHNOLOGY

Laser cutting technology dates to 1965 when Peter Holdcroft experimented with a focused CO₂ laser beam to cut 1 mm steel sheet, which marked the start of the technology as we know today [1]. Nowadays this technology is being used for cutting of various materials, e.g. wood, paper, cork, some kind of plastics and textiles. Etching can be performed on almost anything, including wood, aluminium, stainless steel, cardboard and paper, plastic, marble, stone, tile and glass [2].

1.1 Technology

Laser cutting is a technology that uses high-powered beam to cut material based on computer-controlled parameters. When the laser comes in contact with the material it is either vaporized, burned or melted, depending on the properties of the material. A pressurized gas jet is used to eject the molten or vaporized material, leaving a clear path – a kerf [3]. Consequently, one of the benefits of laser cutting is that it provides a high-quality surface finish without any edge finishing work [4].

Therefore, the laser cutting technology is predominantly a thermal process, a derivative from traditional thermal-cutting processes, such as plasma and flame cutting. Compared to traditional thermal-cutting processes, laser cutting concentrates high-density energy on a very small focus point within the material – less than 0.5 mm in diameter – which raises the temperature of the material above its melting point. [5]

A secondary process that is used to cut material without any heat is the short-wavelength ultraviolet (UV) laser-beam ablation technique, which uses photon-induced chemical bond destruction, i.e. chipping, drilling, cutting or other erosive processes. When compared with thermal laser cutting, the latter is considered to be more effective in an industrial setting, concerning cycle time, productivity and profitability. [5]

1.1.1 Laser

Lasers are used for cutting, drilling, welding, marking and surface treatment. Laser as a word stands for Light Amplification by Stimulated Emission of Radiation. Laser is

considered to be the unit that produces the optical frequency radiation in intense, controllable quantities of energy in a specific area. [6]

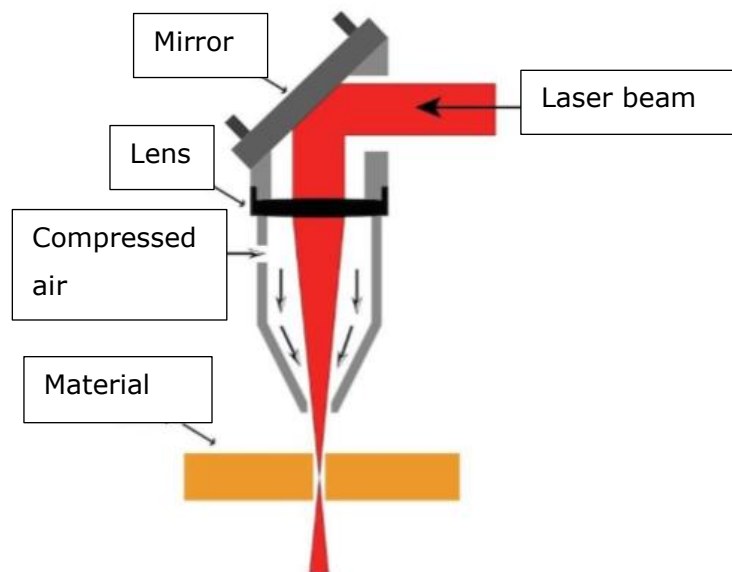


Figure 1.1 Laser head components [7]

The basic components of a laser include an amplifying medium, a means to excite this medium (i.e. energy source), mirrors arranged to form an optical resonator and an output transmission device to cause beam energy to exit from the laser (figure 1.2). The output wavelength is controlled by the type of amplifying medium used. The most efficient industrial lasers use optical excitation or electrical discharge to stimulate the medium and start the lasing action [6]. Enough energy must be transferred into the medium for the particles in the material to get to the excited state. This happens when a particle absorbs energy which allows it to jump to a higher energy level. When the energized electron jumps back to its normal state the same amount of energy absorbed will be radiated in the form of non-coherent radiation. Part of the radiation escapes through the mirror as a focused laser beam [8].

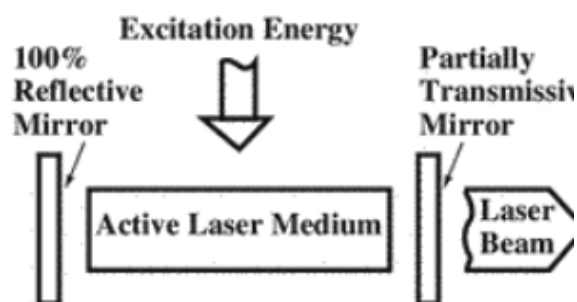


Figure 1.2 Basic components of a laser [6]

To make the beam, the gas is excited with a high voltage current. When excited the laser tube it will pass 2 mirrors, both set up in a 45° angle, the third mirror will guide the beam into the cutting head (figure 1.3). The beam is focused with the help of a lens situated in the cutting head. The beam is then emitted onto the material. The focal length is the distance between the lens and the material surface. [7]

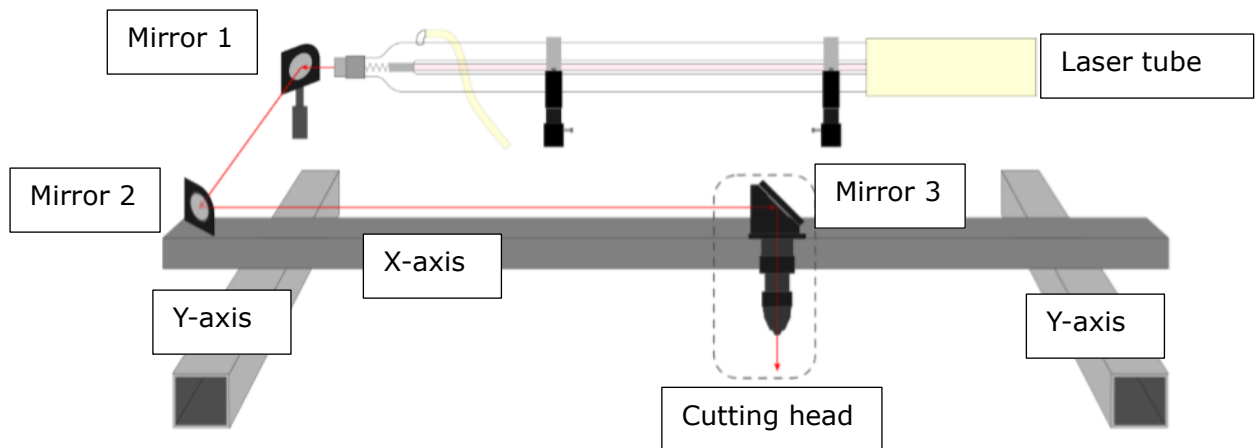


Figure 1.3 Laser beam trajectory [7]

There are different types of lasers based on the medium used: solid state lasers, liquid, gas, plasma and semiconductor lasers (diode lasers) [8]. The most common industrious ones are CO₂ gas laser and YAG (Yttrium-Aluminium Garnet) lasers, i.e. optical fibre lasers [5]. The choice of the laser depends on the specific application. Solid state lasers are commonly used for drilling, cutting, spot and seam welding, marking on thin sheets of metal. CO₂ lasers are used for welding, cutting, surface treatment and marking for both metals and non-metals. The differences between lasers are properties such as wavelength, operating mode, power range and application [6].

1.1.2 Basic overview of a laser cutter equipment

The components of the basic equipment are presented in figure 1.4. The laser system consists of the shell of the machine, the transfer, optical and electrical control system. The machine shell has outputs for cooling, ventilation and compressed air systems. There is also a tool box for additional accessories, which vary depending on the manufacturer and supplier. [7]

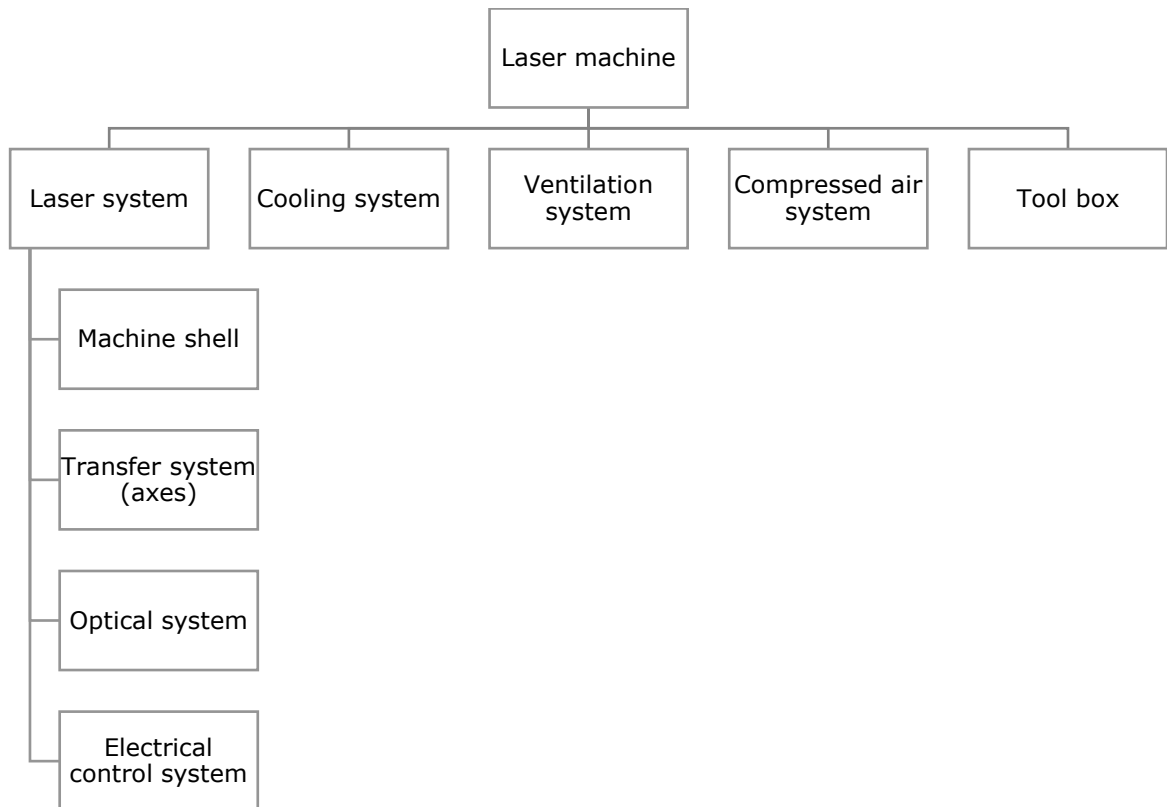


Figure 1.4 The basic components of a standard laser cutter [7]

The laser tube is situated at the back of the machine and attached with sockets (figure 1.5). It is usually made of glass and it is a closed system, meaning its components cannot be replaced. Inside of the tube there are cooling channels, mirrors and gas (CO₂). [7]

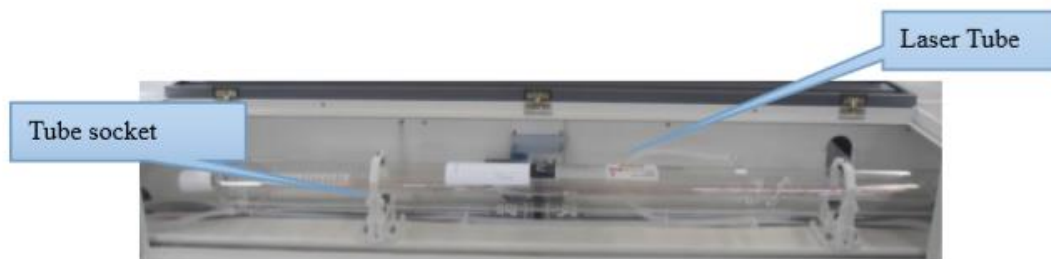


Figure 1.5 The laser tube [9]

The laser cutter has 4 main panels, each have their own function: control panel, switch panel, electrical output panel, ventilation panel, cooling and compressed air panel. The standard laser cutter has 4 sets of wheels, which facilitate moving of the machine. The wheels also have fixators, which fix the machine in place. [7]

The optical system is the most important part of the technology, which includes laser tube, tube socket, mirrors, cutting head and lenses. [7]

The peripheral systems include machinery which are attached to the machine shell with plugs. These include the cooling, ventilation and compressed air system (figure 1.6) [9]. The cooling system consists of a water chiller. The water will flow from one end of the laser tube to the other (from high voltage terminal to low voltage terminal) [9]. It is important for the prevention of overheating. The laser tube emits heat when the machine is working. When the cooling water temperature rises above 30 °C then the beam may not form. Furthermore, the glass may break in high temperatures [10]. The ventilation system consists of an air pipe and an air inlet fan. It is necessary for clearing the working area of fumes emitted from the material [10]. The ventilation system can also be integrated into the machine [11]. The compressed air system consists of an air pump (air compressor). This can prevent the material from burning, also it helps to keep the focus lens clear. [9]



Figure 1.6 The components of the peripheral system [9]

1.1.3 Software

The software that comes with the laser cutter may vary depending on the manufacturer and supplier. In this example the software RDWorks V8 is described.

The software supports the next file formats:

Vector format: dxf, ai, plt, dst, dsb, etc. [12]

Bitmap format: bmp, jpg, gif, png, mng, etc. [12]

Vector files are preferred for a more accurate and clean result. They also allow for both cutting and etching. When using bitmap files, the program allows to convert it into a vector file if necessary (image trace function). [13]

1.1.4 Laser cutting parameters

The quality of the laser cutting process, therefore the quality of the cutting edge, is the result of various parameters related to the system, material and the process. The system parameters include the wavelength of the laser radiation, maximum output laser power and laser beam quality. The system parameters are settings which cannot be modified by the operator. The material parameters include the material type and thickness. The processing parameters include the used laser power, cutting speed, focal length of the focusing lens, focal point position relative to workpiece top surface, type and pressure of assist gas, nozzle diameter and nozzle standoff distance. The operator can alter the processing parameters to optimize the cutting process for high productivity and desired edge quality [3]. These include the minimum and maximum power (%), cutting or etching, speed [12].

The maximum speed and power are determined by the machine. The power chosen is a % of the maximum power, e.g. if the maximum power is 100 W then cutting speed 50% is 50 W. The speed and power are dependent on the chosen material and outcome. The operator will have to test the material first to find the correct balance between the two settings [14]. The faster the speed the more inaccurate the edges may be. The lower the speed the smoother the edges may be, but with the same power % the more affected by the heat the material may become [12].

1.1.5 Cutting of non-metals

The cutting speed is dependent on material thickness, laser power, water and air content of the material. Paper, wood and other cellulose materials undergo vaporization caused by combustion. Thermoplastic polymers are cut by melting. Thermosetting materials are cut by combustion or chemical degradation. Composite materials are easy to cut, but the cut edges may not be of high quality. Non-metal cutting requires a gas jet to remove molten, vaporized or chemically degraded matter from the cut area. [6]

1.2 Advantages and disadvantages

Compared to traditional industrial cutting technologies laser cutting has its advantages and disadvantages.

Some advantages include:

- stable work and cutting area since the cutter does not move the material, therefore it is not necessary to attach the material [15];
- precise cutting process due to laser beam's small diameters, this is helpful when intricate cuts are performed and to lower material deformation [15];
- faster cutting process compared to cutting with conventional tools, e.g. scissors (up to 30 times faster) [16];
- low material contamination since there is no contact with the machinery [15];
- cutting of various materials, e.g. wood, ceramics, plastic, rubber, metals [15];
- more accurate cutting compared to manual cutting [15];
- decreased injuries and accidents that happen with traditional cutting tools [15];
- high level of efficiency and accuracy, producing identical products when mass production is used [15];
- improved material utilization thanks to close-nesting layouts [16].

Some disadvantages include:

- usually high energy consumption and depending on the product the cost of manufacturing can be high [15];
- inconsistent production rate and depending on the material the correct settings require practise [15];
- severe accidents when errors require human intervention, very dependent on safety training [15].

1.3 Safety

The overall safety requirements and instructions for laser cutters depend on the safety class of the specific laser type in use. Since 2002 the lasers are classified based on the new system [17]. If not used properly with caution the laser can cause burning of easily ignited materials, reflection of the laser beam from unsuitable cut material, emission of dangerous gases. It is advised to keep fire safety equipment near the machine [18]. For this a CO₂ extinguisher is recommended, which would also make cleaning the machine easier after an incident [14].

The power supplies and controllers are usually housed in enclosures, which are suited for factory floor conditions. These enclosures help to protect the operator from physical interaction with the laser, waste heat, which is due to inefficient converting of electrical

energy to electromagnetic energy (light), and gases, which are emitted during the process from the material. Laser cutting machine suppliers can also offer safety glasses to protect the workers from the intense light coming from the laser, which can cause serious damage to the eyes. Direct viewing of the beam from the laser is due to that not recommended [6]. Laser cutting machine can also cause skin injuries due to exposed laser if not handled properly [17].

The laser cutter is suggested to be kept in environment where the temperature is kept in the range of 10-38 °C and relative humidity 5-90% [18]. It is also advised to keep it away from too dusty, air polluted [2] rooms with high voltage and strong magnetic field [18]. The cooling system should be kept under 30 °C [18]. If the temperature inside of the machine goes above 60 °C, then the temperature sensor will inform of that. If the machine experiences overheating, then it should be turned off and let to cool down [14].

It is advisable that the machine is operated only by those who have passed training [18]. The operator is advised to stay in close range to the cutter when it is working and also be wearing protective glasses. The operator needs to know the composition of the materials and whether they are safe to cut. The lid should be closed at all times when the machine is being operated. [18]

Most industrious lasers use substantial electrical input at high voltage and high amperage, which requires supervision of electrical standards, e.g. in ANSI Z136.1-2014: Safe Use of Lasers. [6]. Faults in electrical system cause more issues than the exposure to a laser beam. Therefore, it is also advisable to unplug the machine during maintenance. [17]

1.4 Laser cutting in the garment and textile industry

While seeming new and contemporary, laser cutting technology has been used in the garment industry since the 20th century. Due to technological advancements it has become more obtainable for a large variety of companies, including those specialized in technical textile, e.g. furniture and sail, leather, couture fashion and fast fashion manufacturing. Although, there exist many examples of applications, there have been few studies published about this. [17]

1.4.1 Different types of laser cutters used in the garment and textile industry

There are different laser cutting machines available for cutting textiles, ranging from small and simple to large and complex. The choice will depend on the type of materials, application, investment opportunities and desired workflow of the cutting department. [17].

For cutting small details, such as brand labels, appliques and size labels a smaller cutting surface (1600x1000 mm) is suitable. Also, for batch cutting the machine may also be equipped with several cutting heads to speed up the process [19]. For cutting large pieces, such as flags, banners and soft signage, the cutting surface may be as large as 3200x4000 mm [20] or even 1600x6000 mm for cutting parachutes and paragliders (figure 1.7) [21].



Figure 1.7 Golden Laser provided laser for cutting flags, banners, soft signage [20]

Fabrics that consist of small particles that are released during cutting such as filter cloth/industrial filtration fabrics, airbags, sandpaper discs, require a fully enclosed structure to catch these particles to ensure the safety of workers (figure 1.8) [22]. Fabrics that release fumes during cutting or engraving, such as leather, may have a localized hood system instead of a fully enclosed structure [23]. Also, for cutting reflective materials, the specialized machines will have an enclosed system with darkened glass panels to dim reflected light [24].

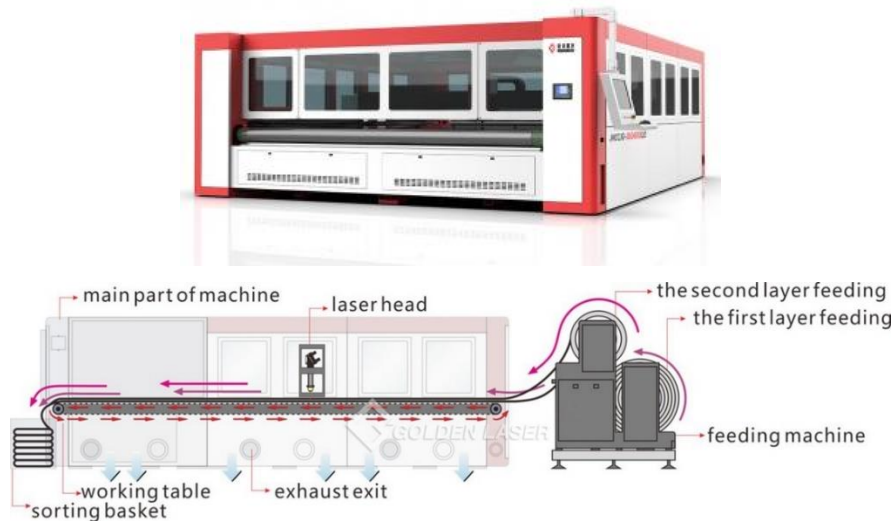


Figure 1.8 Golden Laser provided laser for cutting filter cloth/industrial filtration fabrics [22]

Some laser cutters may be equipped with camera modules that will scan the fabric for registration marks or the contours of pieces. Based on the scan the machine will cut pieces out without previously prepared layouts, for example sublimation printed fabrics for sportswear (figure 1.9). [25]



Figure 1.9 Golden Laser provided laser for cutting sportswear [25]

Some laser cutting machines that are specialized for cutting large batches of fabric from rolls and are commonly used for continuous cutting have a two-part cutting surface. On one half of the surface the cutting takes place. There is also a hood on top of this side of the machine for the safety of workers. On the second half the cut pieces are removed from the cutting board. When all the pieces are cut the machine then spreads the fabric automatically. These two procedures can take place at the same time. The benefit of using this type of machine is that it allows for a smooth workflow and the laser is in use for

maximum efficiency. Based on the parameters of these machines, fabric can also be cut in multiple layers, raising the cutting efficiency even more. [26]

1.4.2 Benefits from using the laser cutter for textiles, compared to conventional cutting methods

Overall, there are many advantages and disadvantages when choosing a laser cutter over conventional cutting machines and tools, which are more specific to those mentioned in paragraph 1.2. Compared to automatic cutters, which cut with speed 5-12 m/min (80-200 mm/s), laser cutters are faster with cutting speed 30-40 m/min (500-700 mm/s). While automatic cutters are used for cutting multiple plies, laser cutters can cut less layers, thus in that comparison being more expensive. The best result, especially for intricate details, is achieved with cutting single or few layers. Additionally, while cutting several layers there is a chance that the layers will become fused together, in the case of synthetic materials. [17]

The problems of low efficiency come with low utilisation. Some operations may be more reasonable to complete with an automated cutting bed, especially if a company already has them by hand. The investment into a laser cutting machine may not justify the cost if the integration of conventional cutting tools and machines along with laser cutters has not been complete. It may not be economically viable to invest in a laser cutter for few operations with low profitability. It is, however, a step towards a more automated production and diversified product portfolio that includes technologically advanced products, giving a clear advantage in a competitive industry. So, the choice of a laser cutter depends most on the end result. [26]

There are several benefits from cutting textiles with a laser. These have been written based on author's training and experience as well as literature. These include:

- Laser cutters allow for precise cuts and complex shapes [27].



Figure 1.10 An example of an intricate cut surface that was performed on leather [27]

- Cut pieces can be easily repeated and they give an exact and uniform result [13].
- Layouts can be nested closely next to each other and that results in high efficiency and low cost of material, this will also eliminate defects with automated cutting machine knife movements [13].



Figure 1.11 An example of a close nest layout [13]

- The edges are sealed, especially for synthetic textiles as the cut edge melts. For natural fabrics the edges do not start fraying as easily [13].
- There will be less fabric dust, meaning less time for cleaning, especially with fabrics that fray very easily when cut, e.g. velvet.
- Depending on the fabric the cut edges are coloured, this can add an element of design, e.g. for natural fabrics that are burned in the process, they will have darker edges, such as leather, cotton, linen.
- The laser does not come in contact with the material and there are no marks made on fabrics, this is especially beneficial when working with delicate fabrics, such as silk fabrics and lace [28].
- Materials which are difficult to cut by hand in one go, such as leather, can be cut with a laser for smooth and correct edge.
- It is possible to make cuts inside of the details, this is helpful when cutting functional cuts, like openings for zippers or holes for eyelets, studs, ribbons [29].
- Laser cutters in manufacturing allow for more comfortable working positions. The workers can sit during longer cutting procedures [29].
- Laser cutters in manufacturing also can raise efficiency as the workers can prepare the next materials or cut files at the same time the laser is cutting; therefore, one worker can perform many tasks [29].
- Laser cutters can engrave the surface for more interesting results, not only can they make intricate patterns, but the laser can engrave off the layer of die, that gives bleach effects to denim without the use of chemicals, no toxic by-products disposal and less energy [17]. It can also cut off a level of hair in the example of fur giving multi-dimensional design.

2. OVERVIEW OF SPORTSWEAR

Sportswear or activewear is a type of clothing worn during physical exercise or sports. Sportswear is expected to have high function and can be worn for several purposes, including protection from environmental conditions, comfort, identification or for performance enhancement with additional design elements and high-performance materials. [30]

During sports the body experiences changes in thermal and fluid balances and therefore clothing used for sports must help maintain the balance between the core, surface and outer temperatures. For designing sportswear, one must understand the physiology of the human body, the purpose of the garment, the type of activity, fit, technology and differences in materials. [31]

2.1 Comfort

Comfort is a state of mind that is satisfied with the surrounding environment, without any perceived pain and discomfort. Comfort in clothing is classified as aesthetic, sensorial and thermal comfort. Aesthetic comfort is associated with the fashion trends and social acceptability as well as aesthetic appeal of the garment design. Sensorial comfort is related to the surface of fabrics and the mechanical properties. From the perspective of fabric properties, thermal comfort has the most relation to comfort. [32] [33]

2.1.1 Thermal comfort

During physical activity the human body undergoes changes in fluid and thermal balance. In order to function properly the human body must maintain a heat balance. Therefore, thermal comfort is associated with the ability to maintain the temperature of the wearer by transferring vapour and heat generated during a physical exercise. Along with the type and intensity of physical exercise, heat balance depends on climate, individual metabolism and personal factors (figure 2.1). [31] [33]

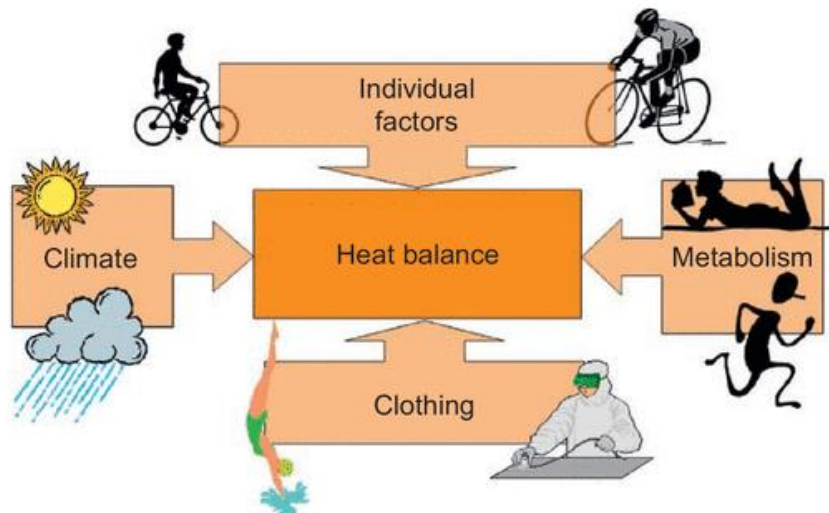


Figure 2.1 Factors determining the thermal balance [31]

Climate

The climate conditions that affect the body are [31]:

- ambient temperature,
- relative humidity,
- solar radiation,
- wind speed,
- altitude pressure.

One of the most stressful weather conditions for the body involves high temperatures, high humidity and open UV-radiation with the absence of wind. High temperatures cause sweating and high humidity with absence of wind make it difficult for the sweat to evaporate. Therefore, preventing heat to dissipate and potentially leading to a heat stroke. The second most stressful condition involves cold weather with high wind speed and absence of UV-radiation. The cold temperatures and winds take away heat from the core of the body and cause freezing of exposed skin. Therefore, it is not advised to take the individual climate conditions into account, but more to regard them as a combined collection of parameters [31].

Clothing

It is said that during rest the body produces about 100 W of heat, while during exercise the body can produce up to 20 times more heat, depending on the intensity of the physical activity. Therefore, in order to maintain thermal stability, the heat, along with the humidity from sweat, must dissipate to the surrounding. Which is the same case when the surrounding temperature exceeds a comfortable one. Contrary, when the surrounding temperature drops it causes the body to lose heat. Therefore, the purpose of sportswear

is to assist in keeping the body from uncomfortable temperatures and to maintain its normal functionality, i.e. to maintain the body's thermal balance. [31]

Another function of clothing is to act as a barrier between environmental conditions and the body, i.e. to provide safety from wind, uncomfortable temperatures and UV-radiation. At the same time, in high temperatures the clothing makes sweat and heat evaporation more difficult because of air motion barrier. [31]

When the clothing does not assist with keeping the body in thermal balance then the body gives out thermal strain signals, such as changes in core temperature, sweat efficiency and cardiovascular strain. If the thermal regulation is not sufficient the body goes into hyperthermia, i.e. body core temperature rises above 43 °C, or into hypothermia, i.e. body core temperature drops below 35 °C. Sweat rate shows the intensity of the activity and also the ergonomics of the thermal environment. Sweating is the body's mechanism to cool down when the core temperature rises. Sweat efficiency is defined as the ratio of evaporated sweat versus produced. Cardiovascular strain is expressed as heightened heart rate due to core temperature changes: when the ambient temperature is high, the heart rate rises as a reflex to release more heat. By diverting more blood to the skin, when the temperature drops the heart rate is lower to compensate the lower pressure of returning blood. [31]

Individual differences

Individual factors that determine thermal balance are sweating dysfunctions and acclimation status. Sweating dysfunction refer to abnormalities, where the body either is unable to sweat enough to cool down (anhidrosis) or sweats excessively leading to unnecessary cooling (hyperhidrosis). Acclimation status is determined by the conditions the body undergoes for a prolonged time. For example, athletes that undergo heat acclimation programs may double their sweating rate. This greatly enhances their capacity to perform in high temperature conditions. Although, this has little benefits in situations where the athletes are required to wear protective clothing, e.g. fencing, where the clothing operates as a barrier for sweat evaporation. [31]

Other individual factors include bodyweight and training level. A person who has a low training level and high body weight have difficulties releasing body heat. Usually, they will produce more heat compared to a leaner and more fit person. [31]

2.2 Important properties of fabrics for sportswear

The properties described in this chapter must be taken into consideration simultaneously when designing sportswear. This may result in a garment that consist of several layers of different type of materials in various locations of the body. These properties are crucial to consider for any type of sportswear, regardless of wearer’s activity intensity levels or environmental factors. [30]

2.2.1 Insulation value

Insulation value depends on how much air is trapped inside, e.g. multi-layered fabrics, or around the fabric, e.g. fabrics with a nap. Insulation is necessary in cold conditions and less in hot conditions [31]. The insulation value of material will be lowered when it gets wet, either by perspiration or sweat. In critical conditions, this can lead to a chill or even hypothermia. In order to ensure enough insulation a multi-layer garment system can be used (figure 2.2). This is where a garment consists of different layers to provide variable insulation. Each layer in this system has a specific purpose, either wicking moisture from the skin or allowing moisture to evaporate. Usually, the insulating layer is then situated in the middle [30]. This can be tested with the hot plate method [31].

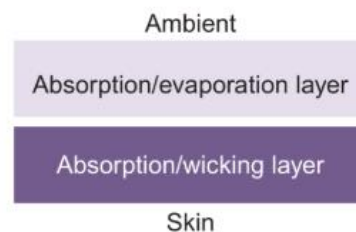


Figure 2.2 Example of two-layer material that combines layers with different properties to enhance or diversify the overall functionality of the material [30]

Insulation value should not only be considered alone when choosing material or layers, but also along with thermoregulation in different areas of the body (body mapping). Areas, where more heat is generated, should be less insulated. Accordingly, the areas where less heat is generated should have more insulation from the condition. Body mapping is discussed more thoroughly in chapter 2.4.3.

2.2.2 Moisture management

Moisture management property is important for transferring water vapour generated by sweating away from the skin to prevent condensation inside the garment. Also, to allow for evaporation of the moisture to the atmosphere. When exposed to wind or cold temperatures this may cause heat loss and fatigue by conductivity, since thermal conductivity of water is around 25 times higher than that of air. Therefore, it is important to recognize the locations on the body where sweating takes place most often and secure vapor permeability in those regions. [31] [33]

The more moisture wicking the fabric usually is the more moisture is pulled away from the skin and transferred to the atmosphere and will leave the wearer feeling dry and comfortable [33]. This can be achieved by:

- using microfibre fabrics;
- using multi-layer fabrics, such as polyurethane foam laminates;
- surface treatments with silicones, alkalis or enzymes;
- yarn blends, such as hydrophilic-hydrophobic yarn blends in one fabric [33].

2.2.3 Air permeability

Air permeability in sportswear shows the material's properties to allow for excess temperature to dissipate into the surrounding. Air permeability is more important in hot weather conditions. In cold weather air permeability should be minimized as air gaps lead to reduced insulation [31]. Air ventilation is closely related to insulation. A high insulation value will result in a low ventilation efficiency. Air permeability efficiency can be raised by using breathable fabrics with low insulation value and high air permeability or by adding ventilation features. The latter have even been researched as more effective than using just breathable fabrics [34].

Ventilation features, or vents, such as zip openings and laser cut ventilation holes can raise the air permeability values of a material [31] [34]. Again, the position of these features must also take into consideration thermoregulation during different levels of activity. So, they must be placed in areas where they will be most effective in assisting with air movement. The effectiveness of these features also depends on air flow, which in turn depends on the activity and environmental conditions. Another influencing factor is other layers in the clothing system. For example, the effectiveness of the outer clothing layer depends on how insulated the layer underneath is [34].

2.3 Testing of sportswear

There are several tests that can be done to evaluate the performance of sportswear. These include textile tests, garment test with a manikin or a human participant in a laboratory and field tests. [31]

2.3.1 Testing of textiles

Textile tests provide results that are relatively inexpensive compared to garment testing and are the basis when choosing materials for a certain product. These include fibre identification, performance testing, such as washing, abrasion, pilling, chemical testing, such as resistance to sweat and cleaning products, flammability, air and vapour permeability [31]. It should be considered that textile tests provide results that are attributed to the specific textile and do not show the performance of the garment itself, especially considered the technology and design. For example, in a garment that consists of multiple layers the performance is determined by all of the textiles combined or how much of the body is covered with the subject fabric and how loose or tight the fit is.

A common test performed to test thermal comfort of fabrics is the sweating guarded hot plate test, described in standard ISO 1092. The test measures thermal resistance, total heat loss and evaporative resistance of fabrics. [35]

2.3.2 Testing of garments

For garment performance testing manikin and wearer trials are more effective in showing the realistic performance of the garment [31]. These tests provide clothing performance results and assist in evaluating the combination of textiles, the design and fit of garments. During manikin testing a full-scale manikin is dressed. The ambient environmental conditions and the posture of the manikin are controlled. The drawback of manikin testing is that it is difficult to simulate accurately the human physiological aspects. Another drawback is that models based on manikin testing are based on the idea that all human bodies are uniform and have constant metabolic rates Manikin test is described in the standard ISO 9920 [35].

Wearer trials are more effective in showing levels of comfort, which is not possible only with manikin and textiles testing. The tests are done in climatic chambers that simulate the conditions in which the garment will be worn [31]. During testing the subjects are

asked to perform a specific exercise, while their physiological parameters, such as heart rate, maximum oxygen consumption and temperature, are measured. Although human testing gives the most reliable results, they are costlier regarding time and resources due to biological variability. Human tests are described in the standard ASTM F2668 Standard Practice for Determining the Physiological Responses of the Wearer to Protective Clothing Ensembles [35].

Field tests can provide results that are realistic and valid, but the problem is lack of reproducibility and lack of control of weather conditions. Therefore, they may be used as parallel test along with the previously mentioned tests. [31]

2.4 Design

The design of sportswear is different from designing, for example, everyday fashion clothes, since the criteria for performance outweighs aesthetics, except for low intensity activities, such as for walking or leisure wear. Therefore, in design sportswear can be classified as leisure wear, i.e. athleisure wear, outdoor wear and performance wear. [30] [31]

Sportswear requirements depend on the activity level and event, e.g. type of sports and environmental conditions. The criteria also vary between different events, such as training, competition, post-exercise. Some examples of sportswear are skiwear, cycling clothes, tennis clothes, water sports, motor racing clothes, athletic clothing, hiking and climbing clothes (figure 2.3). Each example requires a unique designing point of view, from the choice of materials, aesthetic preferences, personal safety and protection from environmental factors to fit. [33]



Figure 2.3 Examples of different sportswear: football clothes [36], hiking clothes [37], skiing clothes [38], moto racing clothes [39], cycling clothes [40]

Using functional fabrics and incorporating them with the latest technological advancements is a big part of designing for sportswear nowadays. The aim of functional sports clothing is to balance demands of the body and demands of the sport (figure 2.4). Critical parts of design are the choice of materials, understanding ergonomics and the physiology of the human body under physical stress, fit and patterns to fulfil the performance of the garment, technology. Also, the synergy of all these steps is crucial. [31]

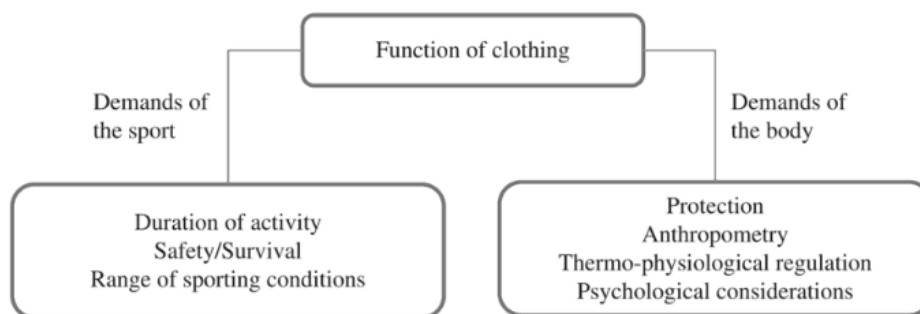


Figure 2.4 Different factors that are related to designing a functional sportswear garment [32]

2.4.1 Ergonomics

Ergonomics is a scientific discipline that combines physiology, engineering, psychology and anatomy and looks at human interactions with other elements in a system. Ergonomic design takes these interactions into account, along with personal limitations, goals of comfort, safety and efficiency, to enhance human performance and compatibility with the surrounding elements. In sportswear, ergonomic design's goal is to increase thermal

comfort, i.e. optimizing microclimate, and to enhance or not hinder individual performance. [41]

Summarizing the previous paragraphs, then the main factors that influence the needs of sportswear are human and personal differences, clothing and environment. The main goal then is to find the balance between these factors due to the multitude of variables. The perceptible factors of clothing include solar penetration and thermal radiation, water evaporation and air permeability and heat resistance. [41]

2.4.2 Fabric choice

The fabric choice ultimately depends on the type of activity and the environment. Fabric selection of sportswear include many different fibres and fibre blends as well as different structures such as knitted fabrics, woven fabrics, nonwoven fabrics and different combinations of the previous. Additionally, these fabrics can have a special finish, coating or laminate to enhance properties. [32]

There are universal performance properties of fabrics especially important in the case of sportswear. The fabrics should be breathable, moisture wicking, quick drying and as lightweight as possible. Dependent on the activity and environmental conditions some sportswear should also be waterproof, water repellent, aerodynamic, abrasion resistant and have high stretch and recovery. This is where synthetic fibres, such as polyester (PES), polyamide (PA) and elastane (EA), have an advantage over natural fibres, like cotton and wool. [32]

2.4.3 Physiology and sweating patterns

During exercise, sweat production will have a delay in the beginning of a sporting activity and at the end, meaning the body will produce heat even after an intense activity has stopped. This factor is crucial with intermittent sports activities performed in cold temperatures, such as skiing, running, hiking, etc, since the wetted clothes will cause an excessive conduction of heat during breaks in activities and at the end [31].

An important factor determining design are sweating patterns. Women are said to have highest regional sweat rates at central upper back, heels, dorsal foot and between the breasts. The lowest values for women were found to be middle and lower outer back,

over the breasts and palms. For men the highest rates were registered at the chest triangle, central lower and upper back. Overall, compared to women men show higher sweat distribution in the torso and less towards the hands and feet. Also, men show a greater sweat rate during both low and high intensity activities, compared to women. Women show a more pronounced delay in sweat, which has been attributed partly to a lower body water content and potential effects of menstruation. [42]

Determining sweat patterns provides knowledge of the areas of the human body where the highest sweat rates are registered. This can aid in knowing what the most important fabric properties are in specific regions of the body (figure 2.5). [41]

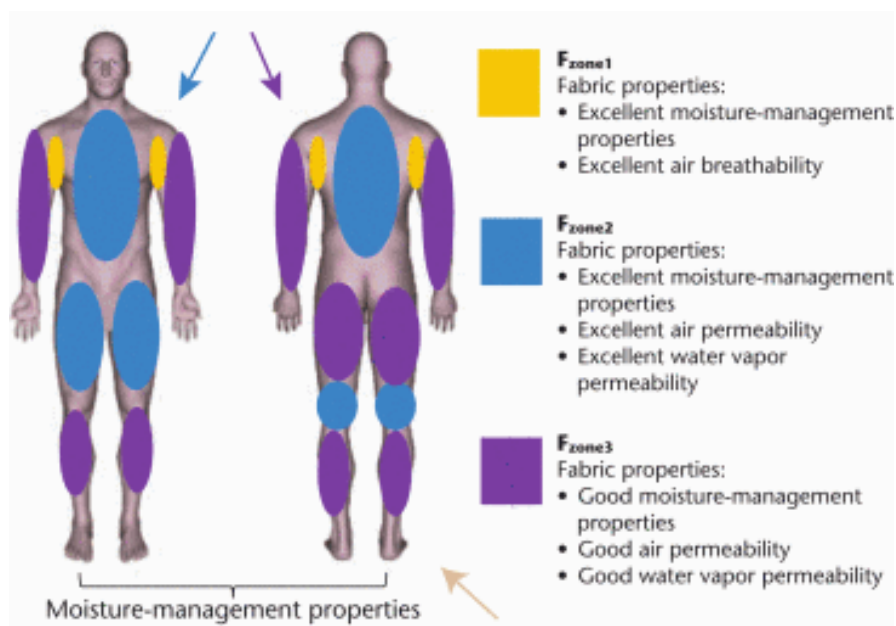


Figure 2.5 Thermal mapping image that is used to determine fabric properties for different areas of the human body [41]

The implementation of this knowledge becomes difficult as different sports have also different functional requirements regarding design and priorities, for example traditional sports, e.g. running, versus extreme sports, e.g. snowboarding. [41]

2.4.4 Technology

Technology of the sportswear is an important factor concerning both quality and functionality. In order to have an ergonomic design the seam type and machinery choice must follow the high requirements, such as high seam strength, elasticity and comfort. Seam types play an important role in maintaining the mobility, therefore seam failures

like yarn breakage or seam slippage should be avoided with proper choice of yarn and technology. Sportswear that are tight fitting require smooth, thin and elastic seams in order to avoid compression of seams and friction due to rubbing seams. [43]

The chosen technology can also have an effect on the garment’s thermal properties. The thinner the seam, e.g. adhesive seams, the higher the air permeability and the less weight the garment will have. At the same time, thinner seams can also cause seam failures, such as breakage and low elasticity. The bulkier the seam, e.g. flatlock, the higher the thermal insulation and the more the weight. On the other hand, coverstitch seams have higher strength, elasticity and durability and can add a design element. [43]

Stitch types used for sportswear

Stitch type depends on material, placement and the purpose of the stitch. Most common stitch types used for sportswear are described in table 2.1:

Table 2.1 Most common stitch types used for sportswear [43] [44]

Class	Stitch type	Description	Examples of products
300: lock stitches	301	Most commonly used stitch for fabric joining	Products from woven fabrics, e.g. jackets, trousers
	302	Used for sewing elastic strips to fabric	Products from knitted fabrics, e.g. sports bras, shirts
400: multithread chain stitches	401	Used for seams that require elasticity. Done by joining layers of fabric together	Trousers, jackets
	402	Used for stitching permanent creases	Back of gloves
500: overedge chain stitches	503, 504, 505, 512, 514	Used to seal fabric edges to prevent fraying, while allowing stretch	T-shirts, sports bras, leggings
600: cover seam, chain stitches	602, 605,	Used for covering or seaming	Athletic shirts, leggings
	606, 607	Created by overlapping two fabrics and joined	Athletic shirts, leggings

Seam types used for sportswear

Technological advancements, such as bonding, laminating, welding, have allowed for more enhanced performance clothing that is also more lightweight, water-resistant, durable and abrasion resistant than compared to conventionally used seams. They can also allow for a better form and fit with strategically placed compression panelling that have good stretch and recovery. These are also called stitch-free joining technologies. Most common seam types are described in table 2.2.

Table 2.2 Most common seam types used for sportswear [31] [44]

Seam type	Description	Examples of products
Adhesive seam	Created with a thermoplastic film between two layers of fabric	Joint seams in jackets, shirts
Welded seam	Created by joining or sealing thermoplastic materials by thermal or ultrasonic means where high seam strength, lightweight and waterproofness is required. Results in a less elastic seam	Backpacks, special waterproof outdoor suits
Taped (sealed) seam	Created with a film form tape that is applied to a seam from inside with heat and pressure in order to make a seam more waterproof. For encapsulation of wearable electronics, e.g. wires, soft controls. For safety if reflective tape used	Seams of rain jackets, rain trousers
Plain seam	Most simple seam created by sewing two layers of fabric together	Most common joint seams in jackets, trousers and other products from woven fabrics
Flat seam	Done by sewing abutted edges of two layers together	Sports shirts, sweatshirts
Lapped seam	Created by lapping two layers of fabric and stitched with one or more rows	Joint sideseams of jackets, trousers,
Edge finishing seam	Created to finish and edge by folding material	One- or two-folded seams to finish sleeves, opening of trousers
Laminated seam	Created by covering a seam on the outside with a laminate/transfer to make a seam more waterproof	Protective laminated panels, reinforced hood peaks, laminated pockets

Choice of needle and thread

Choosing the correct thread for sportswear is influenced by various factors, including strength, durability, elasticity, shrinkage, abrasion resistance, colour fastness of a thread and resistance to chemicals, UV-light and heat. The factors that influence thread choice from the garment are required seam strength, stitch type, stitch density, type of material, cost and type of machinery. [31]

Common choice for thread for sportswear is polyester based thread, either staple spun or staple spun core spun polyester. For seams that involve overedge or coverseam construction the best seam elasticity is provided by using textured thread, for example textured polyester or nylon. Textured threads are also softer to touch and therefore are not abrasive to skin in tight fitted garments. For topstitching the common thread used is a polyester core-spun that has a cotton core and polyester surface. This combination allows a strong surface and heat protection of the core during washing. [31]

The important properties to check in seams are correct stitch density, thread type and size. These factors will influence seam strength, appearance and seam elasticity. This is important especially for fabrics with a stretch or seams that undergo stress. This can be

manually checked with pulling the fabric apart to see if the stitches are showing and pulling the fabric along the seam to check if the stitch starts cracking. [31]

Sewing needles differ in needle point and thickness. The aim of the needle point is to penetrate the fabric without causing damage [31]. For sportswear fabrics a needle with a round point is used (figure 2.6). The most common and standard of them is needle with normal round point (R). Depending on the thickness and the type of material different needles are suggested. For microfibre, densely woven fabrics and coated fabrics a slim set point needle (SPI) is used. For lightweight fabrics a needle with a light ball point needle (SES) and for heavier fabrics heavy ball point needle (SKF) is suggested. [45]



Figure 2.6 Different types of round point needles used for sportswear [45]

3. LASER CUTTING TECHNOLOGY OPPORTUNITIES IN SPORTSWEAR DEVELOPMENT

The previous paragraphs discussed laser cutting technology and sportswear as separate topics. This paragraph joins the two topics in order to describe the possibilities of using laser cutting technology in the product development process of sportswear. Some different examples of how a laser cutter has been used for sportswear production will be included.

3.1 Opportunities

Laser cutting technology can be applied for different outcomes in order to be essential in providing personalized and unique products, which is especially important in a tight competition. Also, since a laser cutter can be a hefty investment for many companies, it is especially important that this investment can be used for a large variety of products and application areas. [17]

3.1.1 Cutting of whole garment pieces

One great opportunity for laser cutting technology application is its use in whole garment pieces cutting, i.e. contour cutting. Garment pieces can be made in a common CAD program, such as Lectra or Gerber, and exported into a vector file, which is then opened in the laser cutter program. The pieces can then be moved around in the user interface, which also displays the size of the cutting area so that the pieces can be nested with accuracy. This method can be used for standard laser cutters without a camera module [46]. This method includes cutting out all pieces of one garment or only the few necessary ones, such as pockets, transfer paper for reinforcement of hood beaks and plackets (figure 3.1).



Figure 3.1 Examples of laser cut details: pocket piece (left) and front plackets (right) that have laser cut reinforcing lining pieces (images provided by Ursuit Baltics AS)

Another possibility is using a special laser cutter with an integrated camera recognition system. Depending on the precision of cutting and the width of the cutter surface, the machine may have several cameras that will scan the fabric. Usually, 1 camera per 90 cm width is a good rule to follow. This type of machine is used for sublimation printed pieces. These types of machines will often have a fabric feeding system, allowing of automatic fabric unrolling onto the cutting area. First, the fabric is printed and rolled. The roll is then placed onto the feed conveyor. The machine will then spread the fabric with the printed side upward. The camera recognition system will start to analyse the spread, based on recognition pinpoints that are printed onto the material. These pinpoints give out information about the cutting trajectory. Depending on the machine, the cameras can also recognize the printed contour. The cameras will then send the information to the laser cutter and based on that the cutting process will be performed. After the cutting procedure has finished, the pieces are collected from the surface and the process continues with additional fabric unrolling onto the cutting surface. This requires the layouts to be made before printing. It allows for all the pieces to have a sealed edge and provide accuracy of the placement of small incisions, such as ventilation holes and zipper openings. [46]

3.1.2 Laser perforation

Garment perforation is one of the most common applications of a laser cutter. Perforations are small openings or holes that can function as ventilation holes for sportswear. They can also be part of a design and function as aesthetic elements on a product. The aim of

these perforations is to increase air flow in areas that need ventilation the most. Functional ventilation holes can situate in various locations on a garment, such as under arm, lower middle back, upper back and shoulders, middle chest, in front of face, ears, bottom, back and sides of calves and thighs. Decorative perforations can situate in various other places and can cover the whole garment.

Examples of various shapes are present, including circles, ovals, triangles, rectangles, stars, half-moons in different sizes and densities. These simple shapes can be placed in a uniform manner or in an abstract way to make up a new shape in its own. These holes can be cut out of a single layer fabric or multiple layers, e.g. through a transfer, making a more durable and stable opening. The examples of garments, where laser perforation is a feature, include sports jackets [47], hiking jackets [48], motorsport gear [49], sports bras [50], T-shirts [51], polo shirts [52], trousers [53], leggings [54], masks [55] and headbands [56] (figure 3.2).

Perforations can be seen in clothing that is used for high intensity sporting activities, e.g. running, but also for lower intensity but prolonged activities, e.g. yoga and hiking. There are also examples of using these perforations on garments that use waterproof or water repelling material as the main material. This may cause controversies in the need for such specialized fabric when the waterproof properties are impaired with the perforations. There can be seen a difference that when the product commercial description states the garment's main material is treated with a water-repellent coating or is slightly waterproof, then the product exhibits perforations even in locations where the rain may penetrate through the fabric, e.g. upper and lower back. These products are not stated to be waterproof but are said to provide cover from direct wind and light rain, i.e. wind shell or windbreaker. For those products that are said to be waterproof by the manufacturer/seller the perforations are located in areas, where there is somewhat protection from direct rain, e.g. under arm and mouth cover [47] [48].

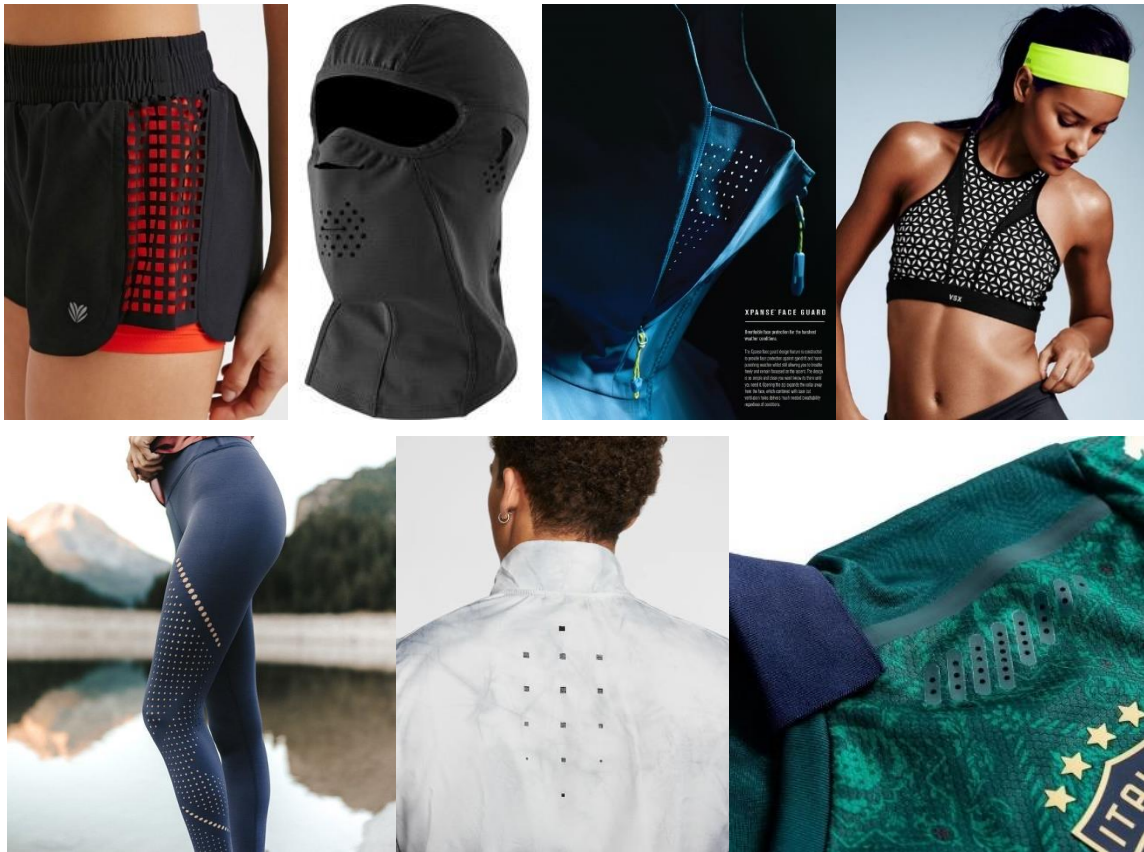


Figure 3.2 Examples of laser cut perforations on various product groups: trousers [53], masks [55], hiking jackets [48], sports bras [50], leggings [54], running jackets [47], polos [52]

Perforating the garment's main fabric can help with lowering the need for additional inventory of fabrics with different purpose. Making ventilation holes directly to the main material can replace other fabrics that aid with providing better ventilation at certain body areas, such as mesh. This can assist in lowering inventory, investment into various fabrics, but also lowering the sewing time and thread that would have been necessary for joining these different fabrics. Furthermore, this eliminates the number of seams that could potentially lead to skin abrasion in clothes close to the skin, e.g. lockstitch seams. Also, since seams can lower heat transfer through the garment as discussed in chapter 2. Therefore, laser cut ventilation holes can result in a more effective transferring of excess heat.

3.1.3 Laser cutting of decorations and accessories

One of laser cutting technology's advantage is the cutting of intricate and detailed elements. For a garment these additional elements can be decorative transfers or functional reflective details, reinforcing elbow, knee and bottom patches, specific size and shape velcro.

3.1.4 Other laser cut openings

Laser cutting technology is a tool for cutting precise openings for zippers, wires, ribbons, elastic, eyelet substitutes (figure 3.3). The problem with cutting opening on details that have been cut previously with other tools is the complicated and precise placement of these openings.



Figure 3.3 Examples of laser cut hood openings for cord and cord fixator (images provided by Ursuit Baltics AS)

4. PRODUCT DEVELOPMENT OF A SPORTS JACKET

To show the possible uses of laser cutting technology for sportswear development a sports jacket was chosen since it has high functional requirements from users and usually consists of multiple details that allow for a variety of applications for laser cutting technology. The product development process consisted of 3 main parts: cutting common sportswear textiles with a laser cutter, testing how properties of different textiles materials change after being cut with a laser cutter and making the final prototype (choosing material and accessories for prototype, constructing patterns, layouting and cutting, sewing prototype, analysing the first prototype and sewing final prototype). The work was divided so that each step would narrow suitable materials, technology and product and allow for final assessment of prepared prototype.

Product development was performed in the Laboratory of Polymers and Textile Technology. The work with the laser cutter was done based on the training provided by the laser cutter supplier Lasermeister (KW Meistrid OÜ).

4.1 Laser cutting materials used for sportswear

The aim of the first part - laser cutting materials used for sportswear - was to explore what results do different textile materials give and also to find out optimal cutting parameters to ensure high quality result in the least possible time. Work towards this aim would also give an additional practical learning opportunity and confidence in working with the laser cutter. 15 different fabrics were chosen for the testing.

4.2 Testing the properties of laser cut textile materials

The second part of product development consisted of testing properties that are affected by laser cutting. This included air permeability and fabric propensity to fuzzing and pilling. 4 different textile materials were chosen to continue in dept properties studies. The results were used to determine the correct fabric for the prototype.

Air permeability is one important factor determining the suitability of a garment for active sportswear. The findings from this test were beneficial in knowing which perforation shapes and their densities would make air flow more effective in areas where heat and sweat is most produced, e.g. under arm area, upper, centre and lower back, chest and

shoulders, in order to help to maintain thermal balance. The aim of measuring air permeability was to find out how cutting ventilation holes will affect air permeability of a material. Also, how different shapes with same area but different density influence the air flow efficiency.

Fabric propensity to surface fuzzing and pilling is an important property to consider since synthetic materials, which are most used for sportswear, melt when cut with a laser, therefore leaving a hard and solid edge. This edge can potentially be abrasive when rubbed continuously against other fabrics. During sports, the body can be in constant movement hence this rubbing action cause damage to the fabrics affected. The aim of measuring fabric propensity to surface fuzzing and pilling was to find out how laser cut perforations can affect the visual quality of the rubbed fabric.

4.3 Making the prototype

The two previous steps in product development aided in choosing the final main material and finalizing the product design. The main principles for developing a sports jacket were:

- To use as much of the main material as possible to prove how laser cutting technology can replace the need for additional material or show additional applications for textiles.
- Cutting perforations to those areas where body heat is most generated.
- Find additional applications of laser cutter, e.g. openings, additional decorations.

5. MATERIALS, METHODS AND DESCRIPTION OF EXPERIMENTAL PROCEDURE

5.1 Materials and methods for laser cutting sportswear textile materials

Overall, the aim in using a laser cutter in the industry is to perform cutting as fast as possible with the highest quality results and accuracy. Time in production amounts to financial and labour resource. Based on that, the test took also into consideration the differences in available machines, including maximum power and speed. Therefore, a wide range of parameters were tested.

For testing how to cut different textile materials with a laser cutter a large variety of different textiles used for sportswear were chosen to provide a complete overview of results. Included were materials that had a different weight, composition, structure, finishing and application. The choice was based on information cited in chapter 2: Overview of sportswear. The textiles were chosen among samples either available in the Laboratory of Polymers and Textile Technology, sourced by.Foxa OY or RiiMeTex webshop (Regno Grupp OÜ). The chosen textiles are listed in table 5.1 (for knits) and table 5.2 (for woven fabrics). For this experimental part the laser cutter Piranha LMP9001300 was used (further technical information in Appendix 1).

Table 5.1 List of tested knitted fabrics

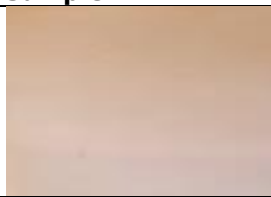


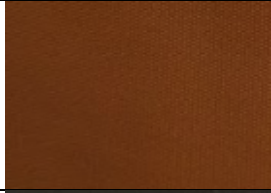
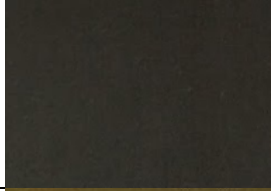

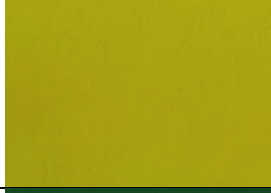

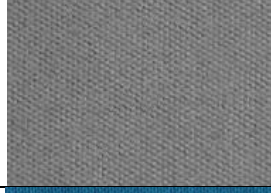



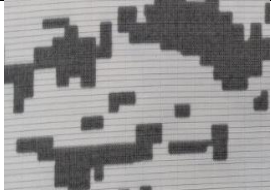
Composition	Weight	Supplier/Manufacturer	Sample
75% PA, 25% EA	225 g/m ²	Kanui Textile	
82% PA, 18% EA	190 g/m ²	Kanui Textile	
86% PA, 14% EA	145 g/m ²	Kanui Textile	

Table 5.2 List of tested woven fabrics

Composition	Weight	Other characteristics	Supplier/Manufacturer	Sample
92% PES, 8% PU	130 g/m ²	waterproof, breathable, water and soil repellent	Finlayson Forssa OY	
76% PA, 24% PU	85 g/m ²	waterproof, breathable, water and soil repellent	Finlayson Forssa OY	
82% PA, 18% PU	220 g/m ²	waterproof, breathable, water and soil repellent	Finlayson Forssa OY	
76% PES, 24% PU	230 g/m ²	waterproof, breathable, water and soil repellent	Finlayson Forssa OY	
72% PES, 28% PA66	110 g/m ²	water and soil repellent, (Scotchgard)	Finlayson Forssa OY	
47% PU, 53% PA	150 g/m ²	waterproof	Finlayson Forssa OY	
100% PA	85 g/m ²	water and soil repellent (Scotchgard)	Finlayson Forssa OY	
100% PES	125 g/m ²	micropolyester	Finlayson Forssa OY	
100% PES+TPU (thermoplastic polyurethane)	200 g/m ²	softshell with webbing backing, waterproof, windproof, breathable, multilayered	RiiMeTex OÜ	

Composition	Weight	Other characteristics	Supplier/ Manufacturer	Sample
100% PES+TPU	310-335 g/m ²	softshell with fleece backing, waterproof, windproof, breathable, multi-layered	RiiMeTex OÜ	
100% PES	115 g/m ²	micropolyester, water repellent	Foxa OY	
75% PA, 24% PU, 1 carbon	85 g/m ²	ripstop,	Foxa OY	

5.2 The experimental procedure for laser cutting sportswear textile materials

The cutting files were prepared directly in the RDWorks V8 program since they were relatively simple. Three cutting files were prepared. The first cutting file consisted of various rectangles in the same size (figure 5.1), which were given different cutting parameters to compare the results. The rectangle size was chosen 1.5 cm x 1.5 cm since the amount of available material was limited. The second cutting file consisted of different circular and angular shapes that could be potentially used for ventilation holes (figure 5.2): circles, ovals, smaller circles and stars. The third file consisted of a circle and square of different sizes (figure 5.3), from 1 mm to 10 mm.

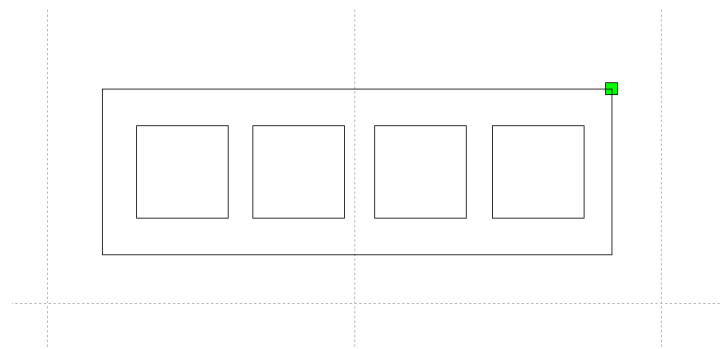


Figure 5.1 Cutting file with rectangles that were given different cutting parameters

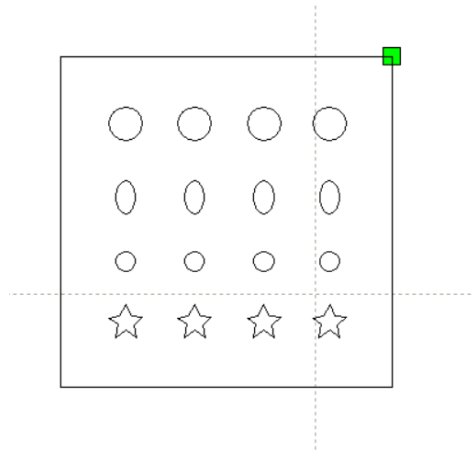


Figure 5.2 Cutting file with different circular and angular shapes

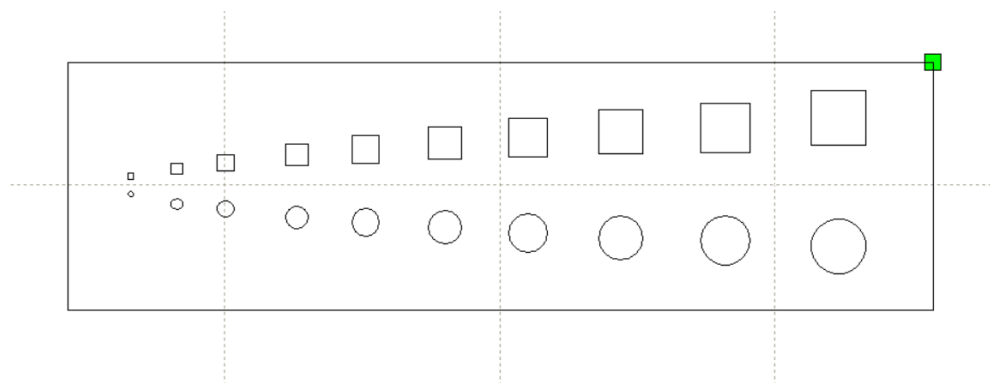


Figure 5.3 Cutting file that consisted of squares and circles from 1 mm to 10 mm size

The fabrics were cut as a single layer and right sides up, excluding when a difference in cut edge quality was to demonstrate. The procedure to find out the optimal cutting parameters was the following:

1. Test the fabric with the lowest possible power setting.
2. Rise the speed until the laser cannot penetrate through the fabric.
3. Rise the power and stop until the maximum speed is reached.
4. Repeat until no visual difference can be made between results of settings.

The results were evaluated based on visual criteria:


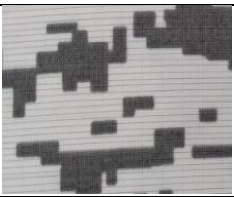




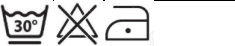
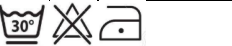
- Are the cut edges uniform and smooth?
- Is there a strong discoloration in the melted edges?
- Is there darkening of surrounding material due to smoke?

5.3 Materials and methods for testing properties of laser cut textiles

The choice for testing how properties change after being laser cut was done so that each of the 4 woven fabrics (table 5.3) from the 12 previously tested represented a category on their own. They were different by structure, weight, composition and other special characteristics. Fabric 1 (micropolyester) represented a lightweight, single layer, treated fabric. The structure from microfibres make it a breathable, moisture wicking and water-repellent fabric. Fabric 2 (coated ripstop) represented the PU coated multi-layered fabric, that has a durable ripstop structure. It is the most lightweight fabric out of the choice. Fabric 3 (mesh softshell) represented the PU coated multi-layered fabric with a mesh reverse side. Fabric 4 (fleece softshell) represented the most heavyweight PU coated multi-layered fabric with a fleece backing. Since the end result was a jacket, knitted fabrics were not taken into consideration.

Before testing, all fabrics were conditioned according to standard ISO 139:2005: the fabrics were left to condition for 24 h prior testing in an environment of 20 ± 2 °C and $65\% \pm 4\%$ relative humidity.

Table 5.3 Chosen fabrics for testing fabric properties

Properties	Fabric 1	Fabric 2	Fabric 3	Fabric 4
Sample				
Composition	100% PES	75% PA, 24% PU, 1 carbon	100% PES +TPU	100% PES +TPU
Weight	115 g/m ²	85 g/m ²	200 g/m ²	310-335 g/m ²
Width	150 cm	150 cm	147 cm	145-147 cm
Other characteristics	micropolyester, water repellent treatment	ripstop, waterproof, breathable	softshell with webbing backing, waterproof, windproof, breathable	softshell with fleece backing, waterproof, windproof, breathable
Supplier/Manufacturer	Foxa OY	Foxa OY	RiiMeTex OÜ	RiiMeTex OÜ
Care				

5.3.1 Air permeability

Air permeability was measured based on the standard ISO 9237:1995 - Determination of the permeability of fabrics to air [57]. The tests were performed with the machine TexTest AG FX 3340 MinAir. Based on the standard, air permeability was first measured from the

unperforated fabric, from 10 different locations, for reference. For this the test specimen was mounted in the specimen holder, right side facing down, and clamped in place. The air flow was recorded until a steady figure was registered, otherwise after at least 1 min. The air flow was expressed in litres per second per square meter. The procedure was repeated with the perforated samples. Tests were performed under the following conditions: 100 Pa pressure drop and 20 cm² area was tested.

5.3.2 Determination of fabric propensity to surface fuzzing and pilling

Fabric propensity to surface fuzzing and pilling was evaluated based on the standard ISO 12945-2:2000 - Determination of fabric propensity to surface fuzzing and to pilling -- Part 2: Modified Martindale method [58]. The tests were performed with the James Heal Martindale Abrasion and Pilling Tester. For each fabric 3 circular test specimens were cut that were 14 cm in diameter and 3 that were 10 cm in diameter. The larger circles were mounted on the pilling table and the smaller on the specimen holder. The test was performed until the last assessment cycle (table 5.4). After each cycle, the samples were evaluated in the colour assessment cabinet Verivide under artificial daylight D65 and graded in accordance with the standard grading scheme (table 5.5).

Table 5.4 Categories of pilling test [58]

Category	Textile type	Abradant type	Loading weight, g	Assessment stage	Number of rubs
2 ^a	Woven fabrics (except upholstery fabrics)	Woven fabric under test (face/face) or wool fabric	415 ± 2	1	125
				2	500
				3	1000
				4	2000
				5	5000
				6	7000

Table 5.5 Grading scheme to evaluate results after each rubbing cycle [58]

Grade	Description
5	No change
4	Slight surface fuzzing and/or partially formed pills
3	Moderate surface fuzzing and/or moderate pilling. Pills of varying size and density partially covering the specimen surface
2	Distinct surface fuzzing and/or distinct pilling. Pills of varying size and density covering a large proportion of the specimen surface
1	Dense surface fuzzing and/or severe pilling. Pills of varying size and density covering the whole of the specimen surface

5.4 The experimental procedure for testing properties of laser cut textile materials

5.4.1 Air permeability

The sample files were prepared in Adobe Illustrator and imported into RDWorks. 3 different shapes and 3 densities were chosen to make conclusions about air permeability changes. The dimensions of the chosen shapes, as well as their area was a constant for all tests (table 5.6). The shapes were divided evenly in the cutting area that was 150 mm x 150 mm. Examples of prepared cut files are shown in figure 5.4. All the cut files are shown in Appendix 2. Calculations of the area of the three chosen shapes are explained in Appendix 3. All cut samples were gathered in a folder (Appendix 4).

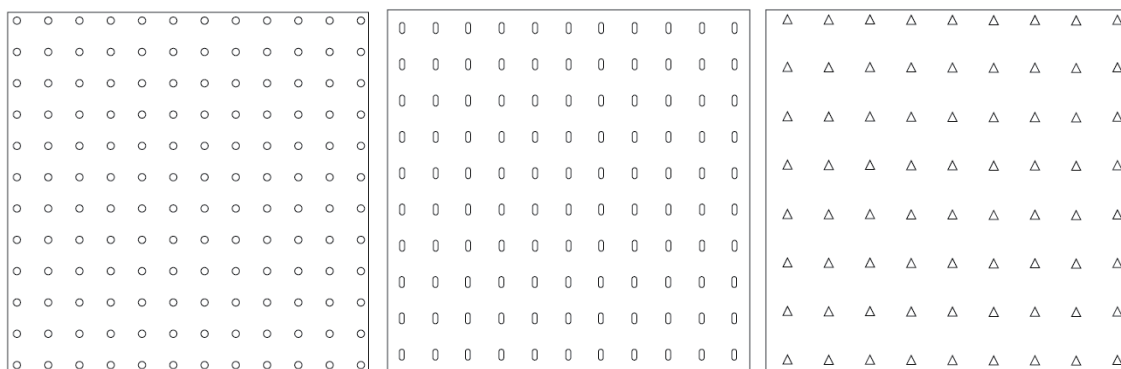


Figure 5.4 Examples of prepared cutting files: circles (left), ovals (middle), triangles (right)

Table 5.6 Dimensions of the chosen shapes

Shape	Size, mm
Circle	3 (diameter)
Oval/ellipse	2 x 4.5
Triangle	3.76 (height) x 3.76 (base)

Table 5.7 shows the differences of perforated area between tests. Compared to test 1, test 2 had 23.6% and test 3 50% less of perforated area. The aim was to have a 25% difference from the initial test between each test to make results comparable. Because the perforations needed to be uniformly divided it was not possible to achieve that aim completely, therefore test 2 had a 23.6% difference instead of 25%.

Table 5.7 Information about perforation division

Test	No of perforations	Whole area, mm ²	Perforated area, mm ²	Density, holes per mm ²	Perforated area, %
1	144	22500	1017.9	0.0064	4.5%
2	110	22500	777.5	0.0049	3.5%
3	72	22500	508.9	0.0032	2.3%

Fabric 1 and 2 were cut with same parameters: 500 mm/s speed and 15-40 W power. Fabric 3 was cut with 400 mm/s and 18-40 W. Fabric 4 was cut with 350 mm/s and 18-40 W.

First of all, the experimental procedure was carried out for all fabrics as-is without perforations for reference. Then, air permeability from the cut samples was measured from different locations (figure 5.5).



Figure 5.5 Measuring air permeability of the laser cut samples. 10 random locations were chosen for registering the result

5.4.2 Determination of fabric propensity to surface fuzzing and pilling

The file for cutting the specimens was prepared in Adobe Illustrator (figure 5.6) and imported into RDWorks. The file consisted of circles of 3mm diameter that covered an inner circle of 7 cm diameter (half of 14 cm that is required for the Martindale machine). The outer circle was 14 cm in diameter. The inner circle was then deleted. The same

perforated area density was used as previously prepared for air permeability test sample no 1.

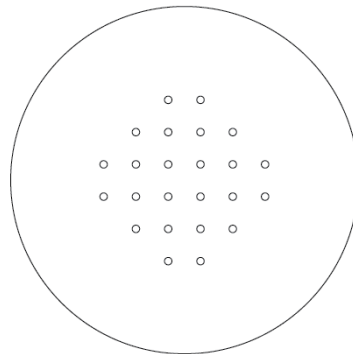


Figure 5.6 Prepared cutting file for testing propensity to fuzzing and pilling

Samples from fabric 1 and 2 were cut with parameters 15-40% W power and speed 500 mm/s. Samples from fabric 3 were cut with and 18-40 W power and 400 mm/s speed. Samples from fabric 4 were cut with and 18-40 W power and speed 350 mm/s.

First, the test procedure was carried out and results evaluated for all fabrics as-is without perforations. These results were used as reference. Then perforated samples were cut and tested. For cutting samples one file was prepared so that the results would be comparable. The sample with perforations was mounted on the pilling table (figure 5.7) and the reference sample on the moving part. This would simulate the movements of hands that rub against the sides of jacket sides.

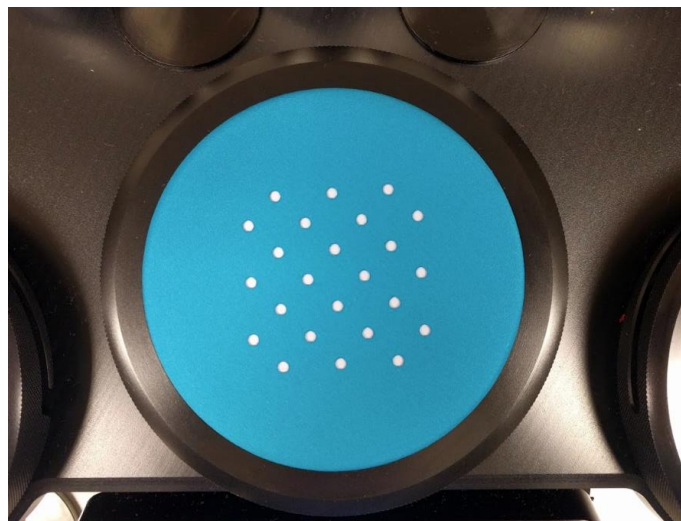


Figure 5.7 How the perforated sample was placed onto the Martindale machine sample holders. Underneath the sample a same size piece of knitted fabric was put underneath to not let the wool fabric underneath disturb the test results. This would also simulate how the outer layer would be worn over a tight fitted knitted shirt during a physical activity

6. TEST RESULTS AND DISCUSSION

6.1 Results and conclusions from laser cutting sportswear textiles

Samples from the tests were gathered in a folder (Appendix 5) and could be useful as a reference point for other future projects, therefore would save time for set-up. The folder is especially useful since there are not enough credible sources about cutting textile materials. Furthermore, the suggested cutting parameters table provided by Lasermeister does not specify suggestive parameters of different textiles but have compressed all textile materials under one name.

The cutting speed intervals indicate the tested intervals that showed required results. Based on all the results a table of suggested cutting parameters for textiles was compiled with optimal and maximum cutting parameters that can be of assistance for cutting textiles in the Laboratory of Polymers and Textile Technology (Appendix 6).

6.1.1 Knitted fabrics

The results of the tests are gathered into table 6.1. Three different knitted fabrics were tested, each with a different composition and weight. All three chosen fabrics suit well for laser cutting. The results showed that the highest quality cut edge was with the most lightweight fabric that also had the least elastane in its content. This edge was the least abrasive against the skin and the edge was smooth. The lowest quality was with the most heavy-weight fabric that had the most elastane in its content. This edge was rough against the skin and demanded high power, otherwise the cut edge was uneven and had short strands of fibres.

The fabrics are put into order by weight, starting from the most lightweight fabric. The lowest power used was 15 W for every test. The table shows results of tested speeds. The optimal speed is therefore dependent of the cut piece shape and size. If more complex and larger shapes are cut, then the maximum speed should be lowered.

Table 6.1 The tested power and speed ranges for knit fabrics

Fabric		Power				
		20 W	30 W	40 W	50 W	60 W
75% PA, 25% EA, 225 g/m ² , Kanui Textile	Speed, mm/s	50	50	75-100	100-150	175-200
82% PA, 18% EA, 190 g/m ² , Kanui Textile		50	75	75-100	125-200	150-300
86% PA, 14% EA, 145 g/m ²		50	75-150	100-200	150-250	225-350

6.1.2 Woven fabrics

All chosen woven fabrics contained polyester and/or polyamide. Additionally, some fabrics had a polyurethane coating for breathability and water-proofness, these properties are important during physical activity.

Most of the chosen fabrics suited well for laser cutting: there were no darkened edges, darkening from smoke, edges were uniform. The only exception was ripstop material, that had 1% carbon in its composition. There were some burning marks on wrong side of the material and there was slight darker discoloration on the right side where the laser beam crossed with the grey vertical stripes. This may indicate the stripes represented the carbon composition. This defect is not very visible from a far, but close-up has the appearance of stains. For the hiding of burning marks on the wrong side the garment may require the use of lining.

The results of the tests are gathered into table 6.2. The fabrics are put into order by weight, starting from the most lightweight fabric. The lowest power used was 15 W for every test, if not stated otherwise. The table shows results of tested speeds. The optimal speed is therefore dependent of the cut piece shape and size. If more complex and larger shapes are cut then the maximum speed should be lowered.

Table 6.2 The tested power and speed ranges for woven fabrics

Fabric		Power				
		20 W	30 W	40 W	50 W	60 W
100% PA, 85 g/m ² , water and soil repellent (Scotchgard), Finlayson Forssa OY	Speed, mm/s	50-200	250-600	-	-	-
76% PA, 24% PU, 85 g/m ² , waterproof, breathable, water and soil repellent, Finlayson Forssa OY		150-225	550-700	-	-	-
75% PA, 24% PU, 1 carbon, 85 g/m ² , ripstop, Foxa OY		50-200	200-675	-	-	-
72% PES, 28% PA66, 110 g/m ² , water and soil repellent (Scotchgard), Finlayson Forssa OY		50-125	175-425	450-600*	-	-
100% PES, 115 g/m ² , micropolyester, Foxa OY		50-225	250-625	550-625*	-	-
100% PES, 125 g/m ² , micropolyester, Finlayson Forssa OY		50-200	250-500	450-600*	-	-
92% PES, 8% PU, 130 g/m ² , waterproof, breathable, water and soil repellent, Finlayson Forssa OY		50-150	150-500	500-650	-	-
47% PU, 53% PA, 150 g/m ² , waterproof, Finlayson Forssa OY		50-150	175-500*	500-650*	-	-
100% PES+TPU (thermoplastic polyurethane), 200 g/m ² , softshell with webbing backing, waterproof, windproof, breathable, multilayered, RiiMeTex OÜ		25-50*	100-400*	350*-400*	-	-
82% PA, 18% PU, 220 g/m ² , waterproof, breathable, water and soil repellent, Finlayson Forssa OY		50-75	100-150	175-425	250-600*	-
76% PES, 24% PU, 230 g/m ² , waterproof, breathable, water and soil repellent, Finlayson Forssa OY		50-100	125-350	375-650*	500-700*	-
100% PES+TPU, 310-335 g/m ² , softshell with fleece backing, waterproof, windproof, breathable, multilayered, RiiMeTex OÜ		25-50*	100*-250*	300*-500*	-	-

*angular shapes should be cut with min 18-20 W power

6.1.3 Conclusions

In conclusion, most materials tested were suitable for processing with a laser cutter. The tests proved that there are various parameter combinations that give similar results on a certain material. Overall, the knitted fabrics required a higher power/lower speed for

cutting through a single layer than woven fabrics. This could be because knitted fabrics had elastane fibres in their content that have a high melting point.

The test also showed that there is also a third variable in the cutting process, next to cutting speed and power. This is the shape and the size of the cut object. Firstly, the circular and angular shapes were cut with different quality, even with same size shapes. This may be because the machine has to make a stop in each corner and has to gather momentum after each corner. Overall, circular objects were cut on lower settings than angular (figure 6.1).

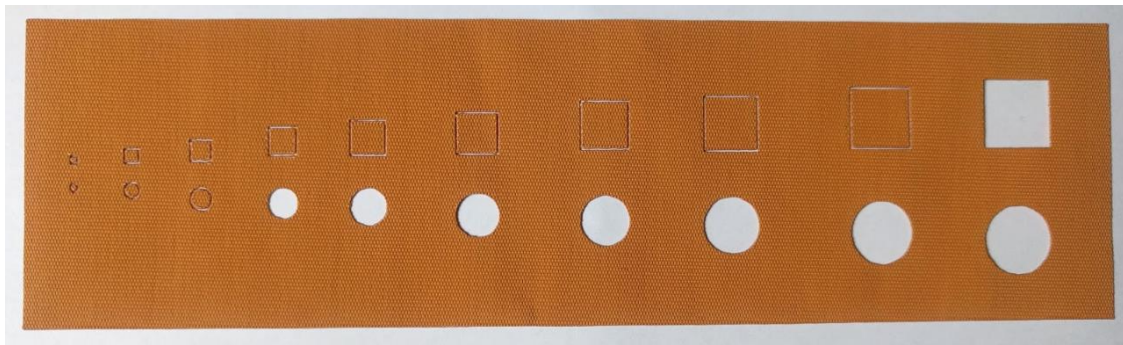


Figure 6.1 The difference of how circles and squares were cut with the same parameters

Secondly, as the size of cut pieces becomes smaller the power should be raised or speed lowered (figure 6.2). Some samples showed that the bigger pieces were cut through and smaller pieces were not. Therefore, for smaller shapes the power setting should be higher or the speed lower than normally used for the particular type of fabric.

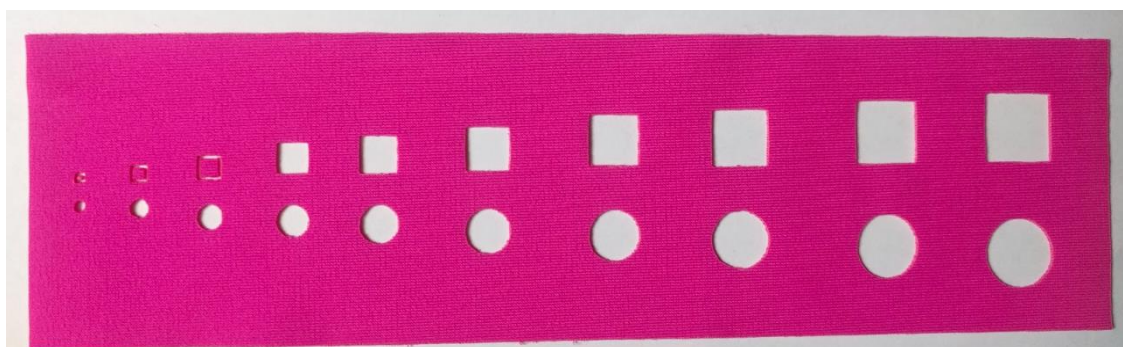


Figure 6.2 Quality of cutting out smaller and larger figures

The speed in the corners of angular shapes was slower, therefore the power range has to incorporate the power setting in accordance to the speed the laser reaches in each point of the detail. Dependent on the speed used, the power range may start from 15%, as

tested during the experimental process. If the power range was not extensive enough, the corners resulted in too burnt or had a cut dot.

One remark that was made during cutting small pieces was that they stuck to the honeycomb board. Synthetic materials melt when cut. Then the pressurised air cools the cut line and the melt material solidifies to the honeycomb surface. This would not pose a problem for cutting larger and few pieces that can be removed by hand. However, it does become a problem if the pieces are small, scattered and in large quantity. In a production they would interrupt a smooth work flow and would require cleaning the honeycomb surface in between each cutting session.

Knitted fabrics were easier to cut across the direction of eyelets than along them. In woven fabrics there was no remarkable difference in cutting direction noted.

Since the cut pieces size represented the smaller dimensions that was under investigation in the practical work/in accordance with the product developed, larger sizes were not cut. The results of the cutting parameters therefore represent optimal parameters for smaller dimensions. For larger pieces, e.g. cutting out a whole piece of a garment, the setting should be tested individually, since the maximum speed used for those pieces can be higher. This was noted when cutting rectangles with larger speeds it did not show any significant change as the speed was raised.

Overall, an observation was made that all the fabrics should be cut right side up to achieve a better-looking result.

6.2 Results and conclusions from testing properties of laser cut textiles

6.2.1 Air permeability

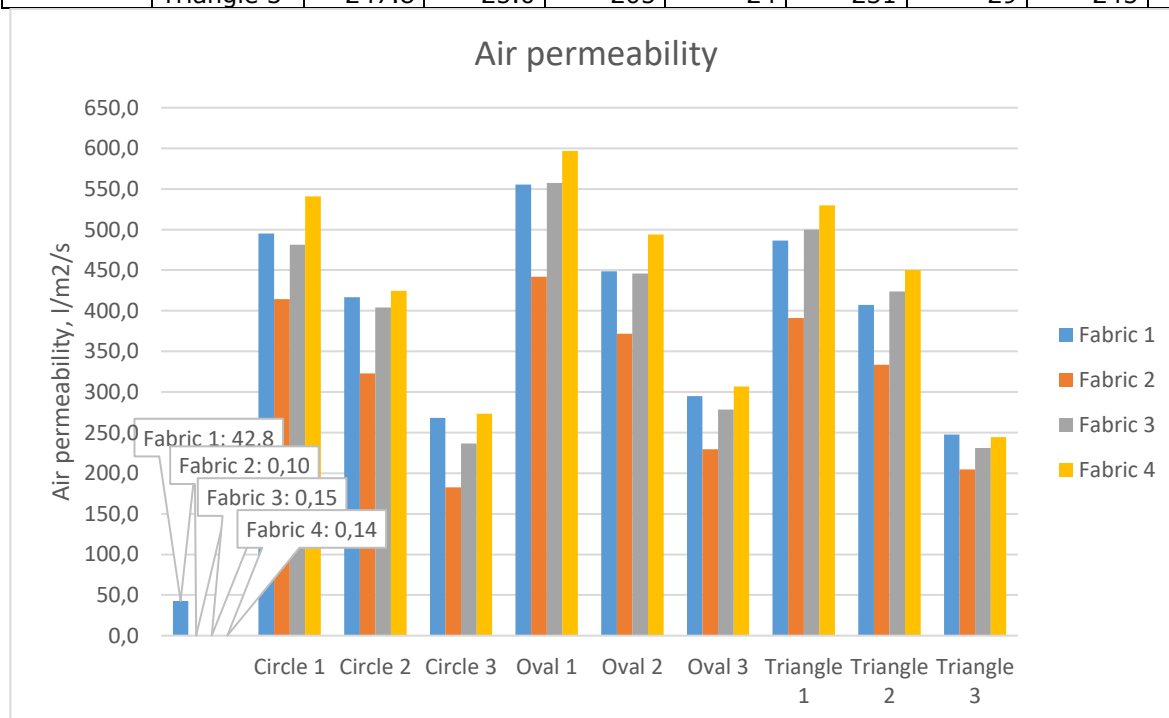
The summarized results are gathered to table 6.3 and graph 6.1. All results are visible in Appendix 7. Based on the results the most air permeable fabric was fabric 1 since it was the only single-layered fabric. The least air permeable was fabric 2, which had the PU coating on the reverse side. From the softshell fabrics, fabric 3 was slightly more air permeable than fabric 4, which was the most lightweight of the two.

Overall, perforated fabrics had multiple times higher air permeability compared to the reference fabric samples. On average the difference of air flow of perforated samples was 217400% higher compared to unperforated samples (table 6.4). From the perforated samples the largest difference on average between the reference fabric was registered for fabric 2. The least difference between unperforated and perforated samples showed fabric 1.

From the cut shapes, the highest value of air permeability was recorded with oval and the minimum result was with triangle perforations. Therefore, elongated circular shapes are more effective in air flow management compared to angular shapes.

Table 6.3 Results of air permeability test. All figures are expressed in units l/m²/s

Test	Fabric 1		Fabric 2		Fabric 3		Fabric 4		
	Average	SD	Average	SD	Average	SD	Average	SD	
Uncut fabric	42.8	1.5	0.10	0.02	0.15	0.01	0.14	0.01	
Perforated fabric	Circle 1	495.3	16.5	414	20	482	32	541	37
	Circle 2	416.7	30.7	323	24	404	25	425	17
	Circle 3	268.1	24.0	183	26	237	41	273	34
	Oval 1	555.3	16.8	442	29	558	37	597	34
	Oval 2	448.7	24.9	372	9	446	11	494	29
	Oval 3	295	25.2	230	23	278	31	307	27
	Triangle 1	486.5	24.1	391	24	500	36	530	22
	Triangle 2	407.2	21.9	334	25	424	35	450	25
	Triangle 3	247.8	25.0	205	24	231	29	245	19



Graph 6.1 Results of air permeability tests

Table 6.4 Average air permeability compared to reference samples. The results express the difference in air permeability in %

Shapes	Air permeability difference, % more			
	Fabric 1	Fabric 2	Fabric 3	Fabric 4
Circle 1	1058%	406973%	312562%	373828%
Circle 2	874%	316992%	262173%	293468%
Circle 3	527%	179271%	153471%	188766%
Oval 1	1198%	434183%	361913%	412556%
Oval 2	949%	365028%	289510%	341601%
Oval 3	590%	225440%	180614%	211933%
Triangle 1	1037%	383888%	324445%	366152%
Triangle 2	852%	327601%	275095%	311311%
Triangle 3	479%	200882%	149965%	168987%

The results showed that perforated fabrics improve the efficiency of air permeability of fabrics multiple times. The choice of perforation shapes, sizes, densities and placement on clothing ultimately depends on the climate and activity. There are no standards that refer to a minimum air permeability value for certain types of active clothing. The values also show results for a certain region that is perforated and do not state the comfort of a whole garment. Testing the properties of textiles provide comparable results, but in the end, do not account for the comfort levels of garments on a human.

6.2.2 Fabric propensity to surface fuzzing and pilling

Based on results from un-perforated fabrics (table 6.5) the best propensity to fuzzing and pilling was recorded with fabric 2 and the worst with fabric 1. Overall the results showed good resistance. Based on the results from perforated fabrics, they indicated half a grade to one grade lower propensity. The samples presented more fuzzing of the surface than pilling. Half of the fabrics started showing signs of fuzz already from the first assessment stage (fabrics 1 and 4).

Table 6.5 Results from measuring fabric propensity to surface fuzzing and pilling

Fabric	Assessment stage	No of rubs	Without perforations	Perforated
			Average grade	Average grade
Fabric 1	1	125	5	5-4
	2	500	5	5-4
	3	1000	5	4
	4	2000	5-4	4
	5	5000	4	4-3
	6	7000	4	4-3

Fabric	Assessment stage	No of rubs	Without perforations	Perforated
			Average grade	Average grade
Fabric 2	1	125	5	5
	2	500	5	5
	3	1000	5	5
	4	2000	5	5
	5	5000	5	5
	6	7000	5	5
Fabric 3	1	125	5	5
	2	500	5	5
	3	1000	5-4	5-4
	4	2000	5-4	5-4
	5	5000	4	4
	6	7000	4	4
Fabric 4	1	125	5	5-4
	2	500	5	5-4
	3	1000	5-4	4
	4	2000	5-4	4
	5	5000	5-4	4-3
	6	7000	5-4	4-3

6.3 Final conclusions and choosing the final fabric for prototype

For the prototype one fabric had to be chosen based on the results. The main tests that aided in that choice was testing the change in properties of laser cut materials, since the choice was already narrowed down for these tests. For making the final choice the fabrics were evaluated based on the following criteria:

- Chosen fabric should have a significant difference of air permeability between cut and uncut samples
- Chosen fabric should have a good propensity to surface fuzzing and pilling when rubbed with laser cut perforations, i.e. maximum half a grade lower result compared to uncut samples

The first requirement would show that the prototype would aid in having perforations for increased air flow, but otherwise has properties that can provide a safe barrier between the body and the elements. The second requirement will testify for the durability of the fabric when rubbed with abrasive laser cut perforations, therefore leading to a long-lasting and high-quality product.

Based on these criteria fabric 2 and 3 showed the best results. Fabric 1 did not show the benefits of perforations and showed little resistance to surface fuzzing. Fabric 4 showed a grade lower resistance to fuzzing. Between fabric 2 and 3 the choice was made for fabric 3 since it had a pleasant to the touch backing and would be suitable for an unlined jacket. Fabric 2 had a PU coated backing and therefore the jacket would benefit from a lining.

7. MAKING THE PROTOTYPE

For developing a softshell sports jacket commercially available products were first reviewed along with outdoor gear reviews. It was gathered that softshell jackets work well for low to moderate intensity activities and low to moderate raining conditions. Therefore, they provide moderate protection from outer elements. Due to stretch properties the products from softshell fabrics are suitable for activities that include movement. Although, it should be noted that various softshell fabrics are available, including those with a fleece reverse side or an additional waterproof membrane, so the more specific properties should be considered for individual fabrics. The overall activities, where a softshell jacket is recommended, were hiking, skiing, mountain climbing and biking. Since softshell fabrics have a soft and pleasant to the touch reverse side, they do not require a lining.



Figure 7.1 Some examples of softshell jackets on the market from left: Marmot, Arc'teryx, Patagonia [59]

The developed sports jacket (figure 7.2) took into consideration the results from previous chapter and also the commercially available product reviews. The result is an unlined softshell jacket that is suitable for light to moderate activities and weather conditions. Since softshell fabrics drape less, then the suggested design is a slim fit silhouette that also takes into consideration space for an extra layer underneath. The jacket has a spacious hood that accommodates a helmet, so to be suitable for activities that require the use of a helmet, such as biking and mountain climbing. For a closer fit and protection from outer elements the hood is adjustable vertically and horizontally: around the opening and across the widest part. The jacket has two zippered pockets on the waist

level, which provide access to storage as well as allow to strap bags on the hips, such as hiking backpacks and climbing hip packs. The jacket includes comfortable raglan sleeves that can be adjusted with a velcro covered flap. For additional comfort the jacket includes perforations under the arm, pocket bag, front placket and inside the hood. The jacket also includes laser cut reflective details on the hood, sleeve flaps and lower back, hood elastic band opening transfers, velcro pieces for sleeve flaps and pocket openings.

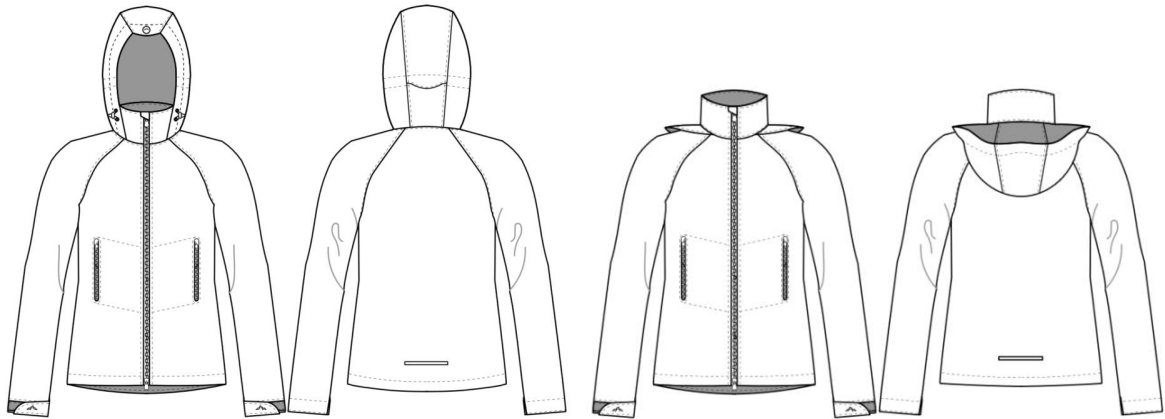


Figure 7.2 The developed sports jacket

7.2 Selection of materials and accessories

All the materials and accessories were sourced from local suppliers that were accessible and reliable during the writing of the thesis. Since the chosen design featured contrast accessories, it was very important to match the contrast colour for all the accessories.

Table 7.2 List of materials



Material	Art	Colour	Weight	Composition	Width	Requirement	Supplier	Care label
Main material	MM001	Blue	200 g/m ²	100% PES +TPU	147 cm	2.33 m	RiiMeTex OÜ	
Transfer fabric	549876XLM	Orange	200 g/m ²	80% PA, 20% EA	150 cm	0.1 m	Karnaluks OÜ	
Interlining	636 851	Grey	39 g/m ²	100% PA	90 cm	0.05 m	Karnaluks OÜ	

Table 7.3 List of accessories

Accessory	Art	Colour	Size	Description	Requirement	Supplier
Binding tape	LAM2	Blue	16 mm	100% PES	6.3 m	Karnaluks OÜ
Reinforcing band	116473	White	10 mm	100% PES	1.7 m	Karnaluks OÜ
Thread	282M	Blue	no 120	100% PES	42 m	A&E Gütermann
	777	Orange	no 120	100% PES	1 m	Coats OÜ
Stopper	UJ62	Orange	23x20 mm	22x20mm, for max Ø4mm cord	5 pcs	Karnaluks OÜ
Elastic cord	2479	Orange	Ø3,5 mm		2.85 m	Karnaluks OÜ
Velcro	119	Orange	25mm	soft+rough sides	0.2 pcs	Karnaluks OÜ
Zipper	2429	Orange	65 cm	6mm, 2 sliders, open-ended	1 pcs	Coats OÜ
	2429	Orange	15 cm	6mm, 1 slider, close ended	2 pcs	Coats OÜ
Transfer paper	H820.U	Orange	90x56 cm	fusible adhesive	0.1 pcs	Karnaluks OÜ
Transfers	033	Reflective	10x20 cm	self-adhesive	0.5 pcs	Karnaluks OÜ

7.3 Construction

The jacket construction was based on a base construction for women's M size slim fitted jacket. The base construction was then altered according to the chosen design. The base construction was plotted and alterations were made by hand. The finalized main pieces (front, back and sleeve) were digitized and imported into Lectra Modaris V8R1 software, where additional pieces were constructed. All the pattern pieces are listed in table 7.4 and visually brought out in figure 7.3.

Table 7.4 List of pattern pieces

No	Piece name	Piece article	Quantity (pcs)	
			Constructed pieces	Required pieces
1	Back	BCK	1	1
2	Front	FRNT	1	2
3	Sleeve	SLV	1	2
4	Pocket bag	PCKT	1	2
5	Pocket zip cover	PCKT-C	1	4
6	Outer collar	CLLR-01	1	1
7	Inner collar	CLLR-02	1	1
8	Front zipper placket	FRNT-PLCK	1	2
9	Sleeve flap	SLV-FLP	1	4
10	Hood outer piece	HD-01	1	2
11	Hood centre piece 1	HD-02	1	1
12	Hood centre piece 2	HD-03	1	1
13	Hood horizontal channel	HD-04	1	1
14	Front bottom edge facing	FRNT-F	1	2
15	Back bottom edge facing	BCK-F	1	1
16	Sleeve bottom edge facing	SLV-F	1	2
17	Hood outer piece facing	HD-01-F	1	2
18	Hood centre piece facing (front)	HD-02-F1	1	1
19	Hood centre piece facing (back)	HD-02-F2	1	1
20	Hanger	HNGR	1	1

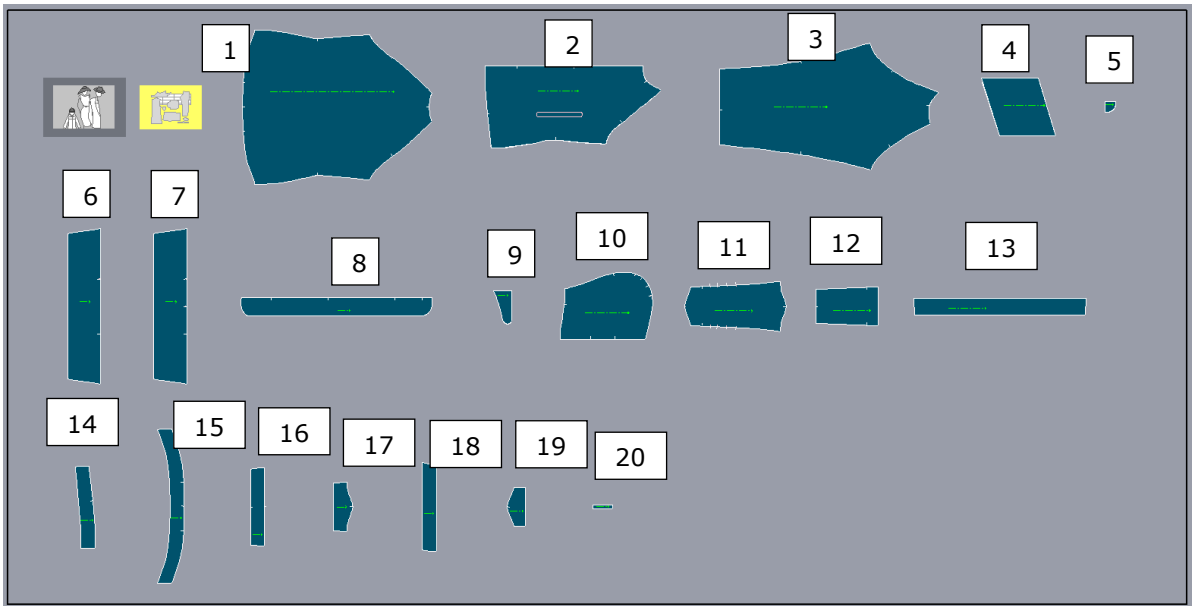


Figure 7.3 Pattern pieces in Lectra Modaris V8R1

7.4 Cutting pieces with a laser cutter

All pattern pieces from main material were cut with the laser cutter in the Laboratory of Polymers and Textile Technology (technical information provided in Appendix 1). This provided an overview of the process of navigating between different software in each production stage. Also, cutting the pieces with perforations allowed for more precise and symmetrical position of perforations since the perforations were cut at the same time as outer contours.

7.4.1 Preparations for cutting

Tests were performed to understand how Lectra files were imported into RDWorks software. Lectra file was exported as a dxf type file that RDWorks software recognizes. It was discovered that seam allowances and notches were not included when files were imported, therefore all pattern pieces with seam allowances had to be modified so that the outer contour would include seam allowance. This procedure is described in detail in Appendix 8. Also, notches were redrawn as lines with the length of 0,5 cm in order to be recognized after conversion. Even though the models were created in Modaris, including the specification of required number of pattern pieces, the pieces were imported as they were visible on the Modaris screen. Thus, this required multiplying the pieces in Modaris and rotating accordingly if symmetrical pieces were

needed. For example, this was done for front and sleeve pieces. This step can also be made directly in RDWorks. For all these pattern piece modifications a separate file and model was created to distinguish files.

The prepared file was then imported into RDWorks. The pieces were placed in a horizontal order: in the direction as they were placed in Modaris, i.e. warp direction was horizontal (figure 7.4). Since the fabric warp direction was vertical on the cutting surface, the pieces were rotated to fit the direction. After this, the grain line was deleted from all pieces, since they were imported as cut lines. The pieces were separated from inner cut lines, such as pocket openings and notches, and therefore required to be grouped with outer contour in order to be moved.

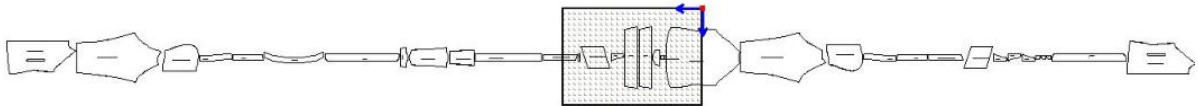


Figure 7.4 Pattern pieces importing into RDWorks

File for perforations and transfers (figure 7.5) was prepared in Adobe Illustrator software and imported in a separate RDWorks cutting file. Openings that would be cut on pieces from main material were selected and copied to the previously prepared file with all jacket pieces. They were then placed in the required locations.

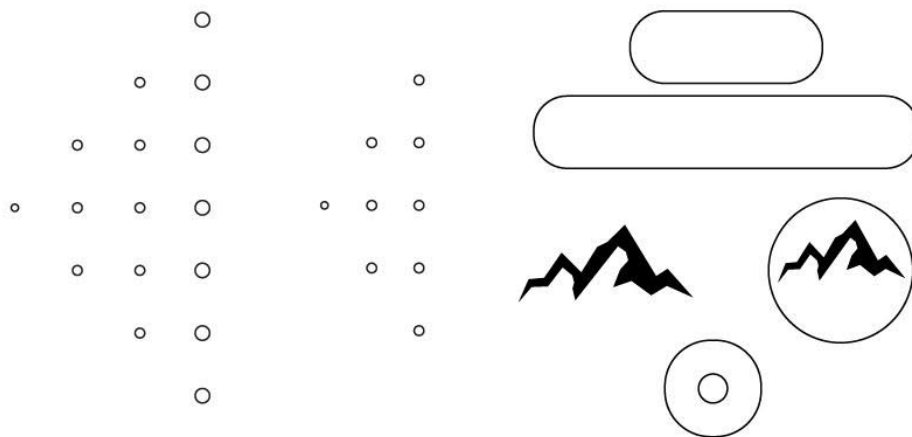


Figure 7.5 Perforations for body (left) and front placket (middle). Shapes for cutting velcro (right up). Shapes for reflective patches (right middle). Shape for elastic band opening reinforcement (right down)

7.4.2 Layouting

Layouts were prepared directly in RDWorks software. The pieces were rotated according to the piece rules and moved in a way that would result in high fabric utilization. The limitations of the cutting surface size were taken into consideration. This resulted in three separate layouts for all the pieces to be cut for one jacket (table 7.5, figure 7.6-7.8). The efficiency of the prepared layouts was calculated based on the width of the fabric and length of the layout and the area of the pieces on that particular layout.

Table 7.5 Comparison of prepared layouts

Layout	Width of fabric, cm	Width of layout, cm	Length, cm	Area of fabric, cm ²	Area of all placed pieces, cm ²	Efficiency, %
Layout 1	130	121.5	83.6	10868	8151.79	75
Layout 2	130	116.2	80.1	10413	6959.25	67
Layout 3	130	102.3	62.4	8112	2622.16	32

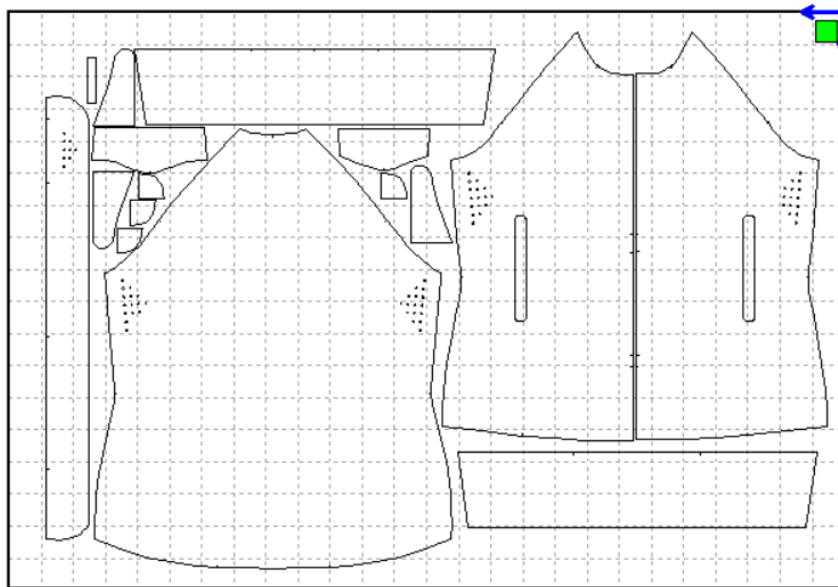


Figure 7.6 Layout 1

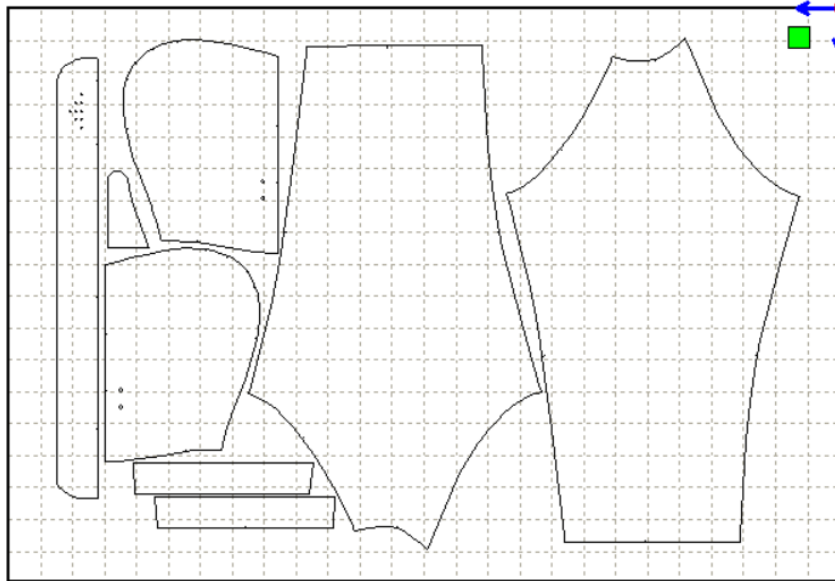


Figure 7.7 Layout 2

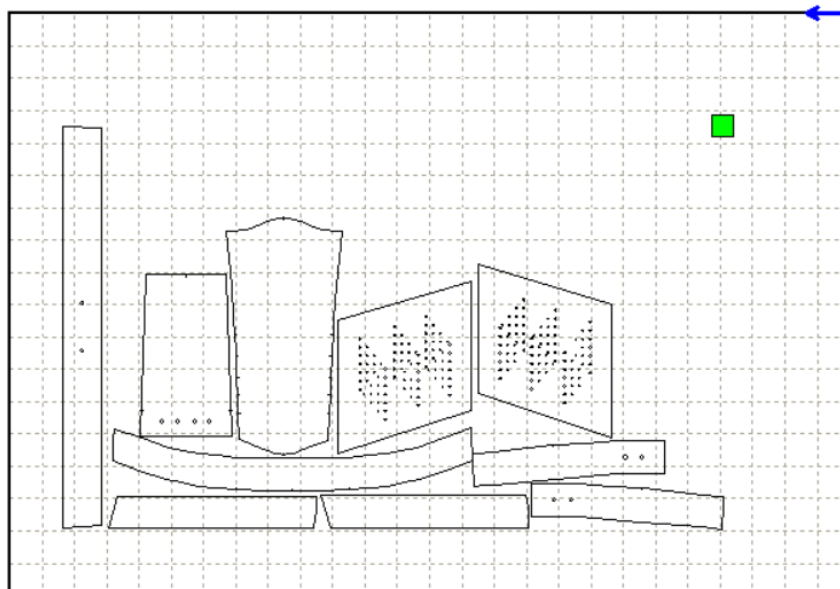


Figure 7.8 Layout 3. This layout was moved to the left corner since there was a defect in the fabric on the right side

7.4.3 Cutting

Due to the size of the cutting surface on the laser cutter, the fabric had to be cut narrower. This was done manually. The fabric was placed on the cutting surface by hand as the specific laser cutter did not have a fabric feeder (figure 7.9). The surface was smoothed to prevent pattern pieces deformation and uneven cutting outcome resulted by fabric creases. The grain line was checked by following the honeycomb pattern on the cutting board.

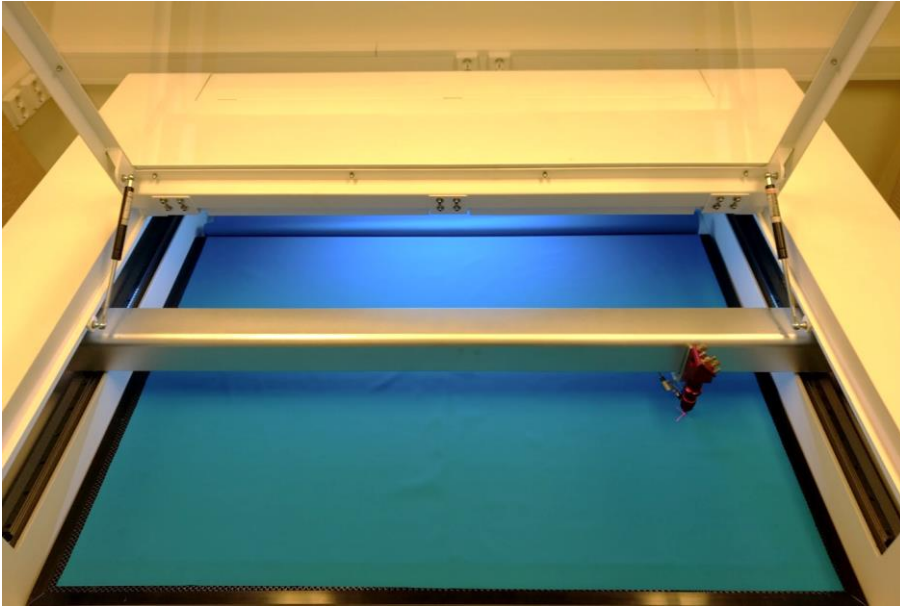


Figure 7.9 Placement of the fabric. The excessive fabric was stored in the back of the laser cutter behind the honeycomb surface. After the fabric was set up the focal length was fixed

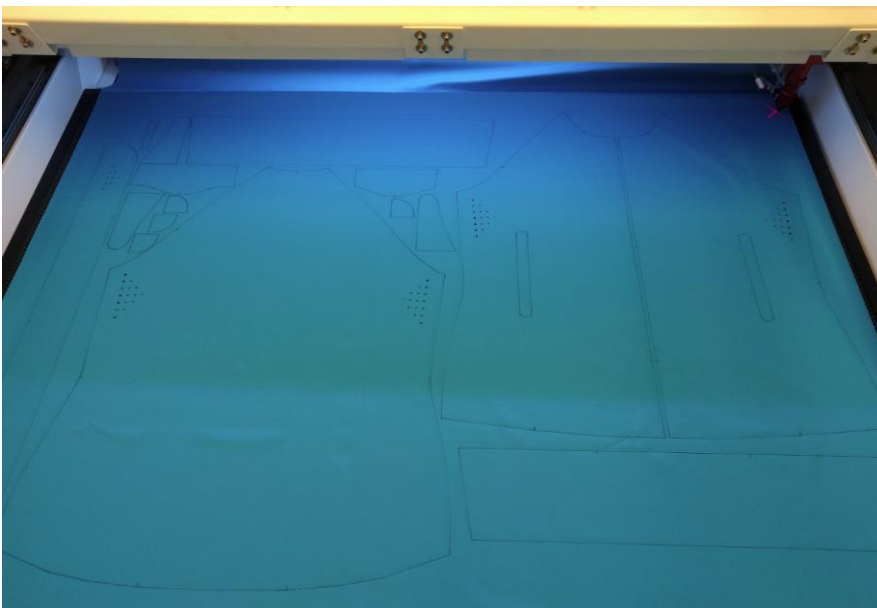


Figure 7.10 Layout 1 cut on fabric

After each layout was cut the pieces were removed from the cutting surface manually. After cutting the main fabric, material for accessories was cut. All cutting parameters are shown in table 7.6.

Table 7.6 Cutting parameters that were used for the prototype for all materials

Material	Cutting parameters	Comments
Main material	400 mm/s, 40 W	Cut in 1-layer, right sides up
Reflective transfer	250 mm/s, 30 W	Cut in 1-layer, right sides down
Fabric transfer	200 mm/s, 60 W	Cut in 1-layer, right sides up
Velcro	100 mm/s, 50 W	Cut in 1 layer, rough and soft sides up

7.5 First prototype

The prepared construction and sewing technology were first checked on a prototype (figure 7.11). For the prototype, the same fabric and accessories were used that were meant to be used for the final product. The aim was to see how the fabric cutting process would look, how the accessories suit for their purpose and to make corrections if necessary.



Figure 7.11 Technical drawing (left) of the first prototype and finished prototype (right)

Based on the prototype corrections in construction and choice of accessories were done.

- Fit: the construction was changed to a slimmer fit to eliminate fabric bulking around the arm.
- Front placket: was made wider to make the perforations more functional.
- Front pockets: the pocket zipper openings were moved higher and made wider to accommodate wide zipper slider, the zipper placket was changed to a zipper cover for a more practical use of the pocket.
- Collar: the collar width was reduced for a closer fit around the neck.

- Hood: the hood elastic band was attached to the edge of hood centre piece for the hood beak piece to have a correct appearance, the hood centre piece was made longer in the back to hide the elastic band and for safety in forests where the visible elastic band loop could potentially get caught on a branch, the locations of openings for elastic band were moved.
- Sleeve: the sleeve flap shape was changed and seam allowance was added to cover the raw edge.
- Material: for the accessories the elastic band opening transfers were changed to more durable ones. Due to low availability, the transfers were prepared with laminating a fabric with an iron-on adhesive paper.

7.6 Second prototype

Sewing technology and specifications are presented in Appendix 9. The second prototype is shown in figure 7.12. The changes in both construction and accessories choice resulted in a more practical jacket. The user comfort level and the practicality of design choices would come out during wearing trials in the environment and activities it was designed for. But the first feedback was gathered with gear that the jacket was assumed to be used with: a helmet and backpack (images in Appendix 10). The helmet successfully fit under the hood and the backpack hip straps did not interfere during the use of the pockets. Additional images of the jacket are provided in Appendix 10.



Figure 7.12 The second prototype

8. DISCUSSION AND CONCLUSION

8.1 Design and function

The result is a fun and unique design that has a large variety of possible colour combinations. The design offers possibilities to change colour combinations based on season and trends, while leaving the overall construction and fit of the jacket the same.

It would require wear tests to see the efficiency of the perforations to make final conclusions about how beneficial the laser cutting technology is for developing unique and comfortable designs. Also, additional tests to study the longevity of the elastic band opening transfers compared to metal eyelets would be required to compare costs.

The wear tests could also provide feedback about the function of the design. The most beneficial feedback could be gathered from those active in the fields where the jacket is intended, including mountain climbers and hikers. Wear tests should be conducted in various weather conditions, the most marginal of which is rain and wind. It would give an overview of how well the seams function as a barrier between the body and natural elements.

8.2 Pattern preparation

For cutting pieces out with a laser cutter required extra steps: the seam allowances were switched with seam lines, notches were made as lines, pieces were duplicated and rotated when symmetrical or multiple pieces were required. After importing the pattern pieces the grain lines had to be deleted, outer lines grouped with notches and other inner lines, the pieces required rotation to align to the grain line on the cutting board. The perforations and other openings were prepared separately and placed on the correct position. These holes could have also been added to pieces in Modaris, which could result in a more precise position, since RDWorks is a relatively simple program and provides inadequate tools to position an object.

8.3 Layouting

The layouts prepared directly in RDWorks software did not result in efficient use of fabric. The highest efficiency was 75% and lowest 32%. Although the latter layout included the

final unplaced pieces and it was done so that the fabric defects would be avoided. For the cutting of one jacket 3 separate layouts were required. This resulted in unused fabric that was between the three layouts. With a continuous layout this fabric could have been utilised. Also, during layouting it was necessary to keep in mind the rules of how the pieces were allowed to be rotated. In a layouting software these layouting rules would have been applied automatically.

The layout could be made as close nested as possible thanks to the precision and small diameter of the laser beam. This was especially helpful in the placement of small details. Although, this advantage could not be utilised to full potential as many pieces were on the larger scale and irregularly shaped.

Using a laser cutter for cutting large pattern pieces requires fabric with width equal or smaller than the width of the cutting surface. Also, an automatic feeding system would allow for more effective workflow.

8.4 Production

The practical work observed the product development of a single prototype jacket. For production the need for all the same steps should be reevaluated. This includes cutting out all pieces of the product. In this particular example, all the pieces do not benefit from laser cutting since the edges are mostly covered with a binding tape or facing. Therefore, cutting could be done with an automated cutter if that is available. It would also lessen cutting time and pattern preparation time (modifying pieces and converting files from CAD/CAM software to laser cutter software).

The pieces with openings or perforations are those that would require additional cutting with a laser cutter. This proposes questions regarding precise positioning of the laser cut openings on previously cut pieces. This could be solved with premade templates that have the piece outer lines cut out and the cutting start point defined (figure 8.1). The perforated piece would then be placed between the cut lines and the laser is positioned to the start point according to the visible laser beam (X). In the settings the piece outer line is set as 0% power and maximum speed and perforations are given standard settings based on the cut fabric.

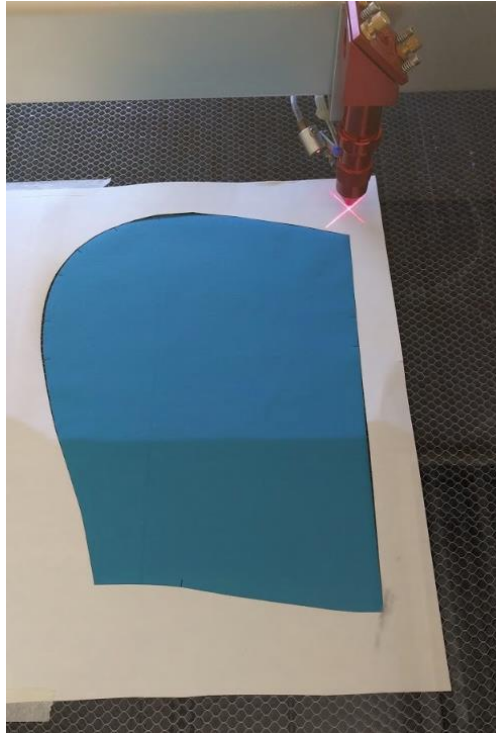


Figure 8.1 An example of how laser start could be positioned on premade cut pieces for precise positioning of perforations. In this example the template is cut from paper

8.5 Investment

One of the most important factors in investing in new technology is whether and when it will pay off. Laser cutting technology is quite a specific technology in regards to its applications. Based on its function it is often compared to conventional cutting tools, especially to automated cutters. The examples of some applications mentioned in previous chapters can testify that a laser cutter can be used for interesting designs and intricate technological solutions and should not be regarded as an alternative to automated cutters. In more advanced laser cutters, for example those with a camera module or two-part system, they show competition by reducing the need for additional software and production preparation time. For example, in the case of cutting sublimation printed fabrics. So, the choice between investing or not depends on the specific company's portfolio, also how much in-house product development is done and whether laser cutting services can be sourced locally.

SUMMARY

Laser cutting is a technology that uses high-powered beam to cut material based on computer-controlled parameters. The application of laser cutting technology in the textile and garment industry can result in personalized and unique products, which can give an advantage in a high competition market. In the example of sportswear, it can be used for either cutting whole pieces when the edges require sealing, cutting perforations for increased air flow in active garments, cutting decorations, accessories and openings for increased function and visual appeal.

The main challenges with this technology are low utilisation and high production costs, in the case where it is viewed simply as an alternative to automated cutters. The choice between investing or not depends on the specific company's portfolio, also how much in-house product development is done and whether laser cutting services can be sourced locally.

The aim of the Master's thesis was to study how laser cutting technology can change the properties and quality of textile materials and be implemented in product development. This was studied in the example of a sports jacket. A jacket was chosen since it consists of many elements where laser cutting technology can be applied.

For studying how properties and quality of textile materials change, 15 different textiles that are common for sportswear were cut and suitable parameters were suggested. They were compiled into a reference table for future student projects. The practical work concluded that the most influential properties that affect the cutting result are fabrics composition and thickness. The properties that had less influence was fabric structure, i.e. weave type. Based on those results, 4 textiles, which represented the averages of the 12 woven fabrics, were chosen to test air permeability and abrasion resistance. These tests showed that laser cut perforations increase air flow several times. Laser cut perforations showed slight surface fuzzing when rubbed. These results showed comparable values for perforated regions and therefore would benefit from wear tests to determine garment overall comfort and function.

The finalized prototype was a softshell jacket that can be used for hiking, climbing, skiing, bicycling, etc, in low to moderate weather conditions. The jacket allows for additional equipment that could be required for those types of activities, such as a helmet or a bag. The laser cut elements included underarm, pocket bag, hood and front

placket perforations, openings for zippers and elastic bands. Also, reflective decorations and transfers were cut.

The product development process included base pattern modification, developing technological sheets, preparation of cutting files, cutting all pattern pieces on a laser cutter and sewing two prototypes. Going through all the steps gave an overview of challenges of each process that would not arise during conventional product development (from choice of materials to CAD/CAM software and automated cutters). The thesis offered solutions to these challenges.

The thesis work could continue in more research in implementation of laser cutter into the cutting department, determination of price for production and research into mass production opportunities. Also, since this thesis put more emphasis on woven fabrics, research into how properties change for knitted fabrics could propose opportunities for further research. For example, how knitted fabrics react to cyclical stretching with perforations in locations where high stretch and recovery is required.

KOKKUVÕTE

Laserlõikus on tehnoloogia, mis kasutab materjalide lõikamiseks suure võimsusega laserkiirt. Laserlõikustehnoloogia võimaldab rõiva- ja tekstiilitööstuses disainida ning toota ainulaadseid ja isikupäraseid tooteid, mis omakorda annab konkurentsieelise. Spordirõivaste näitel saab laserlõikurit kasutada tervete detailide lõikamiseks, et ära hoida lõikeservade hargnemist; perforeerimiseks, et suurendada õhuläbilaskvust; tasku- ja kummipaelaavade lõikamiseks; logode, helkurdetailide ja muude dekoratsioonide lõikamiseks, et suurendada rõiva funktsionaalsust ja luua eristatavat disaini.

Laserlõikustehnoloogia kasutamisega seotud väljakutsed on selle vähene rakendamine ja kõrged tootmiskulud. Seda juhul, kui laserlõikurit vaadeldakse alternatiivina automaatlõikuritele. Investeering laserlõikustehnoloogiasse sõltub suuresti sellest, milline on ettevõtte poolt toodetavate toodete nomenklatuur, kui palju viiakse läbi tootearendust ettevõtte siseselt ja kas laserlõikuse teenust saab sisse osta lähedal asuvatest ettevõtetest.

Magistritöö eesmärk oli uurida, kuidas muudab laserlõikustehnoloogia tekstiilmaterjalide omadusi ja kvaliteeti ning milliseid võimalusi pakub see tootearendusprotsessis. Teemat uuriti spordijope näitel. Antud toode valiti seetõttu, et jope koosneb üldjuhul paljudest elementidest, mille puhul saab rakendada laserlõikustehnoloogiat.

Et uurida muutuseid tekstiilmaterjalide omadustes ja kvaliteedis, katsetati laserlõikust 15 erineva spordirõivasteks kasutatavat materjali juures. Valitud materjalide lõikamiseks soovitati sobilikud parameetrid. Tulemused koondati tabelisse, mida saab võtta aluseks järgnevate projektide puhul. Praktilises töös jõuti järeldusele, et kõige enam mõjutavad lõikamise tulemusi kanga koostis ja paksus. Vähem mõju avaldab kanga omadus oli kanga struktuur. Nende tulemuste põhjal valiti välja 4 kangast, mille puhul katsetati täiendavalt laserlõikuri abil perforeeritud avauste mõju materjali õhuläbilaskvusele ning kanga vastupidavust perforeeringute hõõrdumisele. Valitud kangaste omadused esindasid valimi keskmisi. Õhuläbilaskvuse katsed näitasid, et perforeeringud suurendavad kangaste õhuläbilaskvust kuni mitu tuhat korda. Kõige efektiivsemad sealjuures on ovaalsed ja vähem efektiivsed nurgelised perforeeringud. Tulemused väljendasid perforeeritud piirkondade õhuläbilaskvuse väärtuseid ja seetõttu oleksid rõivaste üldise mugavuse ja funktsiooni hindamiseks abiks ka kandmistestid.

Kangaste hõõrdumisel laserlõigatud perforeeringutega näitasid tulemused, et kare sulatatud serv tekitab mõningal määral karvastatud pinna.

Magistritöö käigus valmis *softshell* materjalist jope prototüüp, mida saab kasutada matkamisel, mägironimisel, jalgrattaga sõitmisel ja muudel tegevustel mõõdukate ilmastikutingimustega, st mõõduka vihma ja tuulega. Jope võimaldab selliste harrastuste puhul ka varustuse kasutamist, sh kiivrit, selja- ja puusakotti. Laserlõigatud elemendid olid perforeeringud kaenla all, taskukotil, kapuutsil ja esiliistul, lukuavad ja kummipaela avad. Samuti olid laseriga lõigatud helkurtransfeerid ja kummipaela avade transfeerid.

Tootearendusprotsess hõlmas jaki baaskonstruksiooni modelleerimist valitud disaini põhjal, tehnoloogia ja spetsifikatsioonilehtede välja töötamist, perforeeringute ja kaunistusdetailide lõikefailide ettevalmistamist, detailide paigutamist laserlõikuri tarkvaras ja detailide väljalõikamist laserlõikuriga ning kahe prototüübi õmblemist. Tootearendusprotsess andis ülevaate iga etapi väljakutsetest. Lõputöös pakuti nendele väljakutsetele lahendusi.

Uurimustööd võib jätkata põhjalikuma ülevaatega laserlõikustehnoloogia juurutamise protsessist juurdelõikusosakonnas, tootmise hinna määratlemisest ja masstootmise võimaluste uurimisest. Kuna lõputöö pani rõhku riide omaduste uurimisele, siis uurimistööd saab jätkata ka sellega, kuidas laserlõikustehnoloogia mõjutab trikotaaž kangaste omadusi ja kvaliteeti. Näiteks, kuidas peavad trikotaažkangas olevad perforeeringud vastu tsüklilisele venitamisele. Seda just eriti piirkondades, kus toodet ja kangast aktiivse tegevuse käigus pidevalt venitatakse.

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APPENDICES

Appendix 1 Technical information of laser cutter

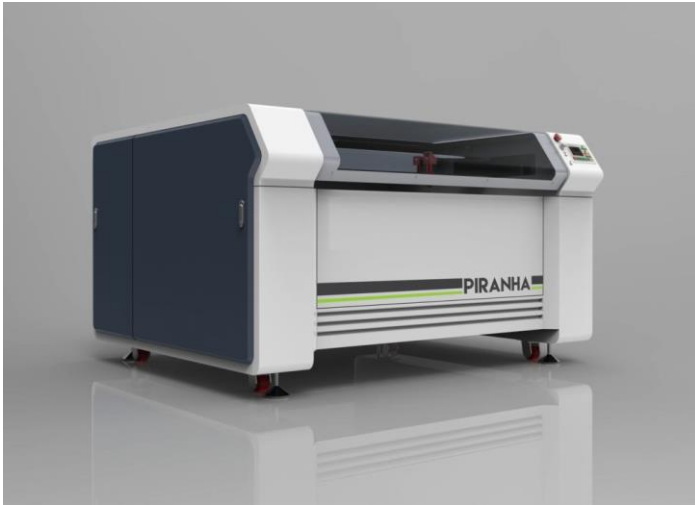


Figure 0.1 Piranha LMP9001300 laser cutter [11]

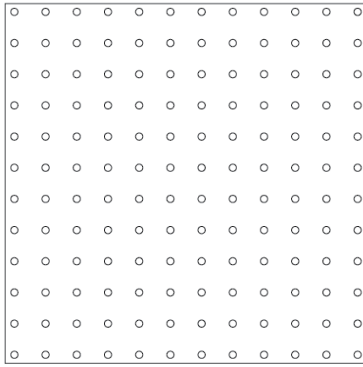
Table 0.1 Technical information regarding the Laboratory of Polymers and Textile Technology laser cutter [11]

Laser power	100 W
Amplifying medium	CO ₂
Work area size	1300 x 900 mm
Z-axis height	400 mm
Laser accuracy	±0.05 mm
Focal length	8 mm
Maximum speed	60 000 mm/min
Preciseness of engraving	4000 dpi
Min diameter of laser beam	0.2 mm
Positioning	Red laser beam
Work voltage	240 V
Weight	360 kg
Ventilation system	Integrated
Gas	Compressed air
Cooling system	CW5A cooling system
Work surface	Ribbed + honeycomb metal sheet
Software	RDWorks
Safety	2 pairs of glasses, temperature sensor

Extra	Wipes for lens maintenance, Wi-Fi module
Suitable materials for cutting	Paper, acrylic, plywood, MDF, wood, leather, felt, fabric, PC, ABS, rubber
Suitable materials for engraving	Paper, acrylic, plywood, MDF, wood, leather, felt, fabric, plastics, ABS, rubber, coloured metal, glass, marmor, granite, ceramic (only with paste)
Not suitable materials for cutting	Metals, PVC

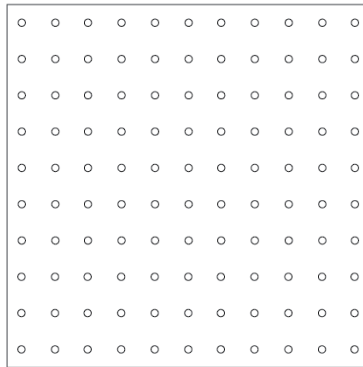
Appendix 2 Cutting files for testing air permeability

The images are sorted from most perforated (left) to least perforated (right).



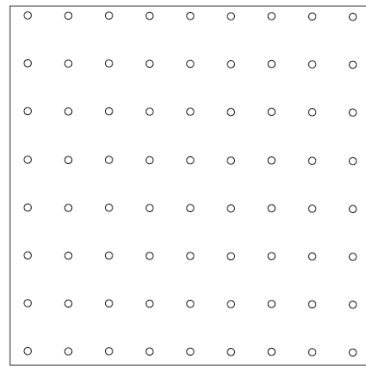
Circle 1

Perforated area: 4.5%



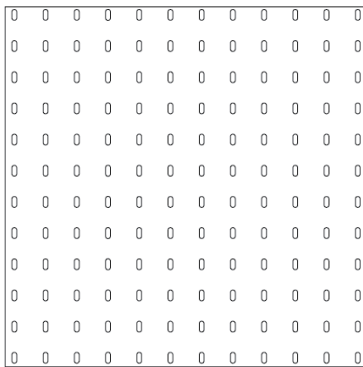
Circle 2

Perforated area: 3.5%



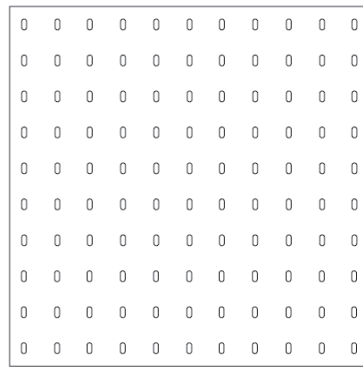
Circle 3

Perforated area: 2.3%



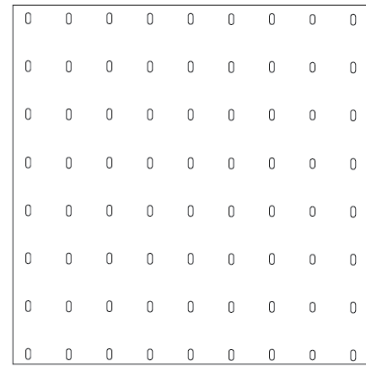
Oval 1

Perforated area: 4.5%



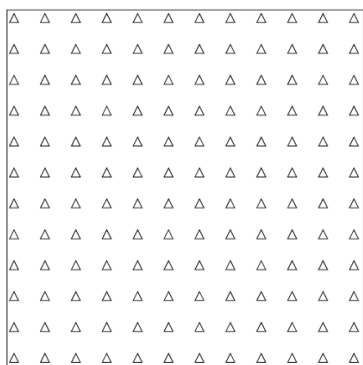
Oval 2

Perforated area: 3.5%



Oval 3

Perforated area: 2.3%



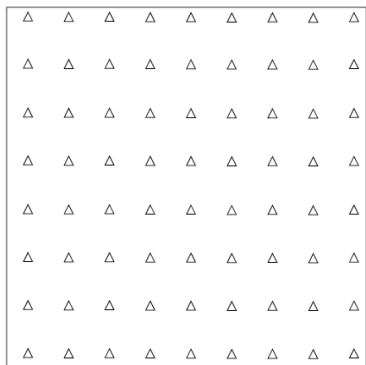
Triangle 1

Perforated area: 4.5%



Triangle 2

Perforated area: 3.5%



Triangle 3

Perforated area: 2.3%

Appendix 3 Calculations for shape area for air permeability tests

Following will be explanation of how the area of the chosen perforation shapes was calculated

Circle area:

$$S = \pi r^2,$$

where r – circle radius

$$r = 1.5 \text{ mm}$$

$$S = \pi \cdot 1.5^2 = 7.07 \text{ mm}^2$$

Oval area:

$$S = \pi \cdot a \cdot b,$$

where a – length of longer half-axis

b – length of shorter half-axis

$$a = 2.25 \text{ mm}$$

$$b = 1 \text{ mm}$$

$$S = \pi \cdot 4.5 \cdot 2 = 7.07 \text{ mm}^2$$

Triangle area:

$$S = \frac{b \cdot h}{2},$$

where b – base

h – height

$$b = h = 3.76 \text{ mm}$$

$$S = \frac{3.76^2}{2} = 7.07 \text{ mm}^2$$

Appendix 4 Folder containing all samples from testing air permeability

Appendix 4 is added to the thesis in a separate form.

**Appendix 5 Folder containing all samples from laser cutting sportswear
textile materials**

Appendix 5 is added to the thesis in a separate form.

Appendix 6 Suggested laser cutting parameters for textiles

Structure	Fabric	20 W		30 W		40 W		50 W		60 W	
		Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s
Knitted fabric	86% PA, 14% EA, 145 g/m ²	50	50	75	150	150	250	200	300	225	350
	82% PA, 18% EA, 190 g/m ²	50	50	75	100	80	100	125	200	150	300
	75% PA, 25% EA, 225 g/m ²	25	50	50	50	75	100	120	150	175	200
Woven fabric	100% PA, 85 g/m ² , water and soil repellent (Scotchgard)	150	200	550	600	-	-	-	-	-	-
	76% PA, 24% PU, 85 g/m ² , waterproof, breathable, water and soil repellent	150	225	500	700*	-	-	-	-	-	-
	75% PA, 24% PU, 1 carbon, 85 g/m ²	100	200	400	675*	500	625*	-	-	-	-
	72% PES, 28% PA66, 110 g/m ² , water and soil repellent (Scotchgard)	100	125	400	425	450	600*	-	-	-	-
	100% PES, 115 g/m ² , micropolyester	100	225	400	600*	500	625*	-	-	-	-
	100% PES, 125 g/m ² , micropolyester	100	200	400	500	500	600*	-	-	-	-
	92% PES, 8% PU, 130 g/m ² , waterproof, breathable, water and soil repellent	100	150	400	500	500	650	-	-	-	-

Structure	Fabric	20 W		30 W		40 W		50 W		60 W	
		Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s	Optim speed mm/s	Max speed mm/s
Woven fabric	47% PU, 53% PA, 150 g/m ² , waterproof	50	150	250	500*	350	650*	-	-	-	-
	100% PES+TPU (thermoplastic polyurethane), 200 g/m ² , softshell with webbing backing, waterproof, windproof, breathable,	25*	50*	350*	400*	400*	500*	-	-	-	-
	82% PA, 18% PU, 220 g/m ² , waterproof, breathable, water and soil repellent	50	75	100	150	400	425	450*	600*	-	-
	76% PES, 24% PU, 230 g/m ² , waterproof, breathable, water and soil repellent	50	100	200	350	400	650*	500*	700*	-	-
	100% PES+TPU, 310-335 g/m ² , softshell with fleece backing, waterproof, windproof, breathable	25*	50*	200*	250*	300*	500*	350*	500*	-	-

Appendix 7 Results of air permeability test

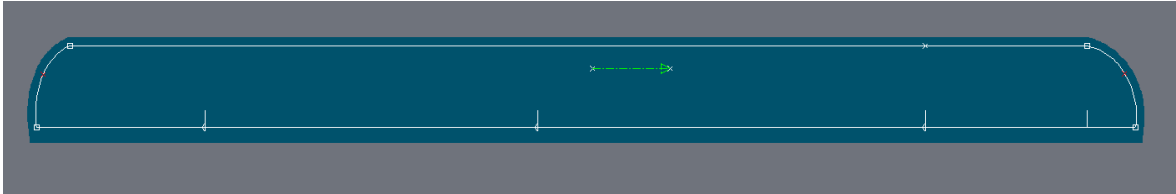
Fabric	Test	Air permeability of uncut fabric, l/m ² /s	Air permeability of perforated fabric, l/m ² /s								
			Circle 1	Circle 2	Circle 3	Oval 1	Oval 2	Oval 3	Triangle 1	Triangle 2	Triangle 3
Fabric 1	1	42.20	469	426	252	588	422	336	502	396	260
	2	40.70	509	473	254	561	513	243	437	415	295
	3	43.20	465	450	297	564	456	273	494	388	213
	4	42.80	476	387	268	541	429	299	497	466	267
	5	40.60	507	395	272	575	470	308	496	386	250
	6	43.00	503	461	296	539	449	302	522	411	279
	7	42.50	500	408	295	556	419	308	487	392	215
	8	42.10	515	400	209	531	445	307	506	403	223
	9	45.50	510	391	264	535	435	260	479	391	244
	10	45.20	499	376	274	563	449	314	445	424	232
		Average	42.8	495	417	268	555	449	295	487	407
	SD	1.5	17	31	24	17	25	25	24	22	25
Fabric 2	1	0.120	426	397	219	424	366	180	411	343	220
	2	0.119	419	311	214	397	366	232	366	305	232
	3	0.137	418	322	177	480	381	243	391	331	196
	4	0.096	417	310	150	475	375	224	415	361	195
	5	0.103	429	327	148	445	366	212	360	399	229
	6	0.076	367	313	169	393	376	254	423	316	211
	7	0.103	430	309	203	458	359	240	365	323	206
	8	0.086	429	314	221	475	383	268	411	327	203
	9	0.102	428	317	161	456	385	238	355	309	137
	10	0.076	381	308	164	418	360	205	412	322	217
		Average	0.10	414	323	183	442	372	230	391	334
	SD	0.02	20	24	26	29	9	23	24	25	24

Fabric	Test	Air permeability of uncut fabric, l/m ² /s	Air permeability of perforated fabric, l/m ² /s								
			Circle 1	Circle 2	Circle 3	Oval 1	Oval 2	Oval 3	Triangle 1	Triangle 2	Triangle 3
Fabric 3	1	0.152	444	379	246	609	445	291	465	391	261
	2	0.132	437	387	178	590	438	289	528	387	242
	3	0.153	498	384	237	578	433	320	470	438	277
	4	0.145	512	410	169	489	460	217	523	403	261
	5	0.148	514	443	278	511	444	226	528	487	191
	6	0.157	510	401	265	544	467	298	551	381	257
	7	0.165	499	391	266	570	455	297	521	435	208
	8	0.167	516	455	285	584	432	271	466	481	195
	9	0.164	452	373	175	586	432	260	426	398	197
	10	0.157	433	416	266	514	454	314	520	437	222
		Average	0.15	482	404	237	558	446	278	500	424
	SD	0.01	32	25	41	37	11	31	36	35	29
Fabric 4	1	0.155	538	442	315	562	487	318	526	440	244
	2	0.147	590	451	290	628	455	314	548	483	250
	3	0.157	573	420	305	630	497	239	515	433	263
	4	0.169	552	423	289	566	471	340	533	455	233
	5	0.160	458	416	278	568	466	266	561	491	272
	6	0.151	500	456	240	629	476	316	568	433	247
	7	0.124	574	413	182	569	514	323	531	413	269
	8	0.131	505	411	280	543	518	320	505	433	203
	9	0.129	552	410	278	644	493	322	490	436	231
	10	0.123	565	403	274	628	564	308	519	486	233
		Average	0.14	541	425	273	597	494	307	530	450
	SD	0.01	37	17	34	34	29	27	22	25	19

Appendix 8 Modification of patterns in Lectra Modaris for laser cutting

The process is described using the front placket piece:

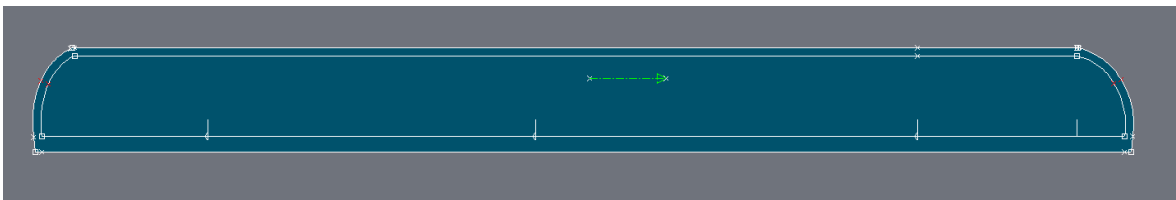
1. The seam allowances are added to the piece



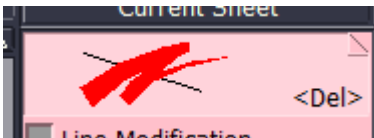
2. The seam allowance is made visible with the function "Generate the piece cut"
(function icon below)



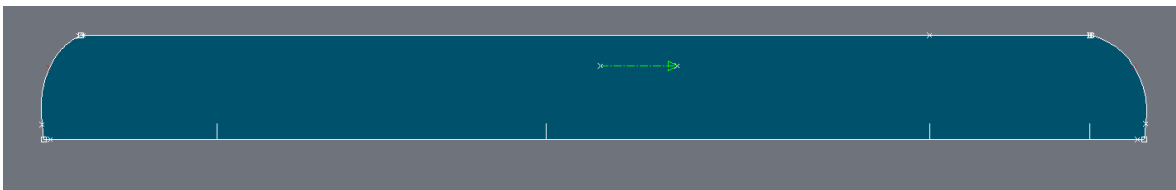
Result:



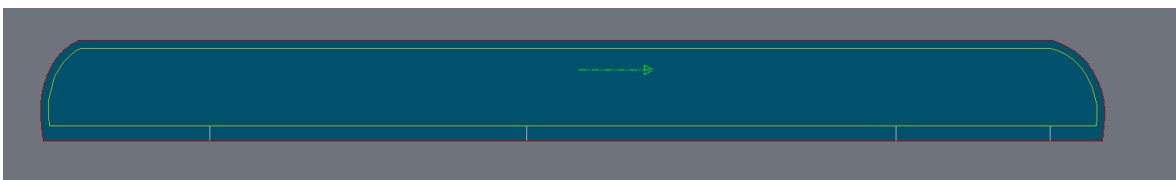
3. The seam line is then deleted (function icon below)



Result:



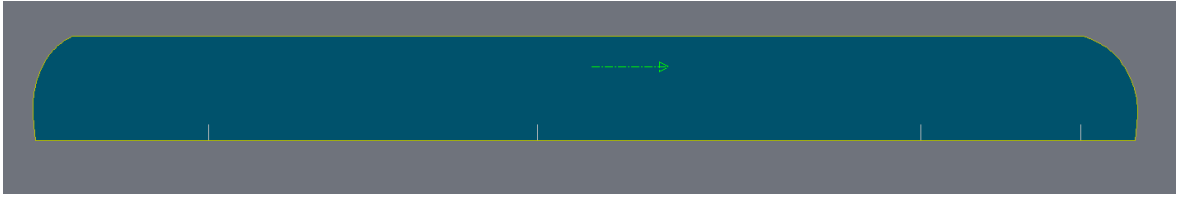
Control: When visualized the cut piece, it is seen that the seam allowance is still recognized



4. The seam allowance is deleted (function icon below)












Result (cut piece visualized):



Appendix 9 Sewing technology

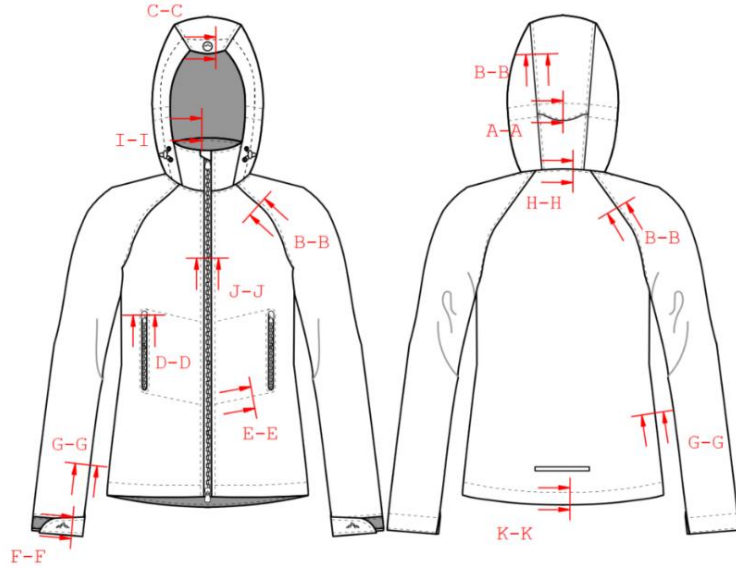
A9.1 Explanation of sewing technology cross-section symbols

Symbol	Explanation
	Main material
	Reinforcing band
	Binding tape
	Elastic band
	Interlining
	Continuing fabric
	Fabric right side
	Zipper
	Basic (joint) seam

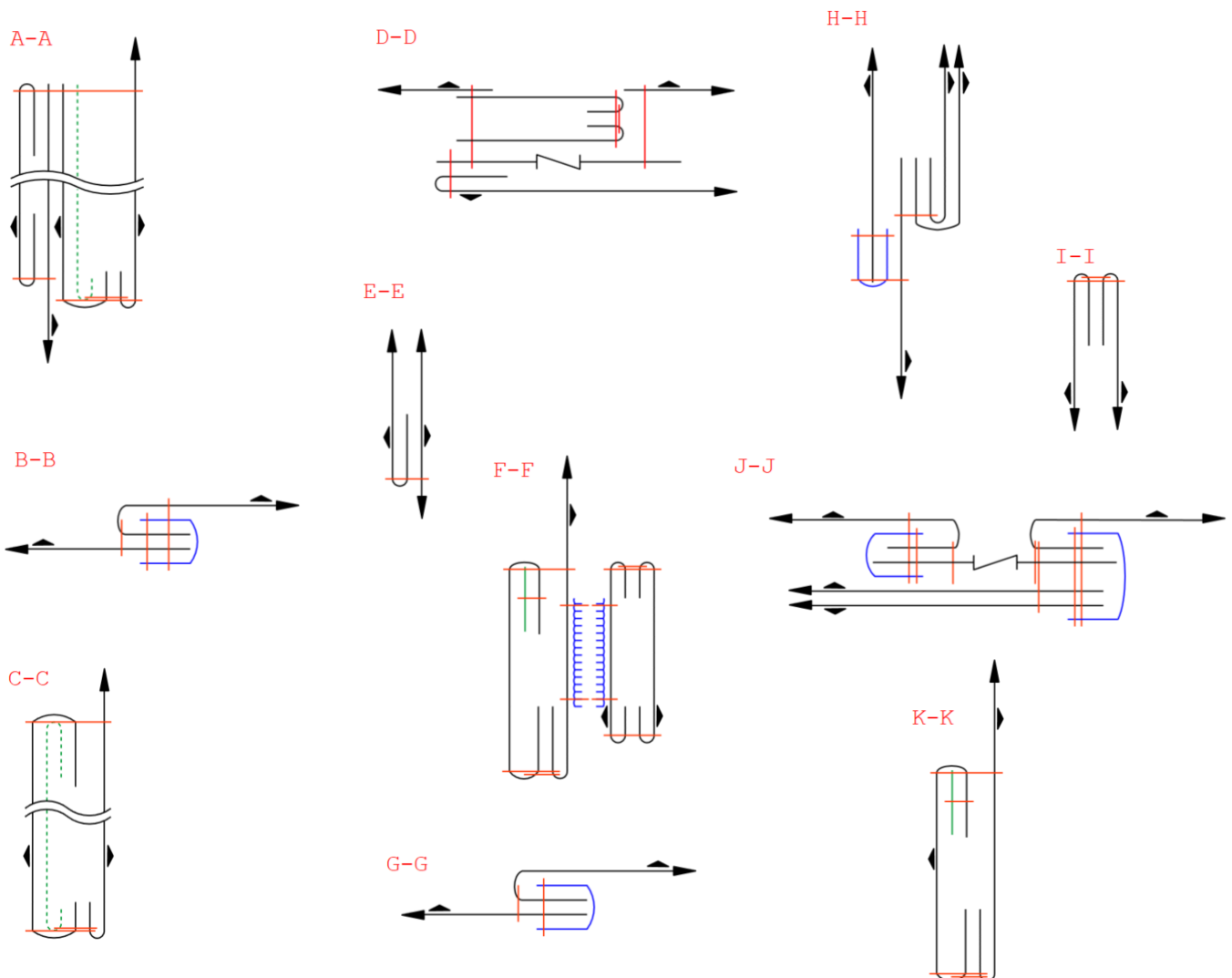
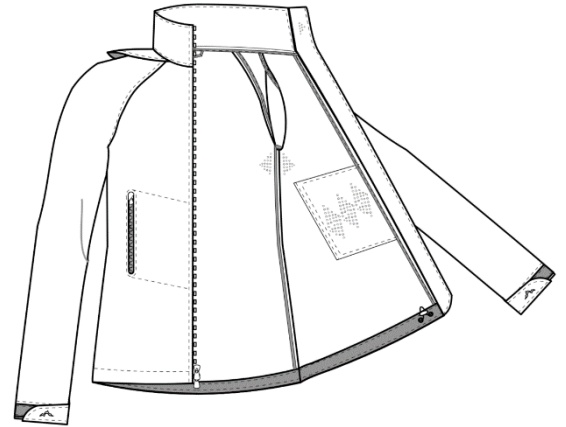
A9.2 Technical specification

Model no	Description	Season
AW-001	Women's softshell jacket	AW20

Front and back view:

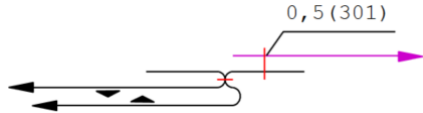
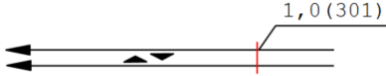
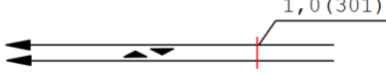
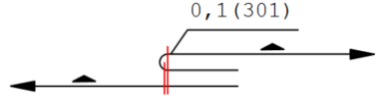
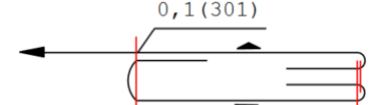

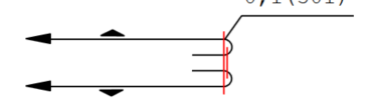
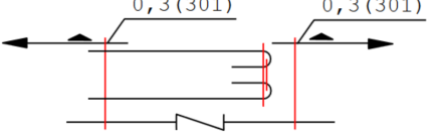
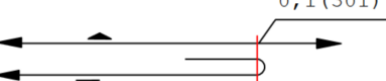
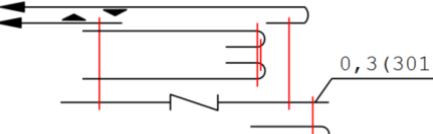
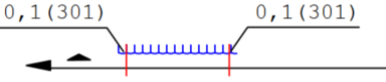


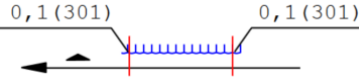
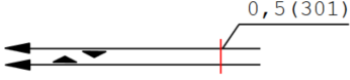
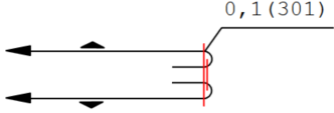

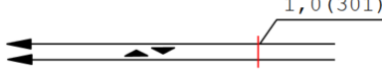
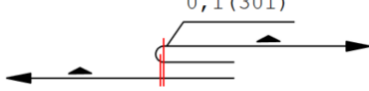


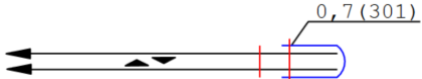
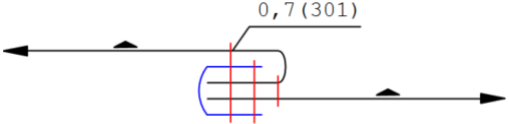
Inside view:


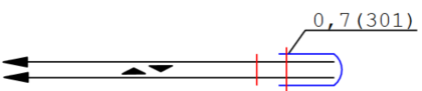

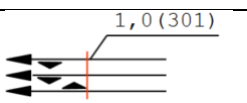
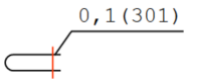
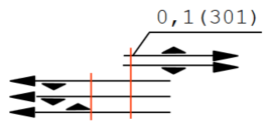

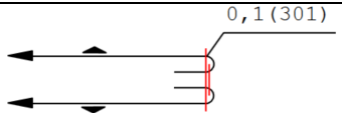
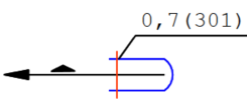

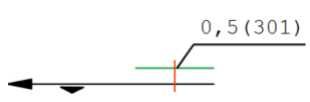



A9.3 Sewing technology

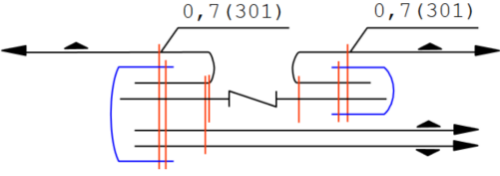
No	Sewing operation	Equipment and tools	Cross-section
1	Join centre hood upper piece with centre facing	Lockstitch sewing machine	
2	Turn right sides out, top-stitch edge	Lockstitch sewing machine	
3	Join centre hood pieces with outer hood pieces	Lockstitch sewing machine	
4	Sew binding to sewing allowance	Juki CP-180	
5	Top-stitch sewing allowance towards centre hood pieces	Lockstitch sewing machine, top-stitch pressure foot of 0,7 cm	
6	Sew horizontal elastic band channel to hood inner side	Lockstitch sewing machine	
7	Enter elastic band and 1 stopper into sewn channel	By hand with hook turner	-
8	Attach elastic band to hood opening sewing allowance with auxiliary seam	Lockstitch sewing machine	
9	Attach elastic band to hood bottom edge sewing allowance with auxiliary seam	Lockstitch sewing machine	

No	Sewing operation	Equipment and tools	Cross-section
10	Enter elastic band through transfer openings and insert 1 stopper for each band	By hand	-
11	Attach elastic band other end to centre and outer hood piece sewing allowance with auxiliary seam	Lockstitch sewing machine	
12	Join hood facings	Lockstitch sewing machine	
13	Join facing to hood opening	Lockstitch sewing machine	
14	Top-stitch seam allowance towards facing	Lockstitch sewing machine	
15	Sew facing with hood main piece	Lockstitch sewing machine	
16	Join zipper cover pieces	Lockstitch sewing machine	
17	Turn right sides out, top-stitch edge	Lockstitch sewing machine	
18	Sew zipper and cover to pocket opening	Lockstitch sewing machine, zipper pressure foot	
19	Sew pocket bag to front bodice pieces	Lockstitch sewing machine	
20	Sew pocket bag to zipper along the length of zipper band	Lockstitch sewing machine	
21	Sew rough side of Velcro to sleeve edge	Lockstitch sewing machine	

No	Sewing operation	Equipment and tools	Cross-section
22	Sew soft side of Velcro to sleeve inner flap	Lockstitch sewing machine	
23	Sew sleeve inner and outer flaps together along curved edge, leave straight edge open	Lockstitch sewing machine	
24	Turn right sides out, adjust sewing allowance of straight edge, top-stitch edge	Lockstitch sewing machine	
25	Sew sleeve flap to sleeve lateral edge sewing allowance with auxiliary seam	Lockstitch sewing machine	
26	Sew sleeve facing to sleeve	Lockstitch sewing machine	
27	Top-stitch sewing allowance toward facing	Lockstitch sewing machine	
28	Sew reinforcing band to facing open edge seam allowance	Lockstitch sewing machine	
29	Sew sleeve to front and back bodice	Lockstitch sewing machine	
30	Sew binding to seam allowance	Lockstitch sewing machine	
31	Top-stitch seam allowance towards sleeve	Lockstitch sewing machine, top-stitch pressure foot of 0,7 cm	

No	Sewing operation	Equipment and tools	Cross-section
32	Sew sleeve and front-back bodice side seam	Lockstitch sewing machine	
33	Sew binding to seam allowance	Lockstitch sewing machine	
34	Sew inner and outer collar together along top edge	Lockstitch sewing machine	
35	Sew hood and outer collar to neckline	Lockstitch sewing machine	
36	Fold hanger in half and top-stitch	Lockstitch sewing machine	
37	Sew hanger to neckline sewing allowance with auxiliary seam	Lockstitch sewing machine	
38	Sew front placket pieces together along curved edge	Lockstitch sewing machine	
39	Turn right sides out, top-stitch edge	Lockstitch sewing machine	
40	Sew binding to inner collar seam allowance along longer edge	Lockstitch sewing machine	
41	Sew bodice front and back facings side seams	Lockstitch sewing machine	
42	Sew reinforcing band to facing upper edge seam allowance	Lockstitch sewing machine	
43	Sew facing to bodice pieces	Lockstitch sewing machine	

No	Sewing operation	Equipment and tools	Cross-section
44	Top-stitch seam allowance towards facing	Lockstitch sewing machine	
45	Enter elastic band with 2 stoppers through transfer openings	By hand	-
46	Sew elastic band open ends to facing centre front seam allowance with auxiliary seam	Lockstitch sewing machine	
47	Sew zipper to front piece centre front (right and left bodice)	Lockstitch sewing machine, zipper pressure foot	
48	Sew front placket to right front bodice on top of zipper stitch	Lockstitch sewing machine, zipper pressure foot	
49	Sew binding to right seam allowance	Lockstitch sewing machine	
50	Sew binding to left seam allowance	Lockstitch sewing machine	
51	Sew inner collar to neckline	Lockstitch sewing machine	
52	Sew sleeve facing to sleeve	Lockstitch sewing machine	
53	Sew front and back bodice facing to front and back	Lockstitch sewing machine	

No	Sewing operation	Equipment and tools	Cross-section
54	Top-stitch front placket, zipper and collar in one seam	Lockstitch sewing machine	
55	Final inspection: checking seams, cutting loose threads	-	-

Appendix 10 Supportive images of second prototype



