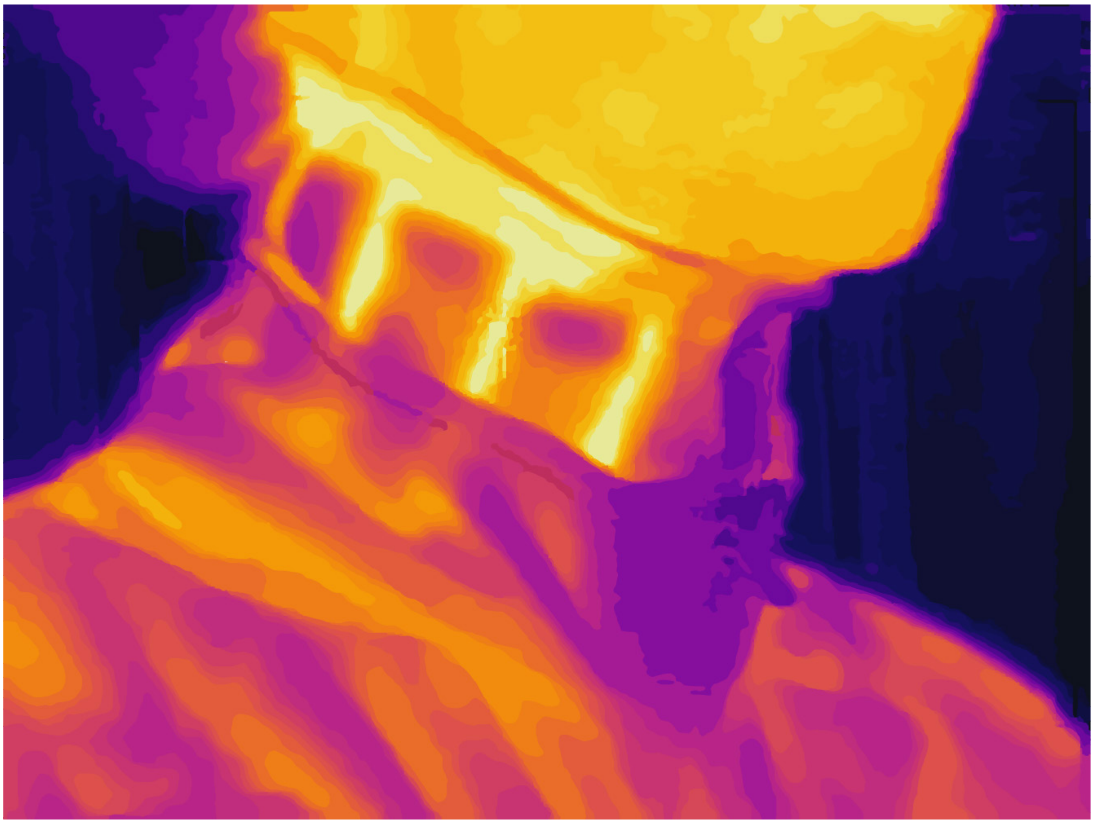
FEEL THE HEAT

EXPLORATIVELY DESIGNING A WEARABLE WEFT-KNITTED HEATER
%% IN COLLABORATION WITH BYBORRE

GUIDED AND ASSESSED BY KASPAR JANSEN & BEYZA BOZALI



MARK LOOPSTRA // BYBORRE // TUDELFT

PREFACE

This thesis is the result of 5 months of study to and development of knitted wearable heat. After realising that during cold winter months, we are continously wasting energy by heating up rooms and buildings instead of just ourselves, I chose to research a new design method for wearable heat. As currently available electrically heated garments severely lack comfort due to bulkiness, motion limitation and heavy battery packs, smart textile knits are being explored as an elegant and more efficient alternative. Together with Amsterdam-based textile innovation company BYBORRE, a series of samples were produced with different knit structures and stitch configurations. This thesis offers several guidelines for future designers to work with knitted heat considering knitting technology, heat distribution, and resistance control, and offers a numerical method to predict heat generation. Some yarn deficiencies and possible side-effects are being addressed. I hope this thesis serves as a step towards a more energy-efficient future, where portable heat will be the norm.

I would like offer my gratitude to BYBORRE studio for giving me the opportunity to work with them, and especially to Joao for programming and knitting the samples, while pushing the project. Besides, I'd like to thank my chair and mentor Kaspar and Beyza for their general guidance and fruitful discussions, the personel of IDE's Applied Labs for the resources, and lastly my friends for their mental support and inspiring views.

feel the heat

Mark
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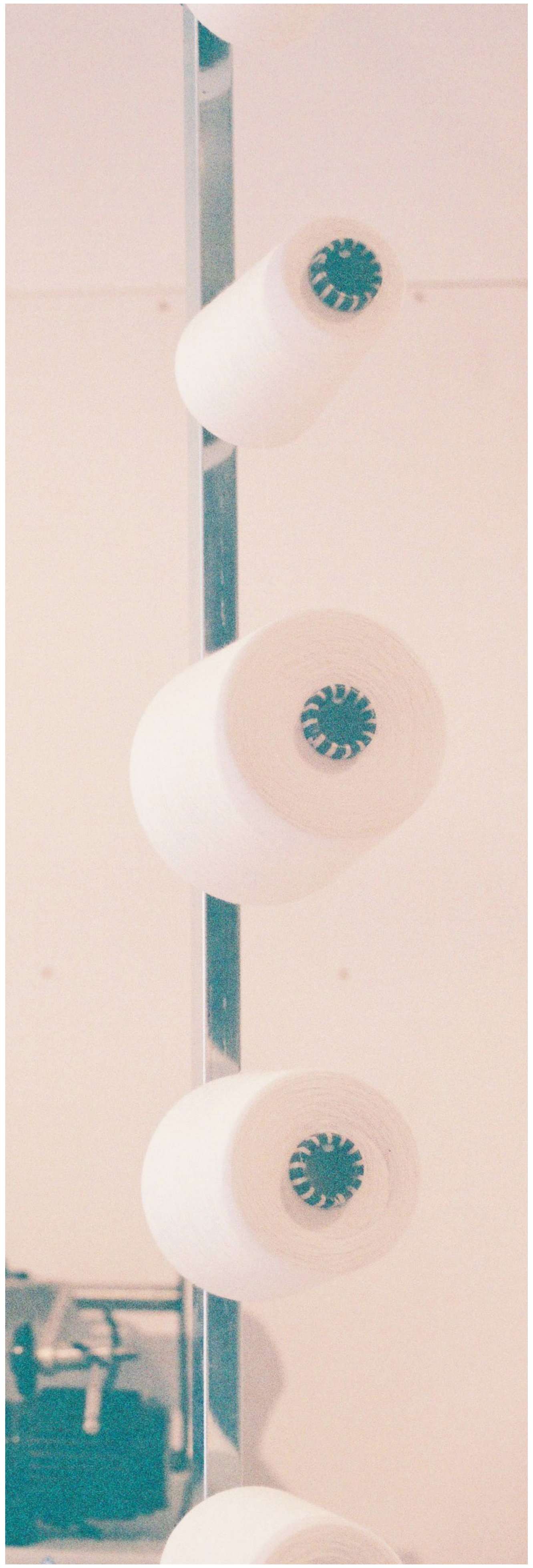
INTRODUCTION

As environmental concerns intensify (and in the face of rising energy prices), the need for innovative approaches to reduce our reliance on energy-intensive heating systems becomes increasingly critical. Electrically heated clothing presents itself as a promising alternative solution to keep ourselves warm during the winter months, both indoors and outdoors. These garments could offer an efficient and practical way to provide individuals with the means to stay comfortably warm while simultaneously minimizing energy usage in domestic settings. By reducing reliance on centralized heating systems and focusing on targeted warmth, heated clothing has the potential to significantly decrease energy consumption, mitigate the strain of high energy costs, and contribute to a greener and more sustainable future.

The integration of conductive yarns into the fabric structure of heated garments, known as smart textile knitting, offers exciting possibilities for enhanced comfort and performance compared to traditional electric heating garments (EHGs). However, as this field is relatively new, research is needed to provide future designers with the necessary knowledge and techniques to effectively handle these materials. Conducting research in smart textile knitting will enable designers to optimize their yarn selection, stitch patterns, resistance control, and fabric structure. Through this, stable electrical conductivity and high durability of the garments could be ensured. This research will contribute to unlocking the full potential of conductive yarns in weft-knitting, potentially leading to the creation of innovative designs that prioritize both functionality and comfort in heated clothing.

While heated clothing used outdoors may not directly contribute to sustainability, it could provide valuable additional comfort with little energy consumption. Smart textile heated garments could specifically hold significant benefits for individuals with specific health conditions, such as nerve issues like Raynaud's disease. This is a condition characterized by reduced blood flow to extremities, leading to cold and numb fingers or toes. Smart textile heated garments could provide targeted warmth to these vulnerable areas, helping to alleviate symptoms and improve comfort for individuals with such conditions.

The research conducted on smart textile knitting, despite focusing on silver-coated compound yarns, can be extrapolated to other types of conductive yarns, such as carbon-based yarns. Therefore, the gained knowledge can be adapted by designers while enabling the development of heated garments that utilize alternative materials.



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TERMINOLOGY & ABBREVIATIONS

SJ = Single Jersey
DJ = Double Jersey

SPCY = Silver Plated Conductive Yarn
SCCY = Silver-Coated Conductive Yarn (these two are similar)

leadwire = the more conductive heating area on the sides of a knitted heater, generally knitted in the wale-direction (vertically).

heater = the less conductive heating areas in a knitted heater, that are designed to heat up; generally knitted in the course-direction (vertically)

SPD = Surface Power Density

Sandwich = Double Jersey knit structure in which the relevant yarn is being insulated on both sides

c-value = the value for constant c, which contains all parameters that are not included in the formula for determining resistance

Wl = leadwire width, generally in wales
Wh = heater width, generally in courses
Ll = leadwire length, generally in courses
Lh = heater length, generally in wales
Nh = amount of heaters

dT = temperature difference
dt = time difference

Knit session = one day of sample iterations at BYBORRE

RESEARCH

1.

HEAT YOURSELF, NOT YOUR ENVIRONMENT

While nowadays fashion has grown to be a platform for designers, artists, tailors, but also for the entire society to visually express themselves, the role of clothing in thermal management is equally, if not more, important. For about 100.000 years (Hunt, 2021), clothing has been the primary means to keep humans thermally comfortable, by providing cooling in a hot environment and heating in a cold environment (Qiu et al., 2020).
Nevertheless, the thermal management function of clothing is becoming increasingly relevant; The finite availability of fossil fuels have increased our awareness to energy consumption and have motivated us the save energy wherever we can, for both environmental as financial reasons.

In modern society there are generally two ways we keep ourselves warm: The aforementioned, by insulating ourselves with clothes, but also by staying inside, using building heat to protect us from outside. Whereas insulating ourselves with many (thick) layers of clothing limits our body movement, heating entire buildings is very energy-costly, and counts for a large part of global enerygy consumption: According to the United States Department of Energy, space heating and cooling contributes to 15.2% of all domestic primary energy usage (Qiu et al., 2020).

Alternative ways of thermal management are therefore being investigated.
One approach to this is Personal Thermal Management (PTM), which aims to supply a suitable thermal dose to an individual for her/his/x optimal thermal comfort, rather than providing a multitude of people with equal temperatures through building heating.

An obvious way to do this is through electrically heated garments (EHGs). Generally, electrical heating products use embedded heating elements to generate heat. In most EHGs, a single electrical heating wire is used that is connected to a power supply. Other possible heating elements for EHGs are graphite elements, electrically conductive rubbers, neutralised textile fabrics, positive temperature coefficient polymers and carbon polymer heating fabrics (Wang et al., 2010).

Currently, EHGs are mainly used for medical purposes, and by people working in extreme climate conditions.
However, As it can be expected that warming the microclimate around the body is more efficient than heating up an entire room, EHG's are a promising solution for increased energy-efficiency for our entire society. Some EHG benchmarking is discussed in the next chapter.

Despite promising to be a low-energy solution to coldness discomfort, the true answer is that EHG's are still far from reaching the kind of comfort that we get from central heating. According to Wang et al., (2010), the largest bottleneck for EHGs might be the battery capacity. Batteries with acceptable size and weight to carry around, have not been able to prove themselves longlasting enough to maintain

WHY NOT(YET)? THE ANSWER IS BATTERIES.

human thermal comfort in extremely cold environments (Wang et al., 2010b). Although battery technology is becoming more advanced as we go, it should be taken into account that batteries are heavy and large. Besides, heating elements in current EHGs are usually made of a simple heating pad.

FIGURE 1: NASA LIQUID COOLING SUIT (LIQUID COOLING GARMENT, S# 073, MITCHELL, N.D.)

These elements cannot integrate with the human body well, and limits our flexibility. Next to that, specifically for low-end EHGs, the temperature control systems inside EHGs are often not well designed and the temperature can not change smartly according to real-time need in different parts of the body.

A third common problem with heating wires is that they can not produce heat uniformly over a selected area; it produces heat only along the paths where the wires extend. The heat relies on radiation and conduction to the spaces between adjacent wires (Wang et al., 2010).

Other technologies to design active heating garments are:

- Phase Change Materials (mainly for cooling purposes)
- Chemical heating products
- Fluid/Air flow heating garments (see figure 1)

Tests and analyses of these technologies' advantages and disadvantages can be found in "A Review of Technology of Personal Heating" (Wang et al., 2010).

With the introduction of Smart textiles (E-textiles), opportunities have opened up to design and develop EHGs with much higher effiency and comfort potential. These two factors actually go hand in hand: A super-efficient heater will need the smallest accompanying battery, which immediately targets the aforementioned bottleneck. Besides that, production methods such as knitting allow for thin, stretch able fabrics, which could make an EHG feel like a regular garment. Heat uniformity can be increased as well, as the yarns allow for a precisely designed heating element.

The goal of this research is to find design guidelines for people that want to work with knitted EHGs.
The guiding principles in that process will be comfort, production scalability and energy efficiency.

Therefore, next to lab measurements, user research will is done in order to figure out how we can optimally feel the heat.

A SUPER-EFFICIENT HEATER WILL NEED THE SMALLEST ACCOMPANYING BATTERY.

FIGURE 2: ALPHATAURI OVEMA V1.C1.03, N.D.

HOT APPAREL

Many researchers have been working on the development of smart heated garments. In 2021, Saidi et al. developed a detailed overview of relevant research projects. They also listed companies that offer commercially available heated apparel and highlighted a few.
Most of the EHG's that are currently for sale are accompanied by poorly photoshopped images of happy people in a cold environment, wearing jackets with orange glowing heating elements. Some brands however, like Alphatauri, have tried to design and market a functional, comfortable but also stylish heated garment. Most of the brands seem to use single resistance wires rather than conductive yarns. This makes sense, as you might find out through this report, as conductive yarns are still in the middle of the development stage. However, 'Duran, a Chinese company, claims to be the first company to have developed and commercialized carbon fiber heating yarns, and it is the only one capable of precisely controlling fiber strength during production to ±5% (per meter)' (Saidi et al., 2021).
In this chapter, some of the most interesting EHG brands that were discovered are being highlighted. In appendix 4.3, an overview of the benchmark can be found that compares, among others, voltages, powers and prices.

FIGURE 3: BERTSCHAT® HEATED INSOLES, N.D.

From browsing through available options it can be concluded that brands are indeed struggling with batteries, and are finding innovative ways to integrate them into a garment: From integrating it with the padding of a shoesole (figure 3), to stuffing it in a thick pillow (figure 4), to leaving it in a jacket pocket (figure 2).

One can ask to whom exactly this clothing is targeted. Heated garments have been available for a long time, whereas awareness about indoor energy use has only become a big topic in the Western society since the beginning of the energy crisis in 2021. So, is it a luxury thing? Are these products targeted to people who just want that extra bit of comfort? Or is medically-oriented; Is the apparel meant for those who get cold quickly due to poor bloodflow?

FOR WHO IS THIS?

Most brands (e.g. Voltheat, Bertschat, California Heat) out there seem to focus on outdoor-apparel and brand their products with a sporty, healthy and active feel. Their tone of voice is inspiring and motivating, telling their targeted customers to go outside, often into nature, to 'explore', 'perform', and 'resist the cold'. Their pricing strategies are similar as well: The price range of these brands' heated apparel lays between $100,- and $300,- per item. EHGs are known to be used by motorcyclists and winter sporters, however during previous research it was discovered out that people who spend many consecutive hours outside in relatively cold climates without moving, are an additional interesting target market for commercial production of EHGs. They are already using EHGs and are actively looking for new products that help them to stay warm. These groups consist of, for example, market vendors, security guards, and traffic controllers.

Dutch household product design company Stoov is, unlike their competition, focussing on the sustainable aspect of heated products. Sharing slogans like 'we warm people, not the planet' they claim to maintain comfort while allowing a reduced indoor temperature when making use of their products, adding to a more energy-efficient lifestyle.

It is hard to say anything about the market for heated garments, but the market for heat-related products is rapidly increasing: The energy crisis has catalysed the market's willingness to invest in alternative heating solutions. For example Stoov, who sells electrically heated blankets and pillows, has made a turnover of 16.4M € in 2022, compared to 1.3M € in 2019 (FD,2022).

FIGURE 4: STOOV PILLOW CAMPAIGN, 2022

IS THIS SAFE?

A question commonly (and rightfully so) asked about EHG's concern safety: Ensuring the safety of these garments is of paramount importance to protect users from potential hazards. Despite often being powered with low-voltage batteries, which takes away the risk of electrocution, (skin) burn is a serious safety consideration for this product category. Manufacturers can enhance the overall safety and reliability of electrically heated garments, contributing to their widespread adoption, in a couple of ways:

DESIGN FEATURES

The design of electrically heated garments should prioritize safety by incorporating specific features, including well-insulated electrical connections, tamper-proof wiring, and reinforced stitching to prevent the exposure of electrical components. The use of flame-resistant materials is also crucial to minimize the risk of fire accidents.

INSULATION

Adequate insulation between the heating elements and the wearer's body should be provided to avoid direct contact and thus reduce the risk of thermal injuries.

POWER SOURCES

It is crucial to ensure that the power source used is reliable and meets safety standards. For battery-powered garments, built-in safety mechanisms, such as overcurrent protection and temperature monitoring, should be implemented to prevent overheating and electrical malfunctions.

TEMPERATURE CONTROL MECHANISMS

Effective temperature control mechanisms are necessary to maintain a safe (and comfortable) level of heat. Thermostats, temperature sensors, and control algorithms should be integrated into the garment's design to regulate the heating elements and prevent excessive temperatures. Overheating protection systems should be in place to automatically shut off the heating elements if the temperature exceeds a predefined limit.

USER GUIDELINES

Providing clear and comprehensive user guidelines is crucial to ensure the safe usage of EHGs. These guidelines should cover instructions on proper usage, maintenance, and storage.

'WE WARM PEOPLE, NOT THE PLANET'

KNITWARM

Unlike the other EHG brands on the market, one brand was discovered that claims to sell 'smart textile' integrated knitted heaters; Knitwarm. A Hong-Kong based company, that started as a project from PolyU and from there quickly developed as a commercial start-up. They sell many different products: from heatable scarves to eyemasks, to blankets, with prices ranging from 120 - 320 USD.
Their products contain silver-plated yarns and are supplied with slim 3000mAh batteries that are integrated into the product (often with a pocket).

SCARF DESIGN

The 'Knitwarm Merino Wool Crossover Scarf' was purchased to further investigate. Despite both the heating element as the actual product being a lot smaller than expected, the Merino wool used in the scarf is very pure and soft, and the scarf offers some nice features. The scarf comes with a battery and a switch button that allows the user to switch between different intensities. The battery connection is solved with an elegant button that is sewn on to the fabric, making contact with the conductive yarns. As the button itself is made from a conductive metal as well, it can easily transfer electricity from a battery into the heating circuit by clicking the battery adapter onto this button. It seems like the conductive yarns have been plated on the back of one side of the fabric, with a second jersey closing the product off from the back. At the spots where the battery connects, however, the plating is reversely shown on the outside (see figure 5).

The Scarf gives its wearer the opportunity to be wrapped around the neck without any additional knot or connection. As the product is quite small, this will not give any wearing difficulties. A smart design choice that has probably been considered by their team is that the battery is at the end of the scarf. The weight of the battery therefore makes the scarf pull your neck, which increases the skin contact it makes. Besides, as the scarf is small, the battery does not get the chance to swing around much. These insights might be used as inspiration during the desing phase of this project.

TESTS

Several quick measurements were conducted to find out the technical specifications of the crossover scarf. First of all, the voltages associated with different intensity modes were measured, same as the overal resistance.

Rtot	**3.6 ohm**
U1	**0.11 V**
U2	**1.75 V**
U3	**2.32 V**
U4	**3.22 V**
U5	**3.92 V**

From these values it can be derived that the maximum amperage running through the product is

Imax = U5/Rtot= **1.1 A.**

THERMAL IMAGE

The scarf was heated on the highest intensity (3.92V) for 10 minutes. After that, a thermal image was made with the FLIR camera to get insights in the maximum heat generation as well as in the homogenity of the heat generation.

The thermal image gave disappointing results. Despite the heat generation to be nice and high, it can be seen in figure 6 that there are some clear hot wires running through the knitted heater in a 'zig-zag' pattern. This indicates that the knitted heater is being supported by an extra metallic wire. As this zig-zag wire gets the hottest, it is likely to assume that this is where the actual current runs through. The silver-coated yarns would just be there to further dissipate the heat with the thermally conductive characteristics of the material. This gives the heater a slightly better heat dissipation, but uses a lot of SPCY to do this.

DISCUSSION

Despite having implemented some smart design choices, it was disappointing to find out that the Knitwarm scarf was actually not integrating true smart textile technology, but only made it seem like they did. As they are selling the products commercially, it seems like they have shortcutted the whole smart textile design process by sneakily integrating some old-fashioned electric parts. Nevertheless, some design choices will be used as an inspiration for further development during this project.

FIGURE 5: KNITWARM SCARF (KNITWARM, 2022)

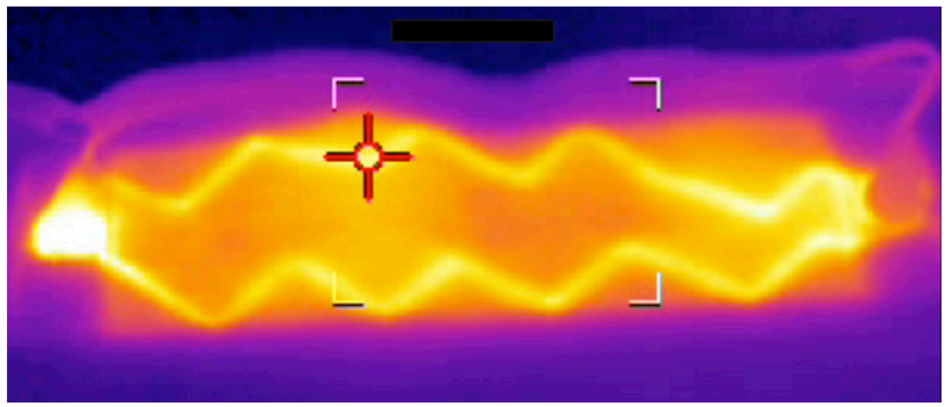


FIGURE 6: THERMAL IMAGE OF KNITWARM SCARF

FIGURE 7: ELECTRICAL CIRCUIT OF KNITWARM SCARF

FIGURE 8: BATTERY CONNECTION OF KNITWARM SCARF

FIGURE 9: DETAIL OF KNITWARM SCARF: A BUTTON IS USED TO CONNECT THE BATTERY

FIGURE 10: CLOSING THE BUTTON TO MAKE CONNECT THE BATTERY

COMFORT

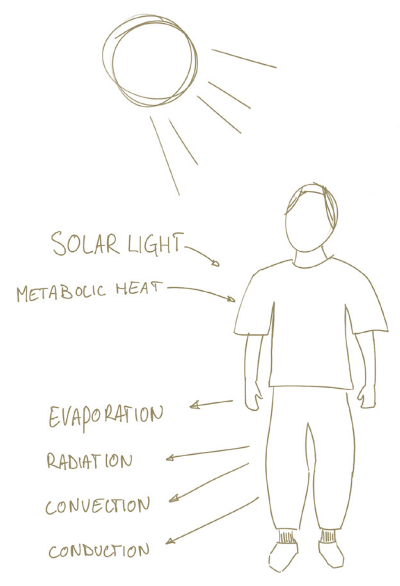


FIGURE 11: SIMPLIFIED MODEL FOR THERMAL COMFORT , (QIU ET AL. , 2020)

The comfort provided by clothing can be divided in two sections: **wearing comfort and thermal comfort**. In this chapter we will be discussing both.

Thermal comfort is influenced by both physical and psychological aspects and is therefore impossible to fully define as a single quantitative term; It is a sensation related to an individual's response to the environment. Because of this, definitions of the term 'thermal comfort' vary from discipline to discipline. Psychologists prefer determining thermal comfort through different scales, of which the most widely used one is the seven-point scale of thermal sensation proposed by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) (De Dear & Brager, 2002).

Engineers, on the other hand, have developed multiple formulas to predict whether an individual is in a thermally comfortable state, of which most of them oppose incoming thermal factors, such as sunlight, to outgoing thermal factors, such as evaporation. For example, Qiu et al. (2020) used a simplified model in their research that takes only sunlight absorption and metabolic heat generation as input pathways, and take evaporation, radiation, convection and conduction as output pathways.
The truth is not only that this model leaves out many other input pathways for heat transmission, but also doesn't take context into account: Some people handle the cold much better than others. According to De Dear and Brager (2002), people that are used to well-controlled thermal environments will become more sensitive to temperature fluctuations that reach out of the comfort zone they are used to. In contrast, people that are used to thermal diversity, build up resilience against daily and seasonal temperature changes (De Dear & Brager, 2002).
Besides limiting body movement, a known problem with traditional EHGs is that they are generally not good at uniformly dissipating the heat over a large surface. This occurs because an optimum has to be found between the heating area and the heat generation: If the heating area is too large, the power supply will not be able to generate a noticable temperature difference. Therefore, heating elements consists of small areas. When knitting with electro-conductive yarns, uniformity over a large area could be reached more easily as detailed patterns of heating yarns can be CNC-produced with the knitting machines.
Repon et al. (2021) investigated the visible uniformity of knitted heating elements by altering different amounts of Elitex 235dtex knit stitches with non-conductive stitches on a 14 Gauge flatbed knitting machine. They found that a width of 4 courses in between the heating parts was already enough to create a clearly visible non-uniform heating area (see figure 12).

It should be investigated whether this non-uniformity can actually be noticed by the human skin, however.

UNIFORMITY

Non-uniform heat distribution can cause localised hotspot, and is likely to result in discomfort. When certain areas receive excessive heat while others remain cooler, individuals will experience uneven temperature perception, causing discomfort and a sense of thermal imbalance. Heat uniformity, on the other hand, helps eliminate such discomfort and ensures a consistent and pleasant thermal experience.
Heat uniformity contributes to a sense of relaxation and well-being. When heat is evenly distributed, individuals experience a soothing and comforting sensation throughout their bodies. This promotes a state of relaxation, relieves muscle tension, and enhances overall well-being (Luo et al., 2016).

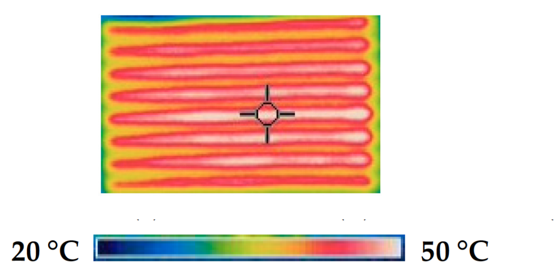


FIGURE 12: IR PHOTO OF A NON UNIFORM HEATING ELEMENT (REPON ET AL., 2021)

HEATING THE HUMAN BODY

Next to contextual variations, heat perception also varies on a local scale. Luo et al. (2020) have developed heat maps that show the average body's sensitivity to heat. As thermally active clothing would ideally target body surfaces with high temperature sensitivities, these maps can be very helpful in designing EHGs.
They found out that regional variances within body parts are 2-3 times greater than potential sex differences. Besides, they found the cheek, neck back, and seat area to be highly sensitive to both warming and cooling, about 2–3 times more than, for example, the feet. This does not automatically mean that those areas are the most suitable to target with active warming or cooling, however. A large role in thermal discomfort is played by blood circulation and by exposure to the environment (see chapter: Health).

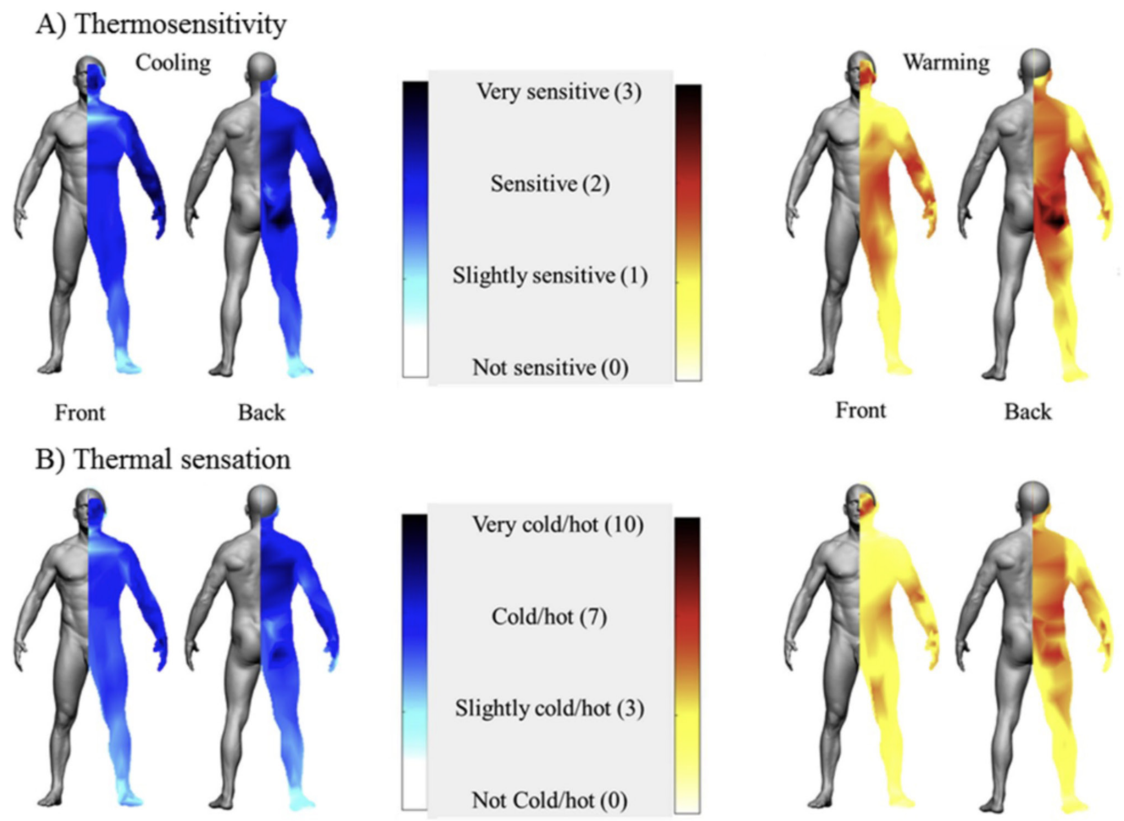


FIGURE 13: IMAGES OF REGIONAL BODY HEAT PERCEPTION (LUO ET AL., 2020)

POWER INPUT

The heat generation of an EHG is dependent on the power input and the amount of time it is being heated (Q=P * dt, see chapter 1.8). Generally there are four voltage ranges being used for EHGs: 3V, 5V, 7V, and 12V. This is because higher voltage batteries will be bigger and have less capacity. This is only suitable for products that need high input power (like electric vehicles). Besides, products that are powered with batteries are often designed for a certain voltage.

12 Volt heated clothing is traditionally targeted on motorcycle riders, and is not intended to be powered by a battery, but by wiring the jacket to a motorcycle's electrical system. Despite this non-portable disadvantage, 12V jackets have proved themselves to supply riders with sufficient heat on the road.

7 Volt products are powered by powerbanks (rechargable, user-friendly battteries), and therefore have the advantage to be portable. Usually, a powerbank is integrated in a pocket in the jacket to make it comfortable to wear. Although a 7V might not satisfy a motorcycle rider during the winter, many 7V heated products (including jackets) are being sold.

Next to 7V, similar **5 Volt** garments are being developed and sold. These garments will generate slightly less heat, but do have the advantage of a smaller, low-weight battery.

Lastly, **3 Volt** batteries are mainly integrated in small garments that do not need as much heat as other ones, like socks and slippers. (Voltheat, 2023).

An overview of current EHGs on the market with their voltages, battery capacities, estimated runtime and prices can be found in Appendix 4.3.

Almost all available heated garments that were explored were adviced to use with batteries containing capacities **around or below 5.000 mAh.** Larger power sources are expected to be too heavy to be comfortable, and therefore will not outweigh the increased battery life.

Batteries usually consists of multiple single cells, that can be placed in a parallel, series, or hybrid configuration. Each option comes with some advantages and considerations:

PARALLEL CONFIGURATION

In a parallel battery configuration, multiple batteries are connected positive terminal to positive terminal and negative terminal to negative terminal. This setup increases the overall capacity of the battery bank while maintaining the same voltage. When batteries are connected in parallel, the positive terminals are connected together, and the negative terminals are connected together, resulting in a combined capacity equal to the sum of the individual batteries. For example, if you connect two 12V, 100Ah batteries in parallel, the resulting configuration will have a total capacity of 12V and 200Ah.

//ADVANTAGES

- Increased capacity: Parallel configurations allow for greater capacity by combining the individual capacities of the batteries.
- Enhanced power output: Parallel connections provide higher current capabilities, making them suitable for applications that require high power delivery.

//CONSIDERATIONS

- Battery matching: When connecting batteries in parallel, it is crucial to use batteries with similar characteristics (e.g., voltage, capacity, and age) to ensure balanced charging and discharging.

SERIES CONFIGURATION

In a series battery configuration, multiple batteries are connected positive terminal to negative terminal, resulting in increased voltage while maintaining the same capacity. The positive terminal of the first battery is connected to the negative terminal of the second battery, and so on. The total voltage of the series-connected batteries is equal to the sum of the individual battery voltages. For example, if you connect two 12V batteries in series, the resulting configuration will have a total voltage of 24V.

//ADVANTAGES

- Increased voltage: Series configurations provide higher voltage levels, which are advantageous for applications requiring higher voltages.
- Uniform charging and discharging: When batteries are connected in series, they tend to discharge and charge uniformly due to the shared current flow.

//CONSIDERATIONS

- Capacity remains the same: While the voltage increases, the overall capacity of the battery bank remains the same as that of a single battery.
- Voltage matching: It is important to connect batteries with the same voltage ratings in series to prevent imbalances and potential damage.

HYBRID

Hybrid configurations combine parallel and series connections to achieve both increased voltage and capacity. This setup involves connecting battery banks in parallel and then connecting those parallel banks in series. By using this hybrid configuration, it is possible to achieve the desired voltage and capacity for specific applications.

//ADVANTAGES

- Flexibility: Hybrid configurations offer flexibility in tailoring the voltage and capacity requirements to suit specific applications.
- Balancing capabilities: Parallel connections within the hybrid setup enable better balancing of batteries, ensuring consistent charging and discharging across the system.

//CONSIDERATIONS

- Complexity: Hybrid configurations require careful planning and consideration of battery specifications to ensure compatibility and optimal performance.
- Monitoring and management: As hybrid configurations involve multiple battery banks, proper monitoring and management systems are necessary to ensure balanced charging and discharging across the system.

As mentioned before, the battery is often what pushes back the comfort in an EHG. by combining single-cell batteries, the shape of a battery can be customly designed. For example, batteries could be placed in a 'chain' configuration to allow for integration in curved parts of a garment. Battery technology is currently widely being explored and researched, and is expected to allow for enormous shape-freedom in the near future. (Li et al., 2022) discuss the recent developments of flexible lithium-ion batteries and highlight the latest achievements based on nature inspiration, including fiber-shaped FLBs, origami and kirigami-derived FLBs, and the nature-inspired structural designs in FLBs in the paper 'Nature-inspired materials and designs for flexible lithium-ion batteries'.

HEALTH

The most widely available EHGs are products for the hands and feet, as these body parts are most likely to suffer from cold.
A large role in thermal discomfort is played by blood circulation and by exposure to the environment. People quickly get cold feet: not because their feet are more senstive to cold than other body parts, but because feet are exposed to cold floors, causing constant cooling conduction. Besides, as feet are relatively far away from the heart, it takes longer for your blood to circulate through the limbs of your body (Cold Feet Causes & Treatment, n.d.).

Poor blood flow can be caused by several conditions:

- Autoimmune conditions (anemia).
- Heart disease.
- Hormonal changes (hypothyroidism).
- Narrow artery blockages or constricted blood vessels.
- Nerve conditions (fibromyalgia).
- Peripheral artery disease.
- Raynaud's phenomenon.

A poor blood flow can however also simply be caused by an unhealthy or unbalanced diet.

Besides battling cold, active heating is also known to have positive effects on sore muscles that cause back pain or neck pain. Heat therapy boosts blood circulation, which allows nutrients and oxygen to travel more easily to joints and muscles. This circulation stimulates the repair of damaged muscles, soothes inflammations, and reduces back- or neck stiffness (Higuera, 2019). Besides blood flow, heat also seems to stimulate milk flow: Philips sells thermopads to stimulate milk flow for nursing mothers (see image below).

FIGURE 14: PHILIPS AVENT THERMOPAD (PHILIPS, 2022)

KNITTING TECHNOLOGY

Knit fabrics provide outstanding comfort qualities due to their inherent softness and flexibility. The global knitted fabrics market size is projected to reach nearly 40 billion dollars by 2031. **Because of its low cost, easy manufacturing and improved elastic properties, weft-knitted fabrics will continue dominating the market** (Fact.MR, n.d.).

Knitting is the most common method of interlooping: forming yarns into loops each of which is only released after a succeeding loop has been formed and intermeshed with it so that a secure ground loop structure is achieved (see figure 15 and 16) (Spencer, 2001). In this report, knitting terminology will be used of which the most important ones are explained below.

WEFT AND WARP KNITTING

Weft knitting and warp knitting are two distinct methods of creating knitted fabrics, differing in their construction techniques.

Weft knitting, also known as filling or circular knitting, is the more common method. In weft knitting, the yarn travels in a horizontal direction, from left to right, across the fabric. The loops are formed sequentially along the width of the fabric, with each loop interconnecting with the previous one. Weft knitting machines, such as circular knitting machines, are typically used for this technique. Weft knitting allows for a wide range of fabric structures, from simple jersey knits to more intricate patterns like ribs, cables, and jacquard designs.

Warp knitting, on the other hand, involves the yarn traveling vertically, from top to bottom, along the length of the fabric. The loops are formed simultaneously across the width of the fabric, with each loop interconnecting with the neighboring loops. Warp knitting machines, such as raschel and tricot machines, are used for this technique. Warp knitting is known for its high-speed production and the ability to create complex patterns and structures, including laces, nets, and warp knitted jerseys.

The main difference between weft knitting and warp knitting lies in the direction of yarn movement and loop formation. Weft knitting produces fabrics that are more elastic and stretchable in the width direction, while warp knitting yields fabrics that are more stable and less stretchable in the width direction but possess greater lengthwise stability. This research focusses fully on weft-knitting, as BYBORRE's machines are all weft knitting machines, and weft-knitting is more suitable for rapid sample production.

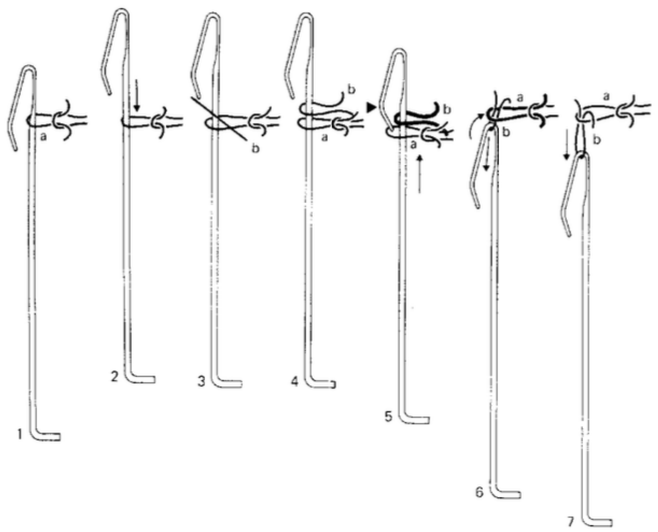


FIGURE 15: NEEDLE SEQUATION IN A KNITTING MACHINE (SPENCER, 2001)

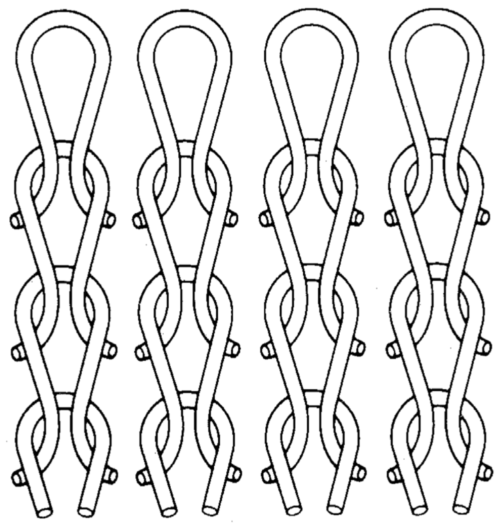


FIGURE 16: KNITTED COURSES (SPENCER, 2001)

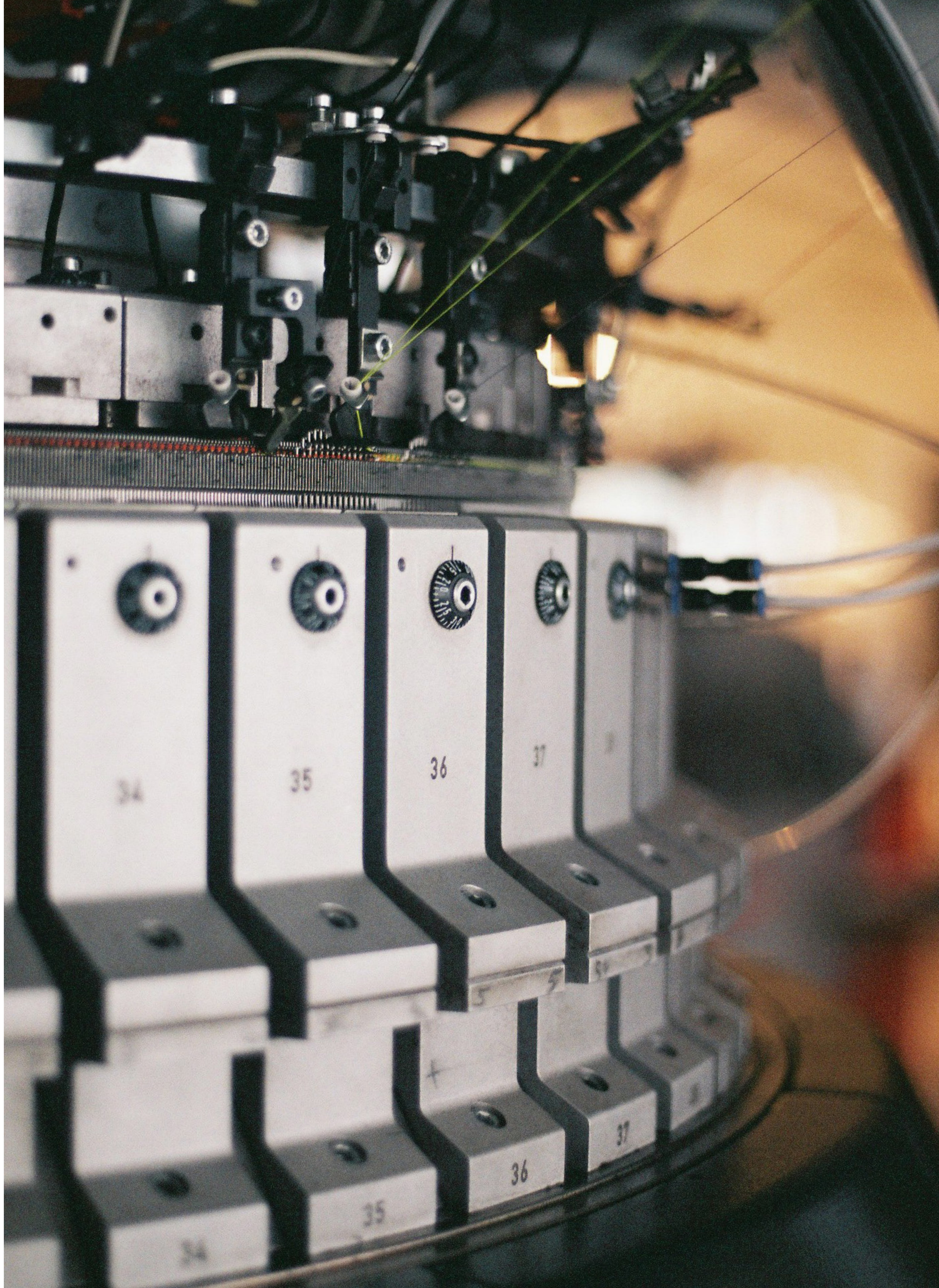


FIGURE 17: CIRCULAR KNITTING MACHINE AT BYBORRE (MARK LOOPSTRA, 2023)

WALES AND COURSES

In knitting, the terms “wale” and “course” refer to two essential elements that define the structure and appearance of knitted fabrics:

A wale is a vertical column of stitches in a knitted fabric (see figure 16). It runs from the top to the bottom of the fabric, perpendicular to the direction of knitting. Each wale is formed by a continuous yarn loop, and the number of wales across the fabric determines its width. Wales contribute to the fabric’s drape, texture, and overall design.

A course, on the other hand, refers to a horizontal row of stitches in a knitted fabric (see figure 16). It runs from one edge of the fabric to the other, parallel to the direction of knitting. Each course is formed by a series of interconnected loops, and the number of courses in a fabric determines its length or height. Courses contribute to the fabric’s stretch, elasticity, and overall structure.

Together, the wales and courses create the fabric’s knitted structure. The arrangement and interaction of wales and courses determine the fabric’s characteristics, such as its stretchability, drape, pattern, and texture. (Spencer, 2001)

STITCH DENSITY

Stitch density refers to the number of stitches per unit length in a weft knitted fabric. It is a critical parameter that affects the fabric’s appearance, characteristics, and performance. Stitch density is typically expressed as the number of stitches per inch (SPI) or stitches per centimeter (SPC).

A higher stitch density indicates that more stitches are present within a given length of the fabric. Fabrics with higher stitch density tend to have a smoother surface, tighter structure, and greater fabric stability. They generally exhibit less stretch and drape compared to fabrics with lower stitch density. Fabrics with high stitch density are often preferred for applications that require better shape retention, such as structured garments or technical textiles. (Spencer, 2001)

YARN COUNT

Yarn count, often expressed in decitex (dtex), is a measurement of the linear density or thickness of a yarn. It represents the weight in grams of 10,000 meters of the yarn. In weft knitting, yarn count plays a crucial role in determining the fabric’s characteristics, performance, and appearance.

A higher yarn count (dtex) indicates a finer yarn with a lower linear density. Fabrics knitted with finer yarns tend to have a smoother texture, softer handfeel, and better drape. They may also exhibit enhanced detail in intricate patterns or designs. These fabrics are commonly used for lightweight and delicate garments, such as fine gauge sweaters, lingerie, or dress fabrics.

STRETCH

Even when knitted with a non-stretch yarn, knitted fabrics are naturally stretchy due to their structure. Of course, a knit fabric’s stretchability can be adjusted to one’s desire, but a minimum stretch of about 18% is unavoidable. With some stitch types, such as rib knits, an intentional extra stretch of up to 100% can be added to a fabric (Tokens, 2022).
Stretch in a garment can add a lot to its comfort: A stretchy piece will fit tightly, is easy to move in and can have some good thermal properties while remaining thin, as it sits to tightly against the body.
However, as explored in chapter 2.5, stretching a fabric with conductive yarns in it could increase its electrical resistance, as the length increases and the area (slightly) decreases. So how should we deal with that? Should we minimise stretch to get a stable resistance? Or should we allow some stretch in order to reach increased wearability and thermal comfort?

As traditional EHGs with electrical wires had the disadvantage of reduced flexibility, stretchability and a heavy battery pack (see chapter 1.1), and are therefore not yet very integrated in our society, **it is chosen to continue designing with fabrics that do stretch**. In this way, an EHG can be developed with optimised wearability and comfort. Besides, As stretchy garments sit tightly to the skin, heat dissipation from garment to skin will be optimised as there is a minimised amount of insulating layers in between.

PLATING

Plating, also known as co-knitting, is a knitting technology that allows two threads to be knitted separately on the front and back of the knitted fabric. Plating may be used, for example, to produce surface interest, colored patterns, or to modify the wearing properties of a fabric. Each yarn (usually with its own physical properties) is guided through its own guide hole to the needle hook, in order to influence its respective position relative to the surface (see image 18) (Spencer, 2001).

Perfect plating is achieved when the underneath yarn doesn not show onto the surface. This is however difficult to achieve (see figure 19), especially with yarns that have circular cross-sections and varying physical properties.

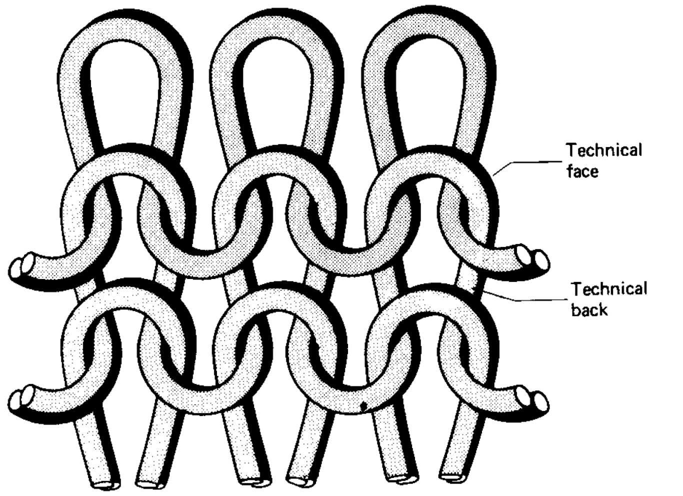


FIGURE 19: PLATING IN WEFT KNITTING (SPENCER, 2001)

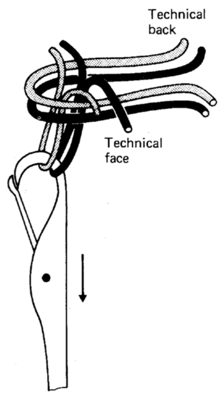


FIGURE 18: THE PLATING RELATIONSHIP OF TWO YARNS (SPENCER, 2001)

PLATING WITH CONDUCTIVE YARNS

When designing knitwear in fashion, a pattern or an image can easily be generated on a fabric by knitting a specific yarn on the front side, while ‘hiding’ that yarn on the back side when it shouldn’t be visible. When knitting electrical circuits in a fabric, this is a bit more difficult: No matter its visibility, if the yarn stays in contact with itself on the backside of the fabric, it will be invisibly connected to its own electrical circuit. Therefore, before and during programming the knit design, it should be well thought through how the conductive yarn will actually run, instead of how it will visibly run.

Plating could be used in designing with smart textiles to achieve higher resistance stabilities and higher endurance against mechanical abrasion. It will not only make a fabric less brittle, but it will foresee a fabric with a protective layer on one side. In experiment E4, E6.4, the influence of plating on electrical resistances are tested and discussed. In the Discussion after experiment 2.4, the challenges of plating with conductive yarns are addressed and discussed.

BYBORRE

Byborre is an Amserdam-based textile innovation company that focusses on the responsible production of knitted fabrics and products. As the fashion industry is accountable for 10% of the global carbon emissions (Appolloni et al., 2023), the company has, as they say, 'committed to democratize the supply chain'. In 2022, Byborre announced that the company will not continue their own clothing brand, but will continue as a full-time Textile-as-a-Service label. Nevertheless, it is a technology-driven company that is pushing the limits of their machines and is continuously trying to innovate.

BYBORRE has been the production partner of this research throughout the entire project, and has played a constant consulting role in the design process.

Byborre has a strong signature style, which can be seen in figure 20; By knitting 3 layers together (a double jersey with a puffable 'filler'), and playing around with connecting yarns, three-dimensional patterns can be designed on a fabric, making garments well-insulating sturdy and unique.

As Byborre is in this way specialised in working with multi-layered textiles, their expertise has been used in order to tackle some design challenges.

FIGURE 20: KNITTED GARMENT OF BYBORRE'S PREVIOUS CLOTHING LINES(BYBORRE, 2023)

CONDUCTIVE YARNS

By integrating electro-conductive yarns into a knit fabric, a smart fabric can be produced without any compromises on comfort, maintanance and wearability compared to ordinary textiles.

If some well-argumented guidelines are designed considering this technology, electro-conductive products can easily be scaled and reproduced throughout the world. This will also push back the production costs of such a product, which makes it more available for a large part of society.
As the motivation behind this research is a desire for more global energy-efficiency, and to propose a new way to look at heating ourselves, the scalability of this technology is of major importance.

Smart textiles are often named intelligent textiles or E-textiles. There is however a subtle difference between these terms: According to ASTM International's definitions, as of July 29, 2019, a smart textile is defined as a textile that reacts to outside stimuli (heat, chemicals, magnetism or mechanical stimuli) but doesn't necessarily have an electronic component, which is the case for E-textiles.

Nevertheless, the most common way in which a textile is made 'smart' happens is by making use of electro-conductive yarns, that altogether form an electrical circuit that can transfer energy or information through a garment. Yarn conductivity can be obtained with different types of materials, of which each of them have their own pro's and cons.

Metal-Based Yarns

Pro: Metal-based yarns, such as stainless steel or silver-plated yarns, offer high conductivity and excellent durability. They are commonly used for applications requiring efficient electrical transmission.

Con: Metal-based yarns, especially those containing precious metals, can be expensive, limiting their widespread use. Additionally, the extraction and processing of metals has environmental implications, raising concerns about sustainability and responsible sourcing.

Carbon-Based Yarns

Pro: Carbon-based yarns, like carbon nanotube yarns or graphene-coated yarns, provide good conductivity while being more flexible and lightweight than metal-based yarns. They offer an alternative with reduced environmental impact and can be suitable for wearable applications.

Con: Carbon-based yarns, particularly those utilizing advanced carbon materials, can be relatively expensive. However, their lightweight and sustainable nature can offset some of the cost concerns.

Hybrid Yarns

Pro: Hybrid yarns combine different types of conductive materials, such as metal fibers and carbon fibers, to achieve enhanced conductivity, flexibility, and durability. They offer a combination of benefits and can be more sustainable by reducing reliance on single-material yarns.

Con: Hybrid yarns can be more complex to manufacture and may have a higher cost compared to single-material yarns.

Coated Yarns

Pro: Coated yarns consist of traditional yarns coated with conductive materials like metal or carbon. They provide a more affordable option compared to fully conductive yarns and can be easily integrated into existing textile production processes. Coated yarns offer balance between functionality and cost-effectiveness.

Con: The conductivity and durability of coated yarns may not be as high as those of dedicated conductive yarns. Additionally, the use of coatings can raise concerns about the long-term durability and environmental impact of the materials.

Some conductive wires that are available have been electrically insulated with an extra layer. This layer makes the wire more resistant to mechanical abbresion through e.g. washing, but takes away the opportunity of making an electrical circuit via knitting or weaving connections with 'bare' yarns. In order to make an electrical connection, insulation of the yarn will have to be removed locally (Cherenack & Van Pieterson, 2012b), making the production process less scalable. Besides, within an electrical circuit build from coated yarns, one breakage could lead to a total defect of the product.

Most metal-based yarns can be used for knitting on flatbed machines, but yarn stiffness and the lack of flexibility will affect the fabric's drape. Carbon-based yarns, on the other hand, being lightweight and flexible, are generally rather suitable for knitting on flatbed machines.

Polymer composite yarns and coated yarns, which combine traditional yarns with conductive materials, maintain the same knitting characteristics as the base yarn and are generally suitable for flatbed machines. Nevertheless, adjustments to knitting parameters may be necessary for optimal results.

In consult with Amsterdam-based knitting company Byborre and the two supervisors of this project, **it was chosen to work with uncoated, silver-plated polyamide yarns** (multifilament);

- The polyamide in these yarns gives them a good resistance against tensile strength, making them suitable for knitting.
- The precious metal silver around the poly-amide core has a relatively high conductivity and is therefore suitable for heating.
- As the yarns are uncoated, we can design circuits by connecting bare yarns with knit stitches.

A brief interview with Byborre's knit technician about difficulties with using SPCY can be found in Experiment 1. Besides, an overview of the SPCY and their datasheets used in this project can be found in appendix 4.1.

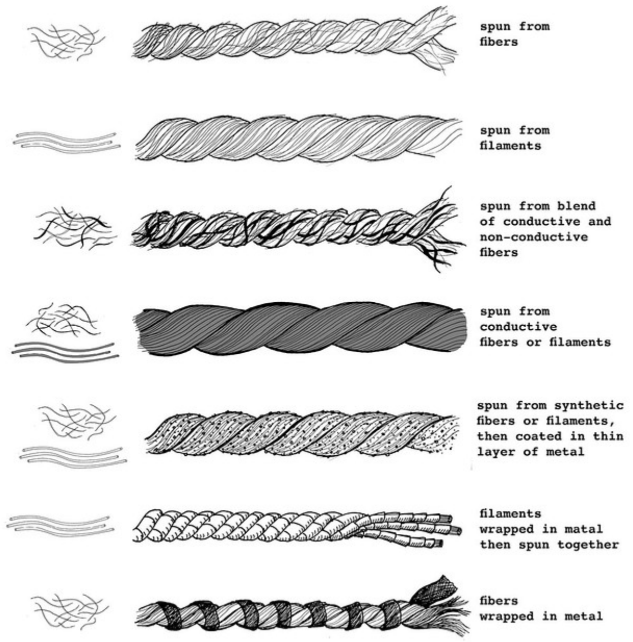


FIGURE 25: WAYS TO MAKE A YARN CONDUCTIVE (KOBAKANT, N.D.)

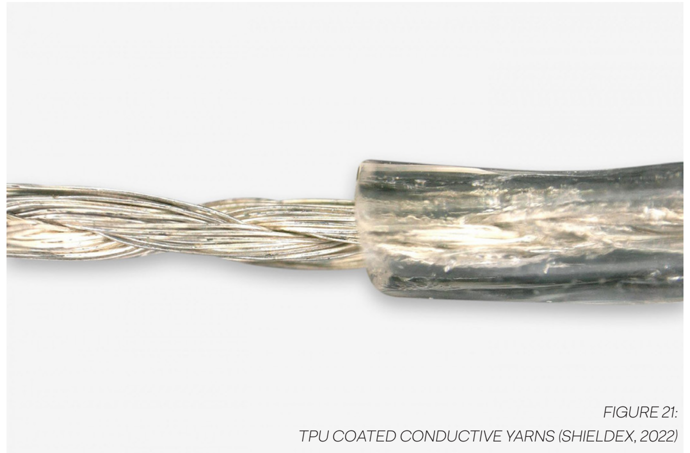


FIGURE 21: TPU COATED CONDUCTIVE YARNS (SHIELDEX, 2022)


FIGURE 22: MULTIFILAMENT CONDUCTIVE YARNS (SHIELDEX, 2022)

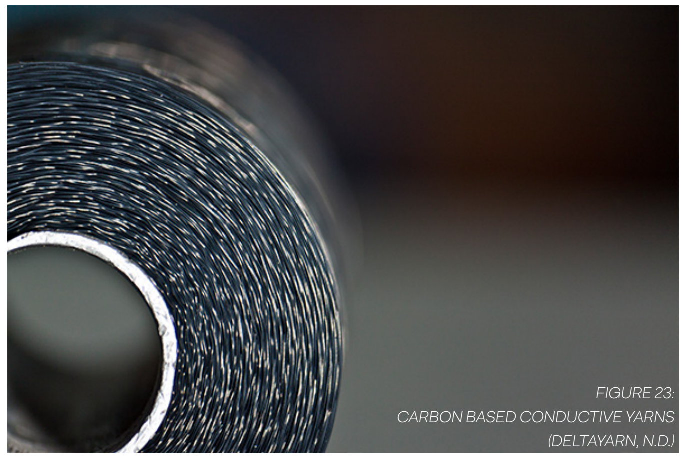


FIGURE 23: CARBON BASED CONDUCTIVE YARNS (DELTAYARN, N.D.)

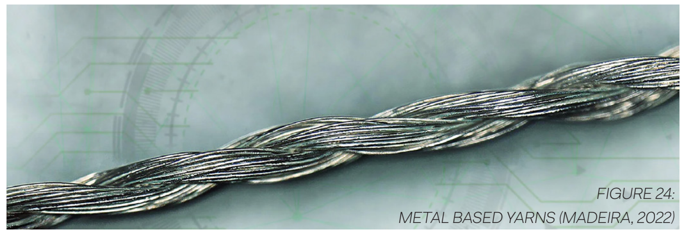


FIGURE 24: METAL BASED YARNS (MADEIRA, 2022)

ELECTRICAL RESISTANCES

Electrical resistance is a fundamental property of materials that impedes the flow of electric current. It is measured in ohms (Ω) and represents the degree to which a material resists the movement of electric charges. Materials with high resistance impede current flow, while those with low resistance allow current to flow more easily. Resistance depends on factors such as the material's composition, dimensions, and temperature. Devices like resistors are specifically designed to introduce resistance into electrical circuits for controlling current and voltage levels.

As is known from electrical engineering, the electrical resistance is in a linear relationship with the length of the conductor. Therefore, when a conductive fabric is stretched (and thus L increases), it can be expected that the Resistance will increase. This phenomenon has been proved in many literature studies. Bozali et al. (2022) used this phenomenon to design a weft-knitted strain sensor.

When designing with conductive yarns, it can be assumed that the electrical resistance of a sample reacts in the same way as a single electrical wire:

$$R := \frac{\rho \cdot L}{A}$$

Where rho is the specific material resistivity, L is the length and A is the cross sectional area of the resistor.
This cross sectional area is determined by the width and the height of the resistant sample. However, in a knit structure it is hard to say a lot about the height of a sample, as it is not only very small, but also non-uniform across a sample. We therefore do not include the height in the area A, but combine it with the specific yarn resistance rho , making it a constant value (c)

$$R := \frac{c \cdot L}{W}$$

If we approach the Resistance with the abovementioned fomula, we take length and width as the variables to determine a resistance, and base the value of c on the outcomes of conducted experiments. This value will vary for different sample experiments, as many parameters have their influence on this. The known parameters that influence the resistance of a knitted heating element with bare (see chapter 1.6: conductive yarns) yarns during this project are listed below.

- Yarn resistivity
- Stitch type
- Stitch density
- Gauge
- Shrinkage
- Plating Y/N
- Plating yarn
- Other additional yarns
- Knit structure
- Stretch
- Heat treatments, such as steaming
- Temperature
- Humidity
- Machine
- Yarn Tension

In the aforementioned formula, c is a single joint value, containing the input many individual values. These values are all kept constant throughout the series of experiments. When predicting a resistance based on the length and width, if one of the abovementioned parameters changed, the value for c (c-value) should be redetermined. That being said, **it should be made sure that the samples used for determining the c-value are treated equally as the designed EHG.**

The challenge of this project is to find a way to predict the electrical resistance of a knitted heater. Some of the abovementioned parameters are being investigated in this project, others have been kept constant due to the limited timespan of this project.

SERIES AND PARALLEL RESISTANCES

There is three ways to configure an electrical circuit:

SERIES

In a series circuit, components are connected one after another in a single path, creating a single loop for the current to flow through. The total resistance in a series circuit is equal to the sum of the individual resistances. In other words, resistances add up in series.

PARALLEL

In a parallel circuit, components are connected side by side, providing multiple paths for current to flow. The total resistance in a parallel circuit is calculated differently. It is less than the smallest individual resistance, as the overall resistance decreases when more paths are available for the current to follow.

SERIES + PARALLEL

In complex electrical circuits, series and parallel configurations are often combined. Components can be connected both in series and in parallel within the same circuit. This combination allows for more flexible circuit designs to meet specific requirements.

In this research, the focus will be on designing a knitted heater with a parallel configured electrical circuit.

CONTACT

In a knitted heater, the resistance is largely determined by the contact between individual stitches. The flow of electricity relies on the continuity of conductive paths created by the interconnected yarn or wire; The tighter and more intimate the contact between stitches, the lower the resistance becomes, allowing for efficient current flow and heat generation.

When stitches in a knitted heater have loose or inadequate contact, the resistance increases. Gaps or poor conductivity between stitches can hinder the flow of electric current and reduce the heating efficiency of the knitted fabric. Therefore, ensuring a well-knit structure with close contact between stitches is crucial for optimizing the resistance and overall performance of a knitted heater.

Maurya et al. (2023) recently explored the heating performance of knitted structures in series-configured electrical circuits, in which they predict the contact resistance of a yarn with the equation of Holms:

$$R_c = \frac{\rho}{2}\sqrt{\frac{\pi h}{np}}$$

where h, rho, n, and p are the material hardness, electrical resistivity, number of contact points, and contact pressure, respectively.

In this research, we will however not focus on these micro parameters, but on how knitting (macro) parameters influence the resistance.

RESISTIVE HEATING

When current runs through a conductor to produce heat, this is called Resistive heating (also known as Ohmic heating or Joule heating). As the name might make you suspect, the amount of heat generated in resistive heating is directly dependent on the electrical resistance of an electrical circuit:
When using a power W with either a fixed voltage or a fixed amperage, the other value will be determined by the resistance R, as

$$R := \frac{U}{I}$$

The Voltage and the Amperage together determine the input power P.

$$P := U \cdot I = \left(\frac{U}{R^2}\right)$$

As can be derived from the formula for heat generation Q:

$$Q := P \cdot dt$$

Where Q is the generated heat, P is the input power and dt is the time in seconds that the power was running through the electrical circuit.

When power P at a certain voltage U is applied to knitted fabric, the resistance of the knit fabric is R0, and the heat Q is generated after a certain period of time, dt

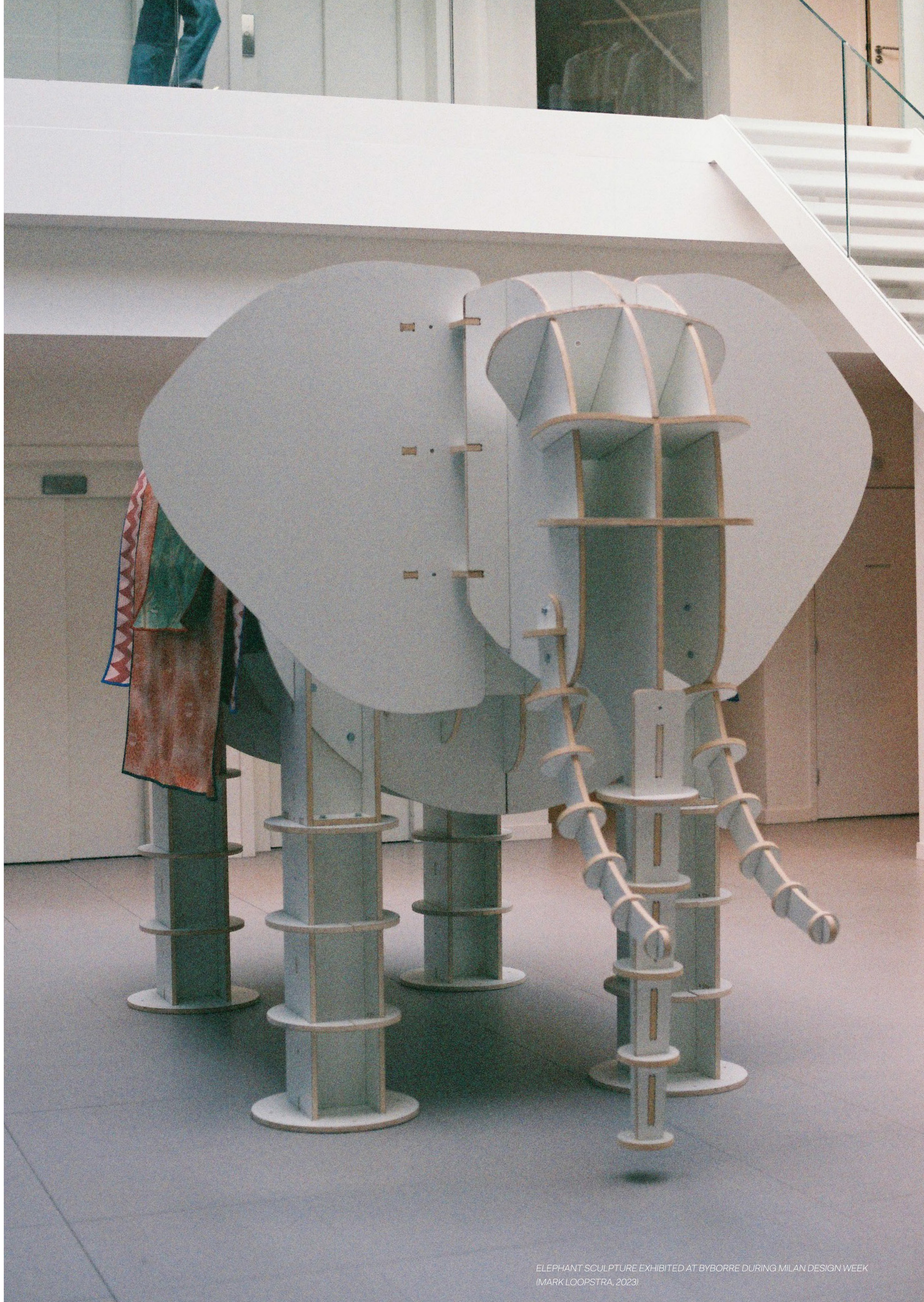
$$Q := \left(\frac{U^2}{R0}\right) \cdot dt$$

Due to the difference in temperature between the fabric and the environment, there is a loss of heat S during the heating process, which corresponds to the heat dissipation coefficient **α** and the changes in temperature (ΔT) and time (**Δ**t).

$$S := \alpha \cdot \Delta T \cdot \Delta t = \alpha \cdot (T - T0) \cdot \Delta t$$

where T is the temperature of the fabric, and T0 is the (initial) temperature of the environment.

To find out whether there is actually a correlation between resistance R and heat generation Q, Experiment 3 was conducted (see Experiment 3).



ELEPHANT SCULPTURE EXHIBITED AT BYBORRE DURING MILAN DESIGN WEEK (MARK LOOPSTRA, 2023)

THE ELEPHANT IN THE ROOM

As mentioned before, and as will be mentioned more often, silver-plated compound yarns come with several deficiencies considering both production and use. Therefore, smart textile technology with these yarns is still in a research phase. It could only yet be implemented on a commercial scale when the aforementioned issues have all been resolved. Nevertheless, the results of this project can be extrapolated to different bare-yarn knitted electrical circuits. That being said, even if e.g. carbon-based yarns turn out to be more promising, this research can be used as a guideline to design with those yarns as well.

This chapter is dedicated to point out the deficiencies of Silver-Plated Compound Yarns.

Durability is a big issue with SPCY. Non-coated yarns have proven to be prone to mechanical abbresion, washing, oxidation, and sweat. Not only will everyday use and washing degrade the amount of metal on a yarn, research has also shown that washing can result in microparts of silver ending up in waste streams (Gaubert et al., 2020).

WASHING

Research has pointed out that SPCY are not very resistant to washing (yet). Repon et al. (2021) compared microscope images and conductivity of silver-plated yarns after several washing cycles (see figure 26). They say that when the yarns are immersed in liquids, they experiences surface damage that affects the silver-plated layer. The resistance of the knitted fabrics is highly sensitive to the quantity of conductive yarns in the structure and the amount of conductive particles on the yarns. **When silver is removed, the number of charge-carrying particles decreases, leading to an increase in resistance**. As a result, the temperature generated on the fabric surface is lower after washing. However, the silver coating is not entirely removed along the entire length of the yarn, ensuring continuous conductivity.

As can be expected from the photos in figure 26, the resistance increases after each washing cycle due to the decrease in the quantity of conductive particles, their distance from each other, and the contact area between them. These negative consequences for washing are not acceptable for a garment that is supposed to be worn. It can be concluded that for commercial use, either the product should not be washed (which would actually be acceptable if the focus is on a material and product combination that generally does not need washing, such as a woolen scarf), it should be very well-coated (at least during washing), or it should be fabricated with a yarn that is better resistant against washing.

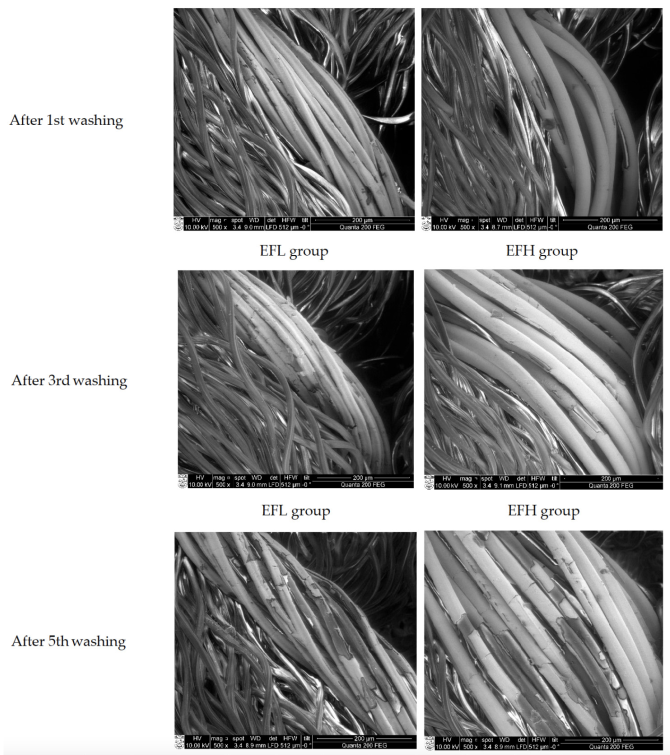


FIGURE 26: MICROSCOPAL PHOTOGRAPHS OF SILVER-PLATED YARNS AFTER WASHING (REPON ET AL., 2021)

SWEAT AND CORROSION

Park et al. (2023) investigated how silver-coated conductive yarns, corrode when exposed to a NaCl solution, which is a major component of sweat. They discovered that corrosion occurs when silver reacts with chlorine ions in the solution, resulting in the formation of silver chloride on the SCCY's surface. This silver chloride then detaches into the electrolyte, causing the silver coating to lose its electrical connectivity. Consequently, the electrical conductivity of the SCCY drops to zero after a couple of hours, as can be seen in figure 27.

To address this issue, the researchers experimented with partially coating the SCCY with gold. The gold coating was applied continuously along the length of the SCCY but only partially in the radial direction. Surprisingly, this radial part-coating of gold significantly extended the SCCY's electrical conduction lifespan to around 192 hours, despite the corrosion rate increasing from 129 to 196 mils per year (mpy).

The results demonstrated that the gold part-coating on the SCCY served as a current pathway for electrical conduction along the length of the yarn. It remained effective until all the silver beneath the gold coating detached from the SCCY strands, causing electrical disconnection. Considering the corrosion behavior, where the local oxidation and detachment of silver occur, the gold part-coating was found to be a more cost-effective solution than fully coating the SCCY's entire surface with gold for maintaining electrical conduction.

However, it can be said that topping a yarn off with gold is also not a very sustainable and material-efficient solution. As for silver, gold is a scarce and expensive material. In Experiment 9: Sweat test, the influence of sweat on the conductivity of SPCY was confirmed. In future research, it would be better to use a different type of conductive yarn (like one mentioned in the previous sample) as the tested material. When commercialising this technology, it is highly recommended to use a different type of yarn than SPCY/SCCY.

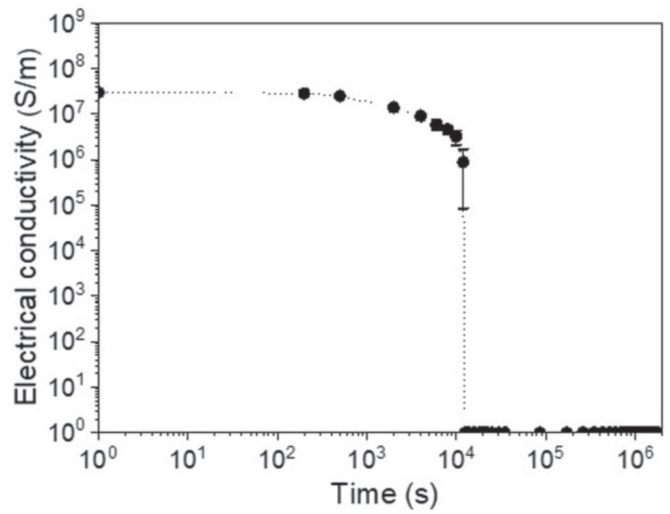


FIGURE 27: CONDUCTIVITY VS TIME DURING A NACL EXPERIMENT (PARK ET AL, 2023)

2.

EXPERIMENTS

THE STOLL WEFT-KNITTING MACHINE USED FOR THE SAMPLE PRODUCTION (MARK LOOPSTRA, 2023)

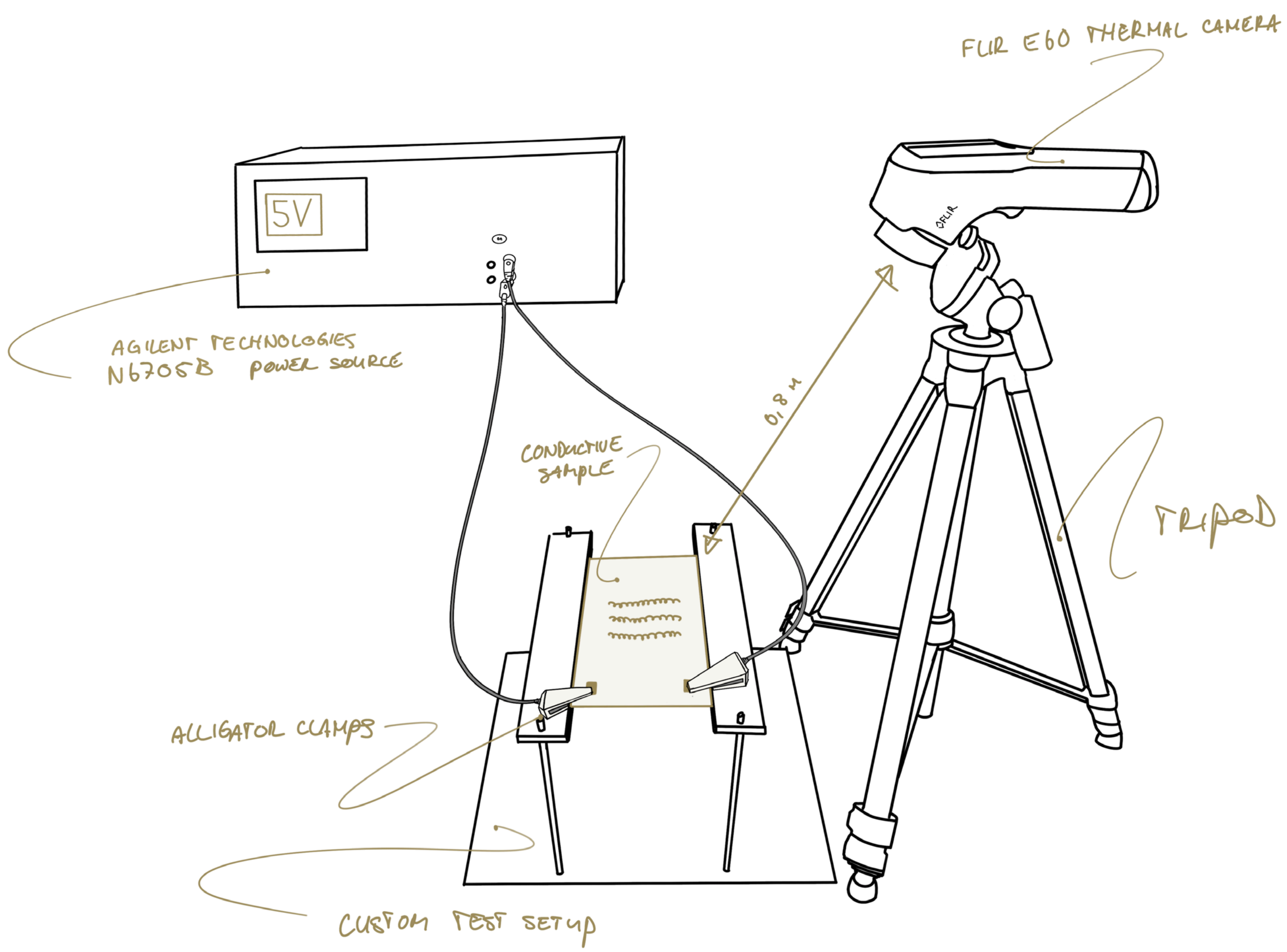


FIGURE 28: VISUALISATION OF THE TEST SETUP

TEST SETUP

As multiple experiments have been conducted under the same circumstances, the general test setup will be elaborated here. All experiments have been conducted accordingly, unless otherwise specified.

- All samples were knitted at Byborre Studio, Amsterdam from March 2023 till July 2023.
- All samples were knitted on a Stoll ADF 530-32 W 14-gauge flatbed knitting machine.
- All experiments were conducted at the 'Applied Labs' section of the faculty of Industrial Design Engineering of TU Delft, the Netherlands. The temperature has been ranging from 19-23 degrees. Relative air humidity has been assumed to be 40% standard.
- The experiments have been conducted from March 2023 till July 2023.
- All power tests have been conducted with the Agilent Technologies N6705B power source.
- Power was transferred to the electrodes of samples with so called 'alligator' clamps.
- Thermal images and recordings were made with a Flir E60 thermal camera, keeping 80 cm distance between the camera and the measured sample. The thermal camera was always set on 'hotspot' mode, measuring the hottest temperature within its given boundaries.
- A custom test setup was designed to measure heat generation through the samples. Therefore during measurements, the conductive parts of all samples have been in contact solely with air.
- Air flow during the measurements has been minimised.
- Relevant data of all yarns used in the experiments can be found in Appendix 4.1: Yarns.
- An overview of all samples used in the experiments can be found in Appendix 4.2: Samples.

EXPERIMENT 1:
KNITTING A FIRST HEATER

The goal of this research is to design an energy- and material-efficient knitted heater that covers a large heating area, and that can be supplied with a low-voltage battery. In this way, it is attempted to contribute to the financial and comfortable appeal of wearable heat:
Knitting allows for scalable production (financial), for breathable and stretchable fabric (comfort). An energy-efficient heater allows for a small battery (comfort). Minimizing conductive material will decrease production costs (financial) while maximizing the heating area and optimising heat dissipation increases comfort.

It is chosen to explore knitted electrical circuits in **parallel configurations**, as these are expected to allow for low resistances (in a parallel configuration, resistances do not add up. See chapter 1.8 resistive heating.), while being able to cover a large heating area. A low resistance is desired in order to keep the input voltage low.

KNITTING WITH SILVER-PLATED YARNS

The involved knit technician at Byborre, Joao, programmed and knitted all mentioned samples. Throughout the project he summed up a couple of remarks about knitting with conductive yarns, that future designers should take into account.

- Conductive yarns generally have a much higher surface friction than other yarns. Therefore, they create a lot of drag. To make the yarns run smoothly, the drag amount on the tensioners should be adjusted accordingly.
- In the long run, the SPCYs cause high wear on the needles, feeders, sinkers, and other metal parts. Therefore, the relative amount of SPCY should be minimised. Besides, these machine parts should be carefully monitored.
- At friction areas, for example on the feeders and guides, tarnish will form, consisting of silver dust. These parts should therefore be cleaned regularly, in order to prevent the dust from spreading to other parts of the machine.

SHIELDEX YARNS (MARK LOOPSTRA, 2023)

INTRO

Sample S0 was knitted as a first experiment to get insights into the heating behavious of a knitted heater. The sample is knitted with two differnet yarns, of which one is conductive, and the other one is non-conductive. The conductive areas are shaped as two vertical parts and two horizontal parts. The vertical parts, from now on called 'leadwires', are the parts where the electrodes are being attached to. They are designed to conduct current from the electrodes to the horizontal parts, from now on called 'heaters'.

In S0, the leadwires are knitted in the wale-direction, meaning that they are knitted vertically, whereas the heaters are knitted in the course-direction, meaning they are knitted horizontally.

SETUP

As described in chapter 'Test Setup' just in front of this experiment, all experiments are ran accordingly.

The sample was charged with 5V for 60 seconds. To visualise its heating behaviour, thermal images were made at t=60s. The current running through the sample at t=60s was measured at 0,61 A.

- Sample S0
- Nh = 2
- Wh = 3 courses
- Lh = 95 wales
- Wl = 6 wales
- Conductive yarn: C2
- Non-Conductive yarn: N1
- date of knitting: 08/06/2023

RESULTS

As can be seen in figure 29 and 30, the sample shows a clear heat difference in the conductive area compared to the non-conductive area. Around the conductive area is a soft glow of heat that is being transfered to the regular yarns.
It is noticed that within the conductive area, the heat is not distributed very evenly. The leadwires have a hotspot on the inner side, where it comes near to the first heater. Besides, the heater further away from the electrode seems to heat up slightly more than the heater close to the electrode.

DISCUSSION

The experiment has proved that a successful electrical circuit can be knitted with conductive yarns. It also shows that **in a parallel configuration, resistances should be designed unevenly in order to achieve an even heat distribution**. Therefore, in the following experiments, two yarns with varying conductivities will be used. This allows for playing around with varying resistivities.

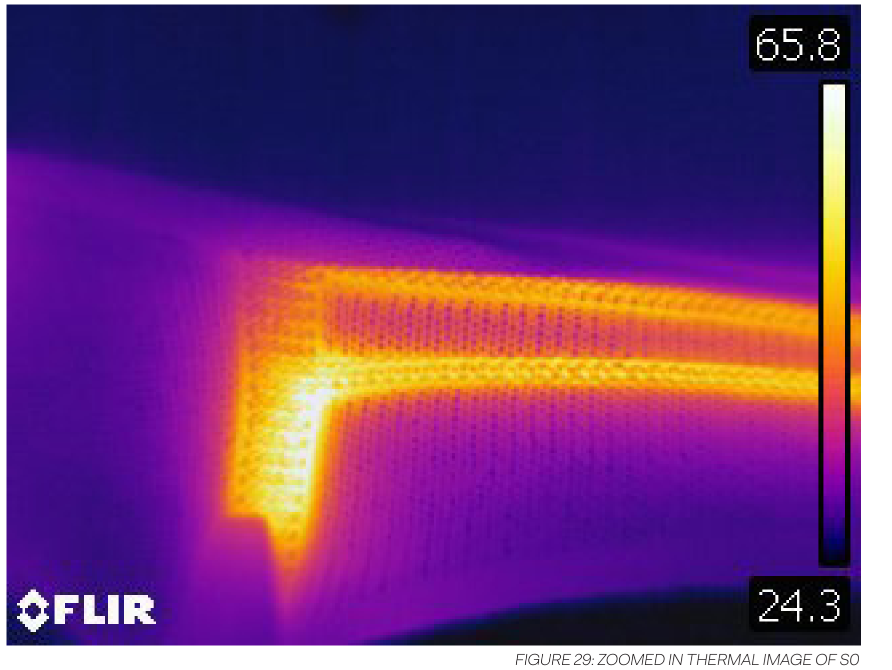


FIGURE 29: ZOOMED IN THERMAL IMAGE OF S0

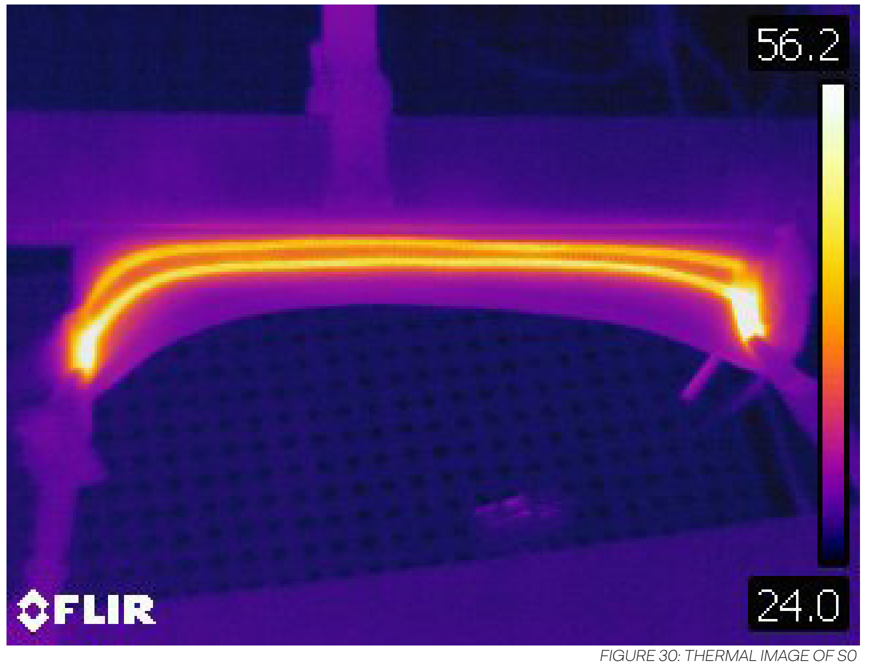


FIGURE 30: THERMAL IMAGE OF S0

EXPERIMENT 2:
PREDICTING RESISTANCES OF SINGLE JERSEY KNITTED HEATERS

Experiment 2 was conducted to find out if the length of a knitted conductive fabric indeed has a proportional effect on the resistance. The samples in the following experiment have all parameters the same, except for the amount of knitted conductive wales:

Sample 1.1: Nwales = 3 wales
Sample 1.2: Nwales = 6 wales
Sample 1.3: Nwales = 9 wales

It makes more sense in this case to work with Nwales instead of width in e.g. milimeters, as the size is small and dependent on many other parameters, whereas Nwales is a clear and absolute value.

Experiments 2.1-2.3 were conducted to proof the following hypotheses:

- **The length of a knitted heater has a proportional relationship with its resistance.**
- **The width of a knitted heater has an inversely proportional relationship with its resistance.**

FIGURE 31: BYBORRE'S EXHIBITION DURING MILAN DESIGN WEEK 2023, SHOWCASING A DECONSTRUCTED NEEDLE (MARK LOOPSTRA, 2023)

The following samples are, unlike S0, knitted with two conductive yarns, having varying conductivities.

The resistances of 9 knitted samples with varying widths were measured with a multimeter. The measurements have been subdivided in three different groups: S1, S2 and S3, referring to the sessions in which they were knitted.
By measuring the resistance throughout several points in the heaters, the c-value can be found by deriving an ax+b type formula being the slope through the graph.

EXPERIMENT 2.1

SETUP

In E2.1, samples S1.1, S1.2 (see figure 32), S1.3 and S1.4 were tested. The heating elements in these samples are knitted in the wale-direction, so they come vertically out of the knitting machine.

Sample S1.1
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 1
- Wh = 3 wales
- Lh = 95 courses
- Wl = 6 courses
- date of knitting: 23/02/2023

Sample S1.2
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 1
- Wh = 6 wales
- Lh = 95 courses
- Wl = 6 courses
- date of knitting: 23/02/2023

Sample S1.3
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 1
- Wh = 9 wales
- Lh = 95 courses
- Wl = 6 courses
- date of knitting: 23/02/2023

Sample S1.4
- Conductive yarn 1: C3
- Conductive yarn 2: C4
- Non-conductive Yarn: N1
- Nh = 1
- Wh = 6 wales
- Lh = 95 courses
- Wl = 6 courses
- date of knitting: 23/02/2023

The samples were placed in a test setup (see figure 29) and

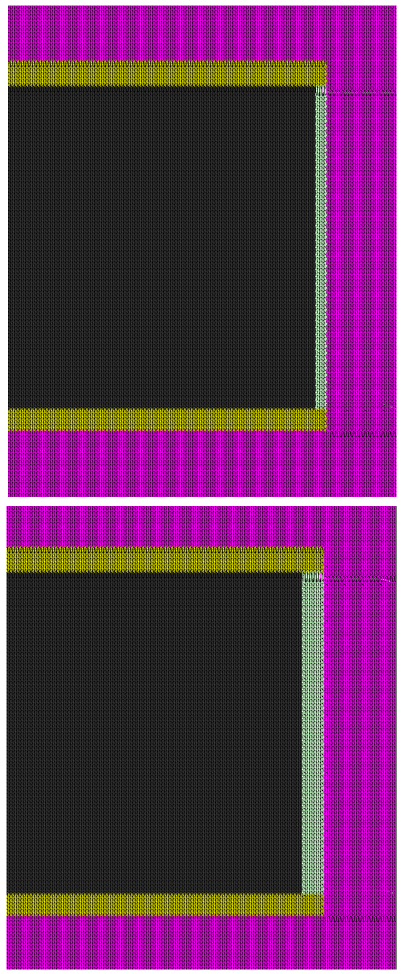


FIGURE 32:TECHNICAL DRAWINGS OF SAMPLES 1.1 (TOP) AND 1.2 (BOTTOM)

were attached to a power source with regular power cables with 'alligator' clamps. Then, voltages of 1V, 2V, 3V, 4V and 5V were run through the samples and their resistances and temperatures were measured on t=0s and t=60s. The same was measurements were performed through the conductive part (lead wire) of one of the samples.

RESULTS & DISCUSSION

In figure 34, the resistance through the samples is plotted against the length/width ratio of the heating elements. In figure 33, the length of the conductor is plotted against the resistance, as no variations in the width of the conductor were produced. The graphs show that there is an overall linear correlation between the resistance and ratio, without any major deviations. The slopes of S1.1 and S1.2 are very similar (5,6 and 5,5), whereas the slope of S1.3 is less steep (2,8).
The slope of S1.4 is a lot steeper, which can be explained by the different yarn conductivity.

Graph 33 shows a similar linear corelation, but less steep as only the length is included in the measurements (c=0,03).

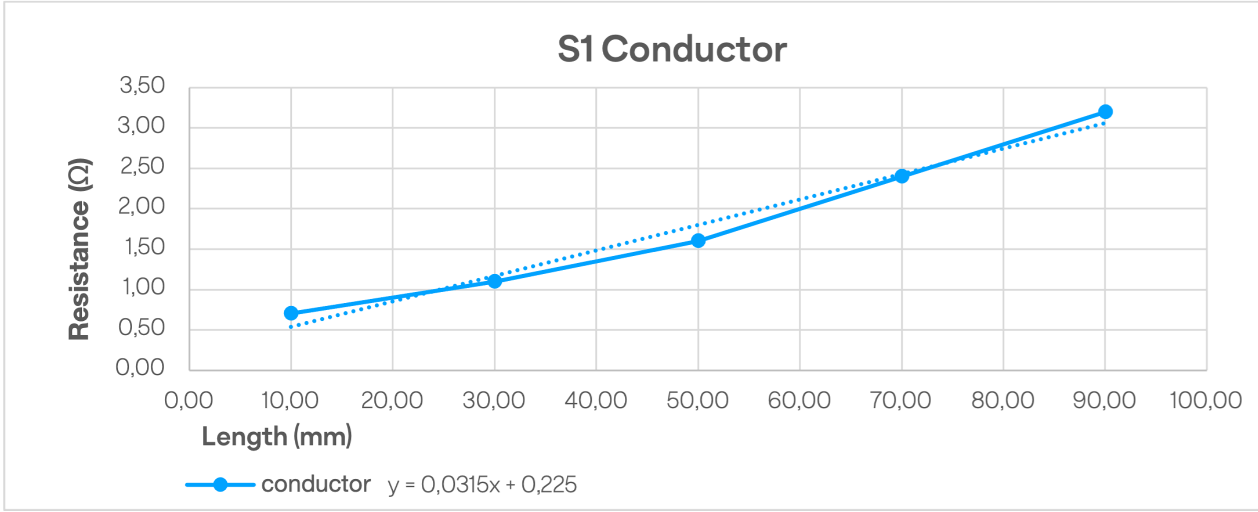


FIGURE 33: RESISTANCE OVER LENGTH GRAPH OF CONDUCTOR IN SAMPLE SESSION 1

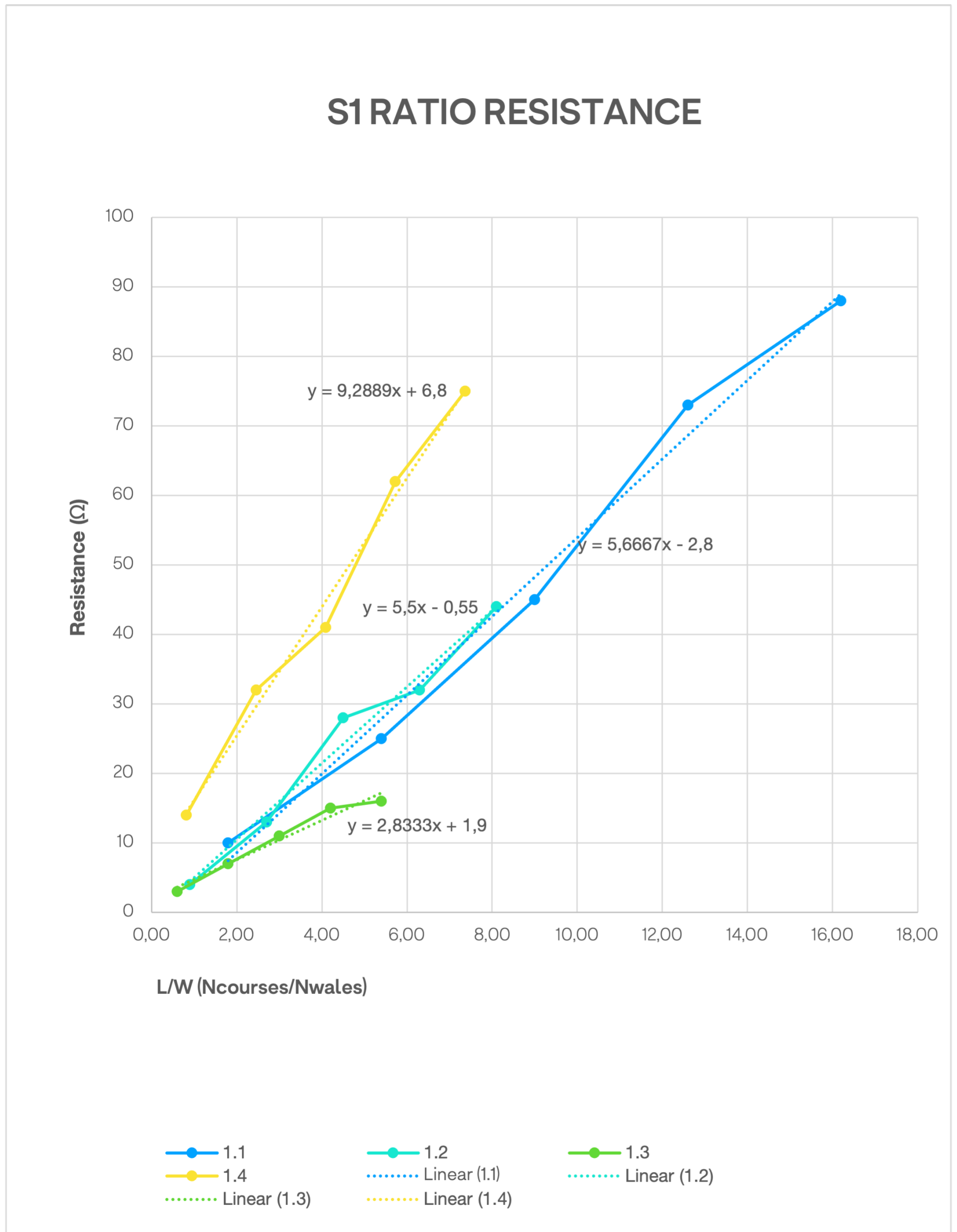


FIGURE 34: RESISTANCE OVER LENGTH/WIDTH GRAPH OF CONDUCTOR IN SAMPLE SESSION 1

In knit session 2, three samples were compared with conductive yarns knitted in the course-direction. Again, the amount of courses was varied between the samples, and were put in a parrallel configuration:

S2.1: 6 courses
S2.2: 2 x 4 courses
S2.3: 2 x 6 courses

In a parallel electrical configuration, the formula for the sum of resistances is as follows:

$$\frac{1}{Rot} := \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} \ldots$$

As the configurations of S2.2 and S2.3 are basically a parallel circuit with two resistances containing 4 and 6 courses each, respectively, it can be expected that the resistance of S2.3 will be twice as low as that of S2.1.

EXPERIMENT 2.2

SETUP

In Exp. 2.2, samples S2.1, S2.2 and S2.3 (see figure 35) were tested. The heating elements in these samples are knitted in the course-direction, so they come horizontally out of the knitting machine.

Sample S2.1
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 1
- Wh = 6 courses
- Lh = 67 wales
- Wl = 6 courses
- date of knitting: 09/03/2023

Sample S2.2
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 2
- Wh = 4 courses
- Lh = 67 wales
- Wl = 6 courses
- date of knitting: 09/03/2023

Sample S2.3
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 2
- Wh = 6 courses
- Lh = 67 wales
- Wl = 6 courses
- date of knitting: 09/03/2023

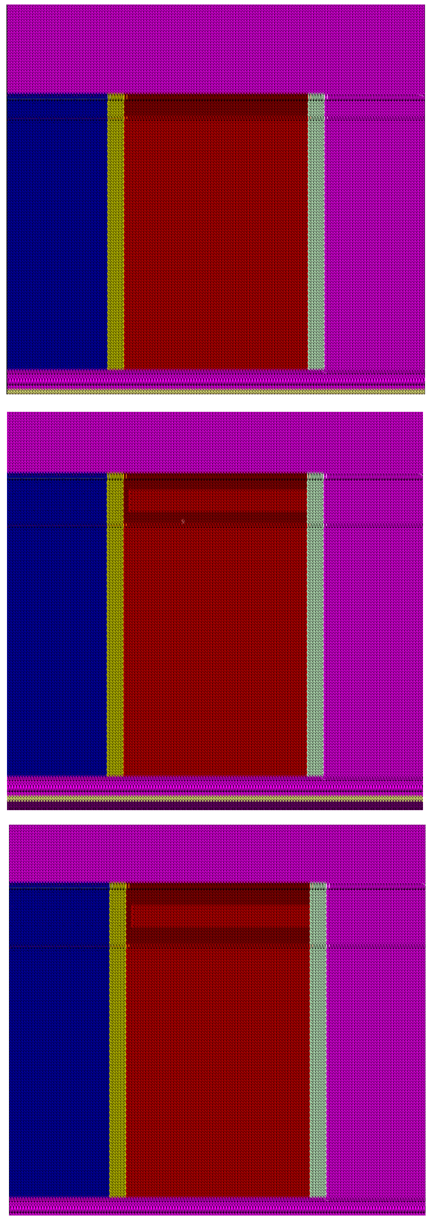


FIGURE 35: TECHNICAL DRAWINGS OF SAMPLES S2.1-S2.3

RESULTS & DISCUSSION

In figure 36, the resistance through the samples is plotted against the width of the heating elements. In figure 37, the resistance is plotted against the length/width ratio of the heaters. It was not possible to measure the resistance through different lengths of the heaters, as the current in a parralel circuit will work its way around the single element.

Figure 36 shows an inversely linear relationship between the resistance and width, and figure 37 shows again the relationship between resistance and L/W ratio. The c-value of the slope in figure 37 is 3,8.

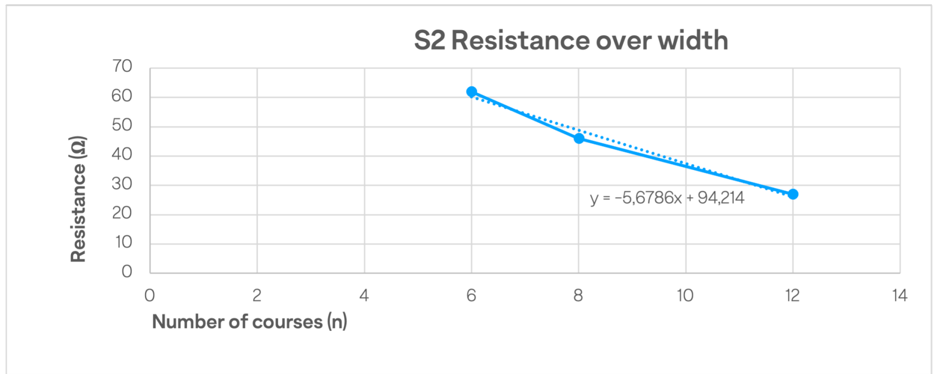


FIGURE 36: RESISTANCE OVER WIDTH GRAPH OF SAMPLE SESSION 2

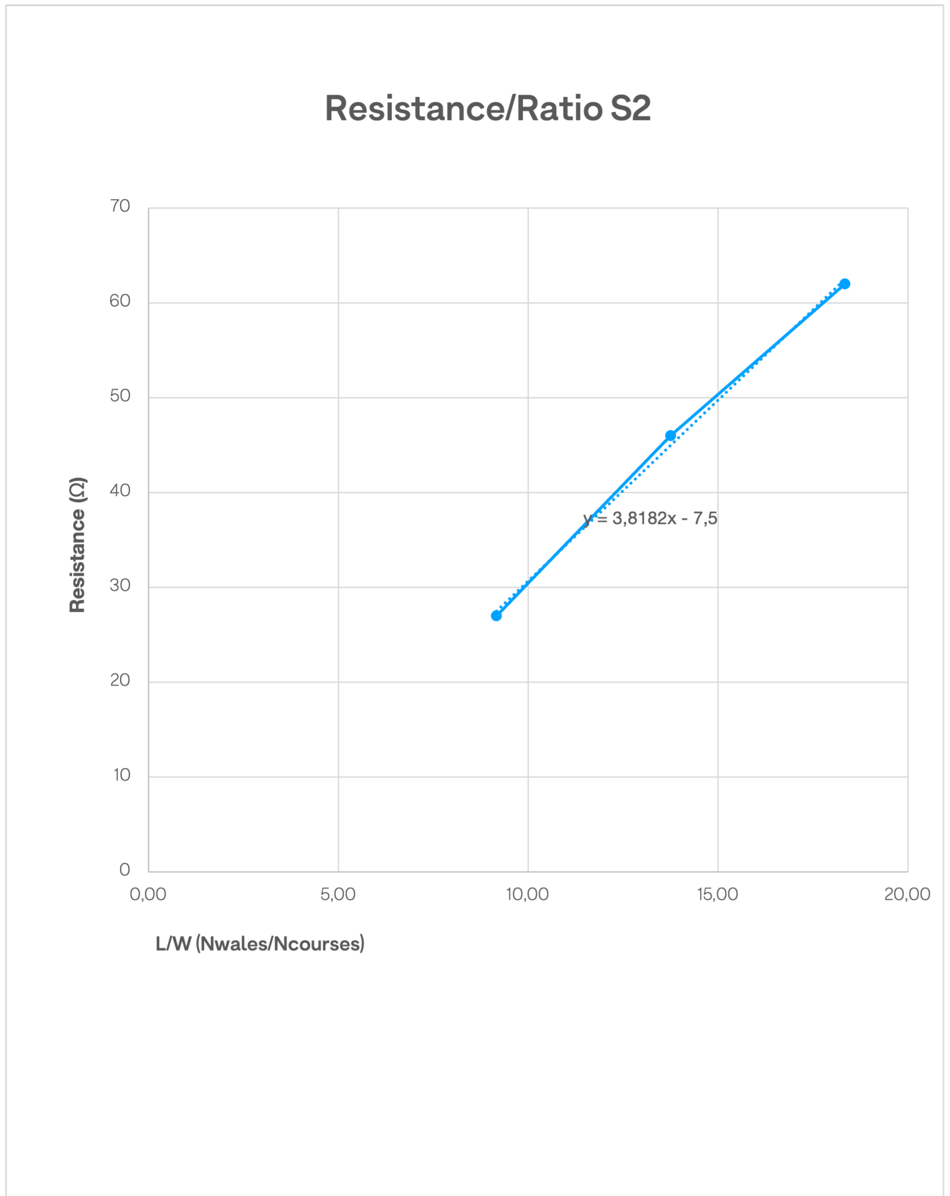


FIGURE 37: RESISTANCE OVER RATIO LENGTH/WIDTH SAMPLE SESSION 2

In knit session 3, two samples were knitted with conductive yarns knitted in the course-direction. The samples contain 6 and 12 courses of conductive yarns respectively, configured in a parralel circuit (see figure 39). It is hypothesized that the difference in resistance of these samples compared to those of session 2, is that there is no extra contact between individual courses, making it harder for the current to flow through.

EXPERIMENT 2.3
SETUP

In Exp. 2.3, samples S3.1 and S3.2 (see figure 39) were tested. The heating elements in these samples are knitted in the course-direction, so they come horizontally out of the knitting machine.

Sample S3.1
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 6
- Wh = 1 course
- Lh = 67 wales
- Wl = 6 courses
- date of knitting: 23/03/2023

Sample 3.2
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl = 6 courses
- date of knitting: 23/03/2023

RESULTS

As can be seen in figure 38, S3.1 gives a measured resistance of 41 ohms, indicating a relatively lower resistance value compared to Sample §.2, which measured 56 ohms. This discrepancy in resistance values suggests that Sample 3.1 offers better conductivity and lower electrical resistance compared to Sample 3.2.

FIGURE 38: RESISTANCES OF SAMPLES S3.1.1 AND S3.2

DISCUSSION

It was anticipated that the resistance of Sample 3.2 would be approximately half that of Sample 3.1, as the amount of heating elements doubled. The results deviated from this expectation, as the measured resistance of S3.1 was 41 ohms, while S3.2 measured a resistance of 56 ohms.

This proves that predicting the conductivity of a smart textile heating element is challenging due to various factors. Unlike a tradional electrical circuit, the contact between individual yarns play a crucial role in maintaining a consistent resistance. Single Jersey EHGs are, due to their physical characteristics, very sensible to external factors.

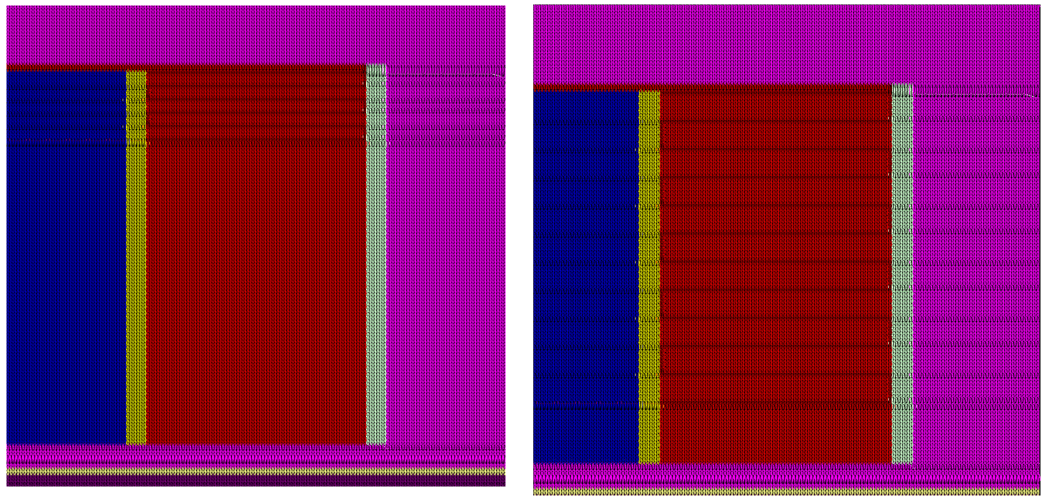


FIGURE 39: TECHNICAL DRAWINGS OF SAMPLES 3.1 AND 3.2

DISCUSSION E2

Comparing multi-course and single-course heating elements, it can be said that knitting with multi-course elements offers several advantages. First of all, multi-course elements show higher consistency in resistance prediction compared to single-course elements. Moreover, in case of yarn breakage, a single-course heating element would become dysfunctional, while multi-course elements provide redundancy and maintain functionality.

The experiments prove that the resistance of a heating element is dependent on its length and width. As the length of the element increases, the resistance tends to increase proportionally due to the longer path for electrical current. Conversely, wider elements allow for multiple paths for current flow, reducing resistance. These relationships between length, width, and resistance should be considered when designing heating elements to achieve the desired heating performance.

There is no surprising difference in resistance prediction between knitting heating elements in the course direction (horizontal) or wale direction (vertical). However, knitting in the course direction offers certain advantagesin terms of programming ease; The course direction allows for simpler programming and control of the knitting machine. More on this can be found in the discussion after Experiment 2.4.

Single jersey heaters are generally not so suitable for heating applications due to their lack of sturdiness and sensitivity to external factors that can influence resistance. Single jersey heaters also allow for skin conductivity when placed directly on the human body, which may lead to discomfort or safety concerns.

Considering stability and safety, it is therefore decided to explore different knit structures in future experiments. By knitting for example a double jersey knit structure and utilizing the plating technique, the resulting heating elements are expected to exhibit improved resistance prediction, increased durability, and enhanced safety. These factors are crucial for the optimal performance, user comfort, and longevity of smart textile heating elements.

EXPERIMENT 3: THE INFLUENCE OF POWER INPUT ON HEAT GENERATION IN SJ KNITTED HEATERS

Experiment 3 focuses on investigating the relationship between input voltage and heat generation in weft-knitted heater samples. The experiment subjects samples from the three previous knit sessions (sessions 1, 2, and 3) to varying voltages and measuring the resulting maximum temperatures using a thermal camera. The data collected from the experiment is then used to construct graphs, and the slopes of these graphs are analyzed and discussed.

The slopes of these graphs serve as indicators of the relationship between input voltage and heat generation in the weft-knitted heater samples. Analyzing the slopes allows researchers to assess the impact of voltage on the heating efficiency and performance of the knitted heaters.

FIGURE 40: THERMAL CAMERA IN ACTION (MARK LOOPSTRA, 2023)

SETUP

To prove the correlation between heat generation Q and power input P, experiments 3 was conducted. It is hypothesized that the heat generation is determined only by input power and time. For this experiment, the same samples were used as mentioned in the previous experiment. The samples of knit sessions 1 are heated with set voltages of 1-5V and variable amperages, whereas the samples of sessions 2 and 3 were heated with set voltages of 2-7V and variable amperages. This difference will not influence the slope values that are conducted from the graphs. The maximum temperature was measured after 60 seconds with the thermal camera mentioned at the beginning of the 'Experiments' chapter, where an overview of the test setup can also be found.

RESULTS

The results can be seen in figure 43, 44 and 45. The graphs show clear linear correlations between input power and temperature. The slopes of the samples with a larger heating area are less steep. The graphs also show a slightly decreasing curve.

DISCUSSION

It can be concluded that the input power is indeed the main cause of heat increase in a knitted heater. In samples with small heating areas, the heat gets concentrated and will thus show a steeper slope. When samples gets hot, a relatively high amount of heat will be dissipated to the air, hence the flattening curves. If we compare the slopes of S2.1 and S3.1, we see that the slope of S2.1 is slightly steeper (13%) than the slope of S3.1, whereas the amount of heated courses is equal. This can be explained through heat clustering: when two heating elements get close to each other, their heat will cluster and the total dT will increase.

THERMAL MASS

In this experiment, the maximum temperature in the samples were measured. However these values do not say a lot about heat dissipation to the body. A conductive mass that is in contact with the heater (such as the hunman body), is likely to absorb the generated energy and therefore will not let the heater reach a 'predicted' temperature.

For this experiment, we can use temperature as a unit because we are comparing values while we keep other parameters the same. However, it should be taken into account that when we draw conclusions for heat dissapation to the human body, we need to work with thermal mass or surface power density (input power per area) rather than with temperature difference.

Input power is very likely the main factor in determining the temperature change in a knitted heater. A higher dT can be achieved by making a concentrated heater, whereas more evenly distributed heat can be achieved by designing a heater with a larger area. It should be taken into account that the maximum dT generated will then be lower.

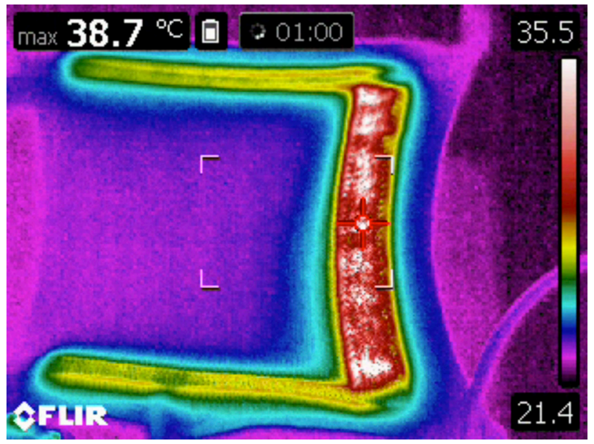


FIGURE 41: IR PHOTOS OF SAMPLES 1.3 AND 4.1 AT T=60S

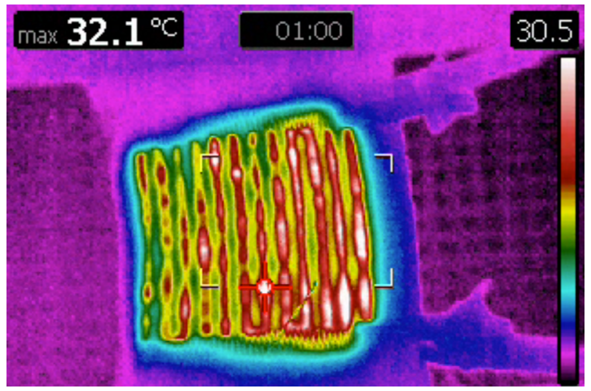


FIGURE 42: IR PHOTOS OF SAMPLES 1.3 AND 4.1 AT T=60S

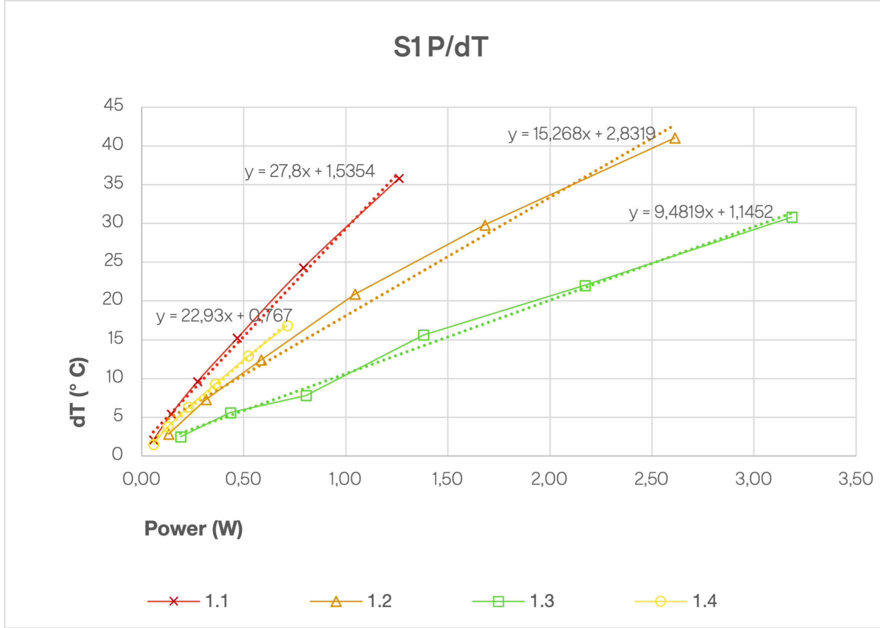


FIGURE 43: POWER INPUT VERSUS TEMPERATURE DIFFERENCE FOR SAMPLE SESSION 1

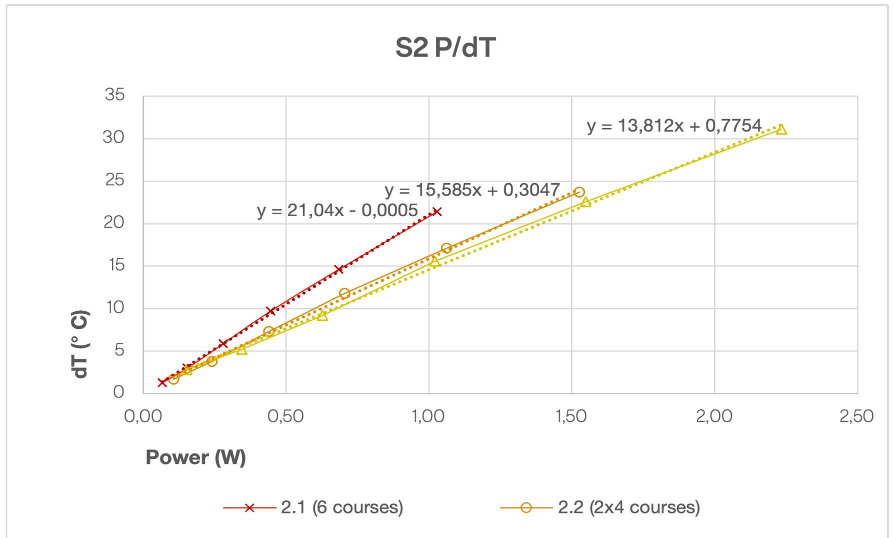


FIGURE 44: POWER INPUT VERSUS TEMPERATURE DIFFERENCE FOR SAMPLE SESSION 2

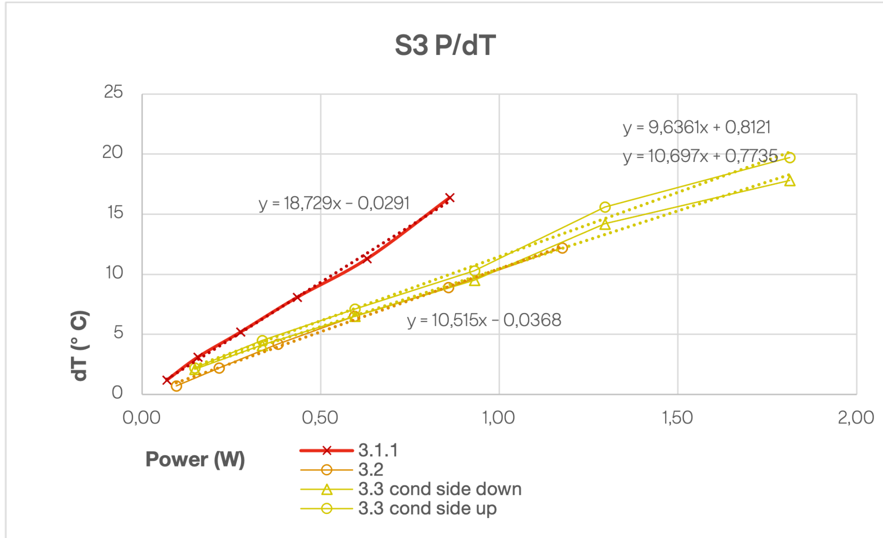


FIGURE 45: POWER INPUT VERSUS TEMPERATURE DIFFERENCE FOR SAMPLE SESSION 3

EXPERIMENT 4: THE INFLUENCE OF PLATING ON THE ELECTRICAL RESISTANCE AND PHYSICAL PROPERTIES OF CONDUCTIVE SAMPLES

During the previous experiments, it was noticed that single-jersey samples prove inadequate due to slackness, inconsistenct resistance performances, poor structural stability, curling (hindering ease of use), and the potential for skin conductivity when put on the human body. Despite the low current flowing through the samples, skin conduction should be prevented for both comfort and safety considerations. Therefore, it was decided to investigate knitting techniques that can address these challenges. The following experiment focusses on plating as a viable method to achieve **higher resistance stabilities, and higher endurance against mechanical abrasion.**

The plating technique offers an innovative approach to incorporate conductive elements, such as silver-plated yarns, into textile structures with improved stability and performance. This technique involves the simultaneous knitting of both conductive and non-conductive yarns, resulting in a dual-layered fabric structure (see chapter 1.5). It is hypothesized that the conductive yarn, typically positioned on the outer layer, will provide the necessary heating functionality, while the inner non-conductive yarn ensures insulation and protection.

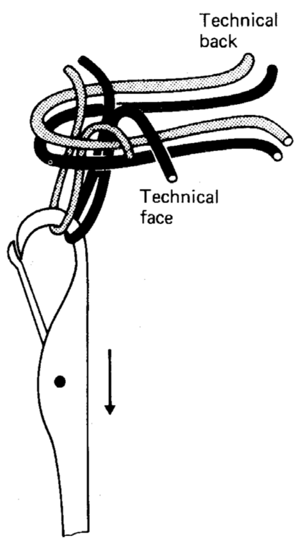


FIGURE 46:PLATING IN WEFT-KNITTING (SPENCER, 2001)

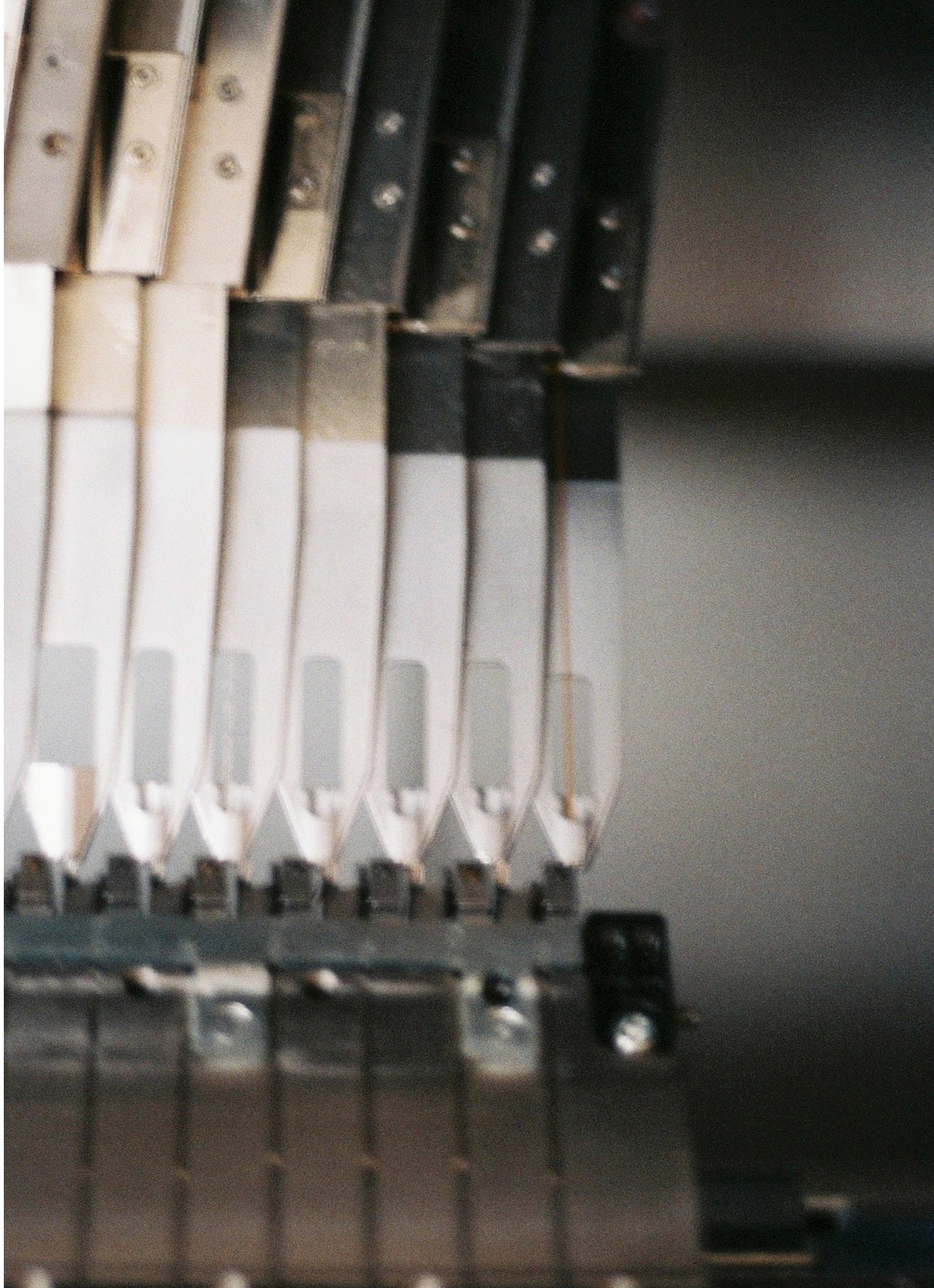


FIGURE 47: YARN CARRIERS (MARK LOOPSTRA, 2023)

EXPERIMENT 4.1

In experiment 4.1, the electrical resistances and physical properties of samples S3.2 and S3.3 were compared. The two samples were knit identically, except that in S3.3, the conductive yarns are co-knitted with the same yarn as the non-conductive base yarn, whereas S3.2 is a simple SJ.

SETUP

The heating elements in these samples are knitted in the course-direction, so they come horizontally out of the knitting machine. It is hypothesised that plating a conductive yarn will increase conductivity compared to regular SJ knitting.

Sample S3.2

- SJ
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 6
- Wh = 1 course
- Lh = 67 wales
- Wl = 6 courses
- date of knitting: 23/03/2023

Sample S3.3

- SJ Plated
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Non-conductive Yarn: N1
- Nh = 6
- Wh = 1 course
- Lh = 67 wales
- Wl = 6 courses
- date of knitting: 23/03/2023

RESULTS

As can be seen in figure 51 (graph), the resistance through the plated sample shows a decreased resistance. The sample also has slightly smaller dimensions and feels more study at the plated areas.

DISCUSSION

As can be seen in figure 48 (plating front side), The conductive yarn is sandwiched between two layers of non-conductive yarn, and it does not make contact with other conductive stitches, as the heating elements in this experiment consist of single course. Therefore, the decrease in resistance can be fully explained by contact change in the yarn structure itself. It can be seen in the microscope images that the yarns consist of many individual fibres. An obvious explanation for the resistance drop would therefore be that these fibres are pressed onto each other more densely, making current flow more easily.

A second and more in-depth experiment about plating techniques and their corresponding conductivity and stability, which covers multi-row heating areas, is conducted in chapter 2.5.

It can definitely be said that plating is a good first step towards more sturdy knitted heaters with increased conductivity. However, it still has the tendency to curl up in the non-plated SJ areas. Therefore, a different knit structure (such as double jersey) should be considered to continue with for future experiments.

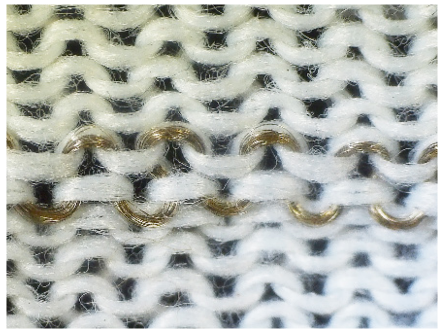


FIGURE 48: PLATING FRONT SIDE

FIGURE 49: PLATING BACK SIDE: ALMOST PERFECT

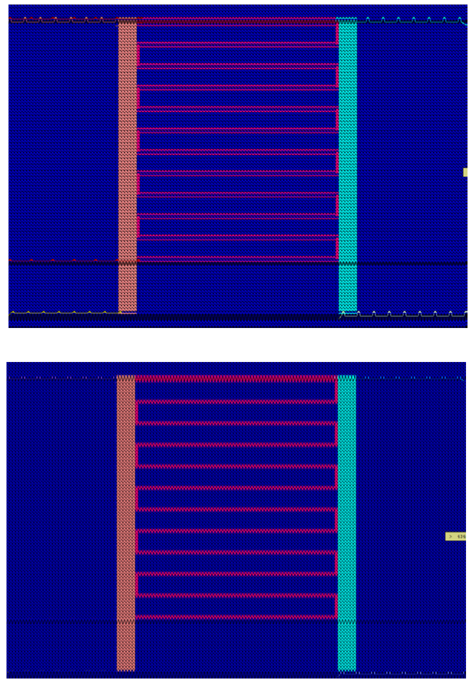


FIGURE 50: TECHNICAL DRAWING OF SAMPLES 3.3: BACK (UP) AND FRONT (BOTTOM)

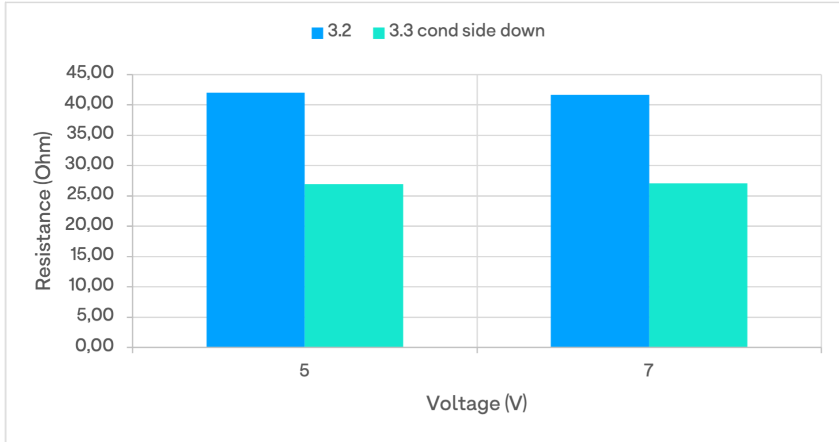


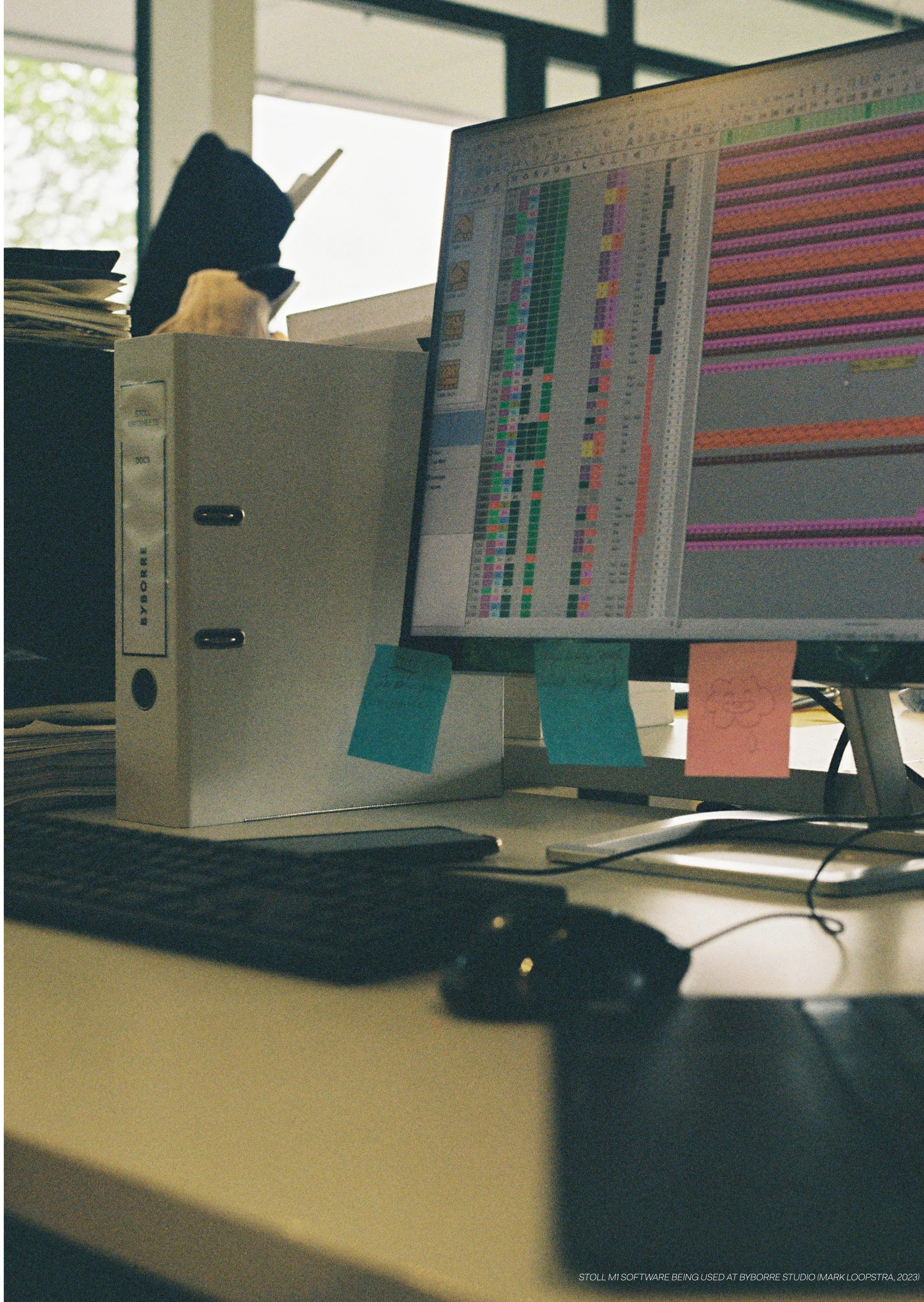
FIGURE 51: PLATING BACK SIDE: ALMOST PERFECT

DISCUSSION

FROM SINGLE TO DOUBLE JERSEY: SANDWICHING THE HEAT

Sweat has proven to severy damage yarn conductivity. It is hypothesized that insulating the conductive yarns with layers of non-conductive (preferably hydrophobic) fabrics could resolve these issues; the results on the conducted experiments can be found in chapter 2.9: Sweat test. An additional possible benefit of insulating the conductive yarns with other materials is improved insulation: According to Byborre's knitting experts, well-insulating material such as wool could trap the heat and decrease heat loss to the air, creating a more efficient heater. It should however be taken into account that the goal is not to make a heater that is as hot as possible: It should be able to supply its wearer with perfect thermal comfort. Breathability of a material should therefore also be taken into account.

To increase sturdiness, safety, and possibly insulation, the double jersey stitch type was chosen to develop for future samples. **This chapter is dedicated to addressing the challenges that come with knitting a double jersey fabric with conductive yarns, and how to deal with them.**



STOLL M1 SOFTWARE BEING USED AT BYBORRE STUDIO (MARK LOOPSTRA, 2023)

DOUBLE JERSEY

A double jersey (also referred to as DJ) is a **weft knitted fabric with two layers, formed by two beds of needles**. These layers can be knitted separately and can be attached by the stitches on the opposing needle bed. They can also be attached to each other with a tuck in between the layers (Joao, 2023).

THE SANDWICH

When double jersey is combined with plating, a three-layered textile can be knitted. In this case, the layer in the middle is insulated by the two layers on the outside.
As mentioned before, it was desired to insulate the conductive yarn for multiple reasons. Therefore, it was decided to continue with a double jersey + plating structure, in which the conductive yarn is placed in the middle. From now on, this structure will be referred to as the 'sandwich'. The sandwich structure can be obtained by either plating the relevant yarn on the backside of the front jersey, or by plating is on the frontside of the back jersey.

OUR SANDWICH

It was chosen to knit the new, second layer, that is part of the DJ, with a wool blend yarn (See appendix 4.1 Yarns, N2) as wool has both thermoregulating and hydrophobic characteristics. The front surface is knitted with the same polyamide yarn as used in the previous experiments. The same conductive yarns were used (See appendix 4.1 Yarns, C1, C2).

Figure 52 displays a screenshot of the Stoll M1 programming software that shows how the DJ + plating structure was programmed. As can be seen in the middle part, the two jersey layers are connected to each other with a covered elastane tucked yarn (See appendix 4.1 Yarns, N3), in the aforementioned figure represented by the orange colour. The left part represents the stitch lengths of every stitch. The tucked stitch is programmed tight in order to keep the two jerseys well together. The part on the right of the figure shows the yarn combination that is being plated on specific yarn carriers, with 1 and 2 representing the front and backside respectively. So, yarn carrier 1 plates the (programmed as) pink yarn in front of the (programmed as) yellow/green-ish yarn. The part in the middle (main display) displays the actions that the corresponding yarns will take.

BYBORRE uses plating combined with intarsia on an ADF machine. Intarsia means that the head of the yarncarrier can 'swivel', which is necessary to knit only in a segment in the middle of the knit, without having to pull the yarn all the way to the left or right.

CHALLENGES

A couple of difficulties were ran into during the process of developing the sandwiched structure.

The conductive yarns had, in combination with its plating yarn, a very high dtex, which resulted in ugly, warped samples. fix this, the stitch length in the plated areas was increased in order to give the yarns more space to be knitted.

After increasing the stitch length, however, the samples still did not come out properly sandwiched. Especially in the leadwires, the plating was far from perfect and conductive yarn often flashed to the surface, in an alternating pattern (see figure 53, 54). After some trial and error, it was discovered that this had to do with the tucking yarn (see figure 55): As the dtex of the conductive yarn C2 was relatively high, the tucking of the connection elastane N3 yarn, that would connect the two jerseys, pulled the non-conductive N1 yarn inside, making the conductive yarn rise to the surface.
As this was quite a struggle, and there was not found a way to stop the tucking yarn from pulling quickly, it was decided to completely leave out the tucking yarn in the plated areas. This seemed like an elegant solution in the beginning. However, later in the project when wider leadwires were knitted, the leadwires got the tendency to blow up like a blister (see figure 57). Again, this was caused by the higher dtex in these areas.

DISCUSSION

The sandwiching technique has proved to be a reliable way to easily foresee conductive yarns of a basic protective layer, and to make the samples much more sturdy while remaining functionality. However, later experiments will show that these layers are not enough to protect the yarns against mechanical abbresion. Besides, some aesthetic trade-offs were made to properly sandwich the conductive yarns. Lastly, as elaborated in Experiments E10, plating severly influences the electrical resistance and thus the heating behaviour through the textile: The right plating technique should be chosen for the right occasion.

The sandwich technique has promising benefits, but comes with some annoying side-effects. In future R&D, more knitting experiments should be conducted to find a way to better insulate the conductive yarns, while keeping control over the resistance.

Nevertheless, the samples tested in the following experiments are (almost) all sandwiches.

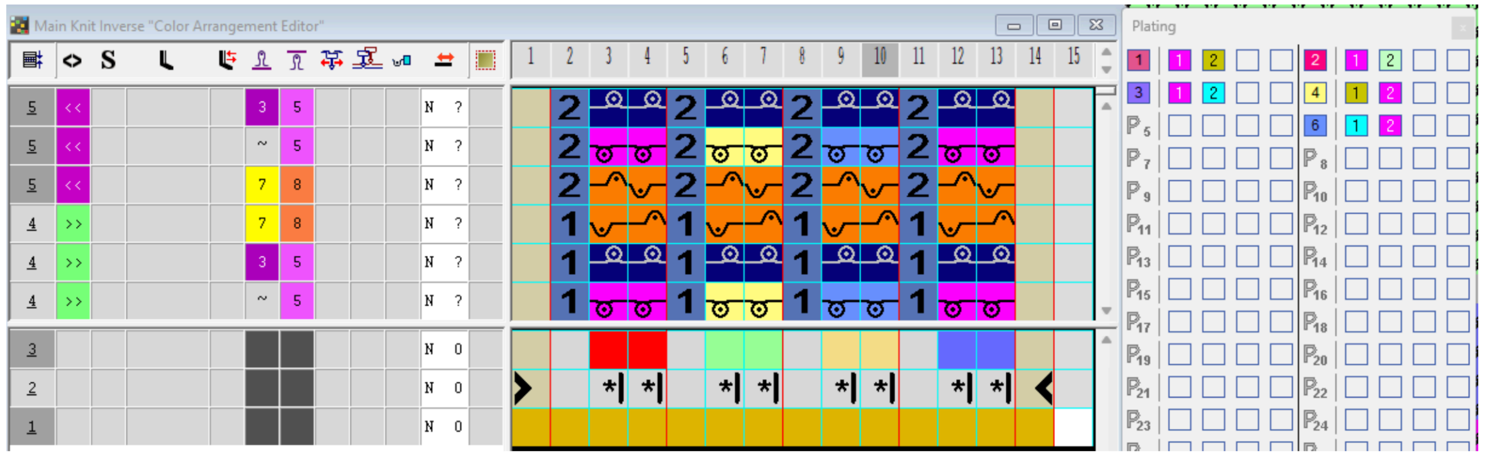


FIGURE 52: STOLL M1 SOFTWARE SHOWCASING THE SANDWICH STRUCTURE

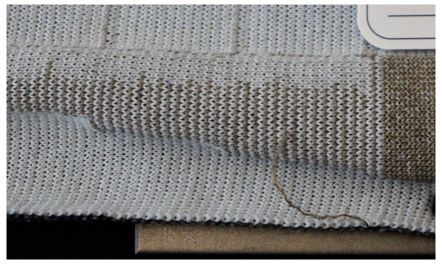


FIGURE 53: CLOSE-UP OF SAMPLE S10.2

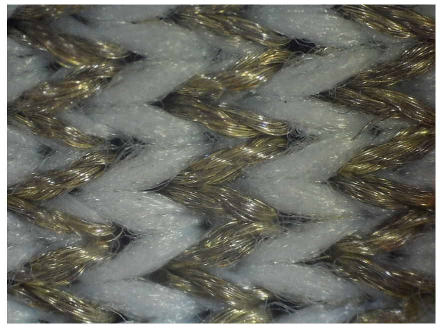


FIGURE 54: MICROSCOPE IMAGE OF SAMPLE S10.2, FRONT SIDE

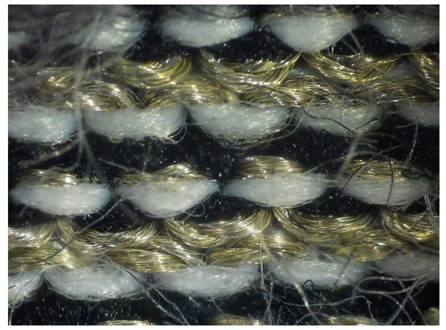


FIGURE 55: MICROSCOPE IMAGE OF SAMPLE S10.2, BACK SIDE

FIGURE 56: SAMPLE S10.1

FIGURE 57: CLOSE-UP OF SAMPLE S10.1

EXPERIMENT 5: THE RESISTANCES AND STABILITIES OF DIFFERENT PLATING TECHNIQUES

It was discovered that the way of plating has a strong influence on the conductivitiy of a knit; when plating the conductive yarn on the front, conductivity will be higher than when plating on the back. Besides that, it was noticed during experiment 6.2 that the plating technique used in the leadwire made the resistance very sensitive to stretch. **This experiment is dedicated to quantify the influence of three different plating techniques on the resistances and corresponding stabilities of knitted resistors.**

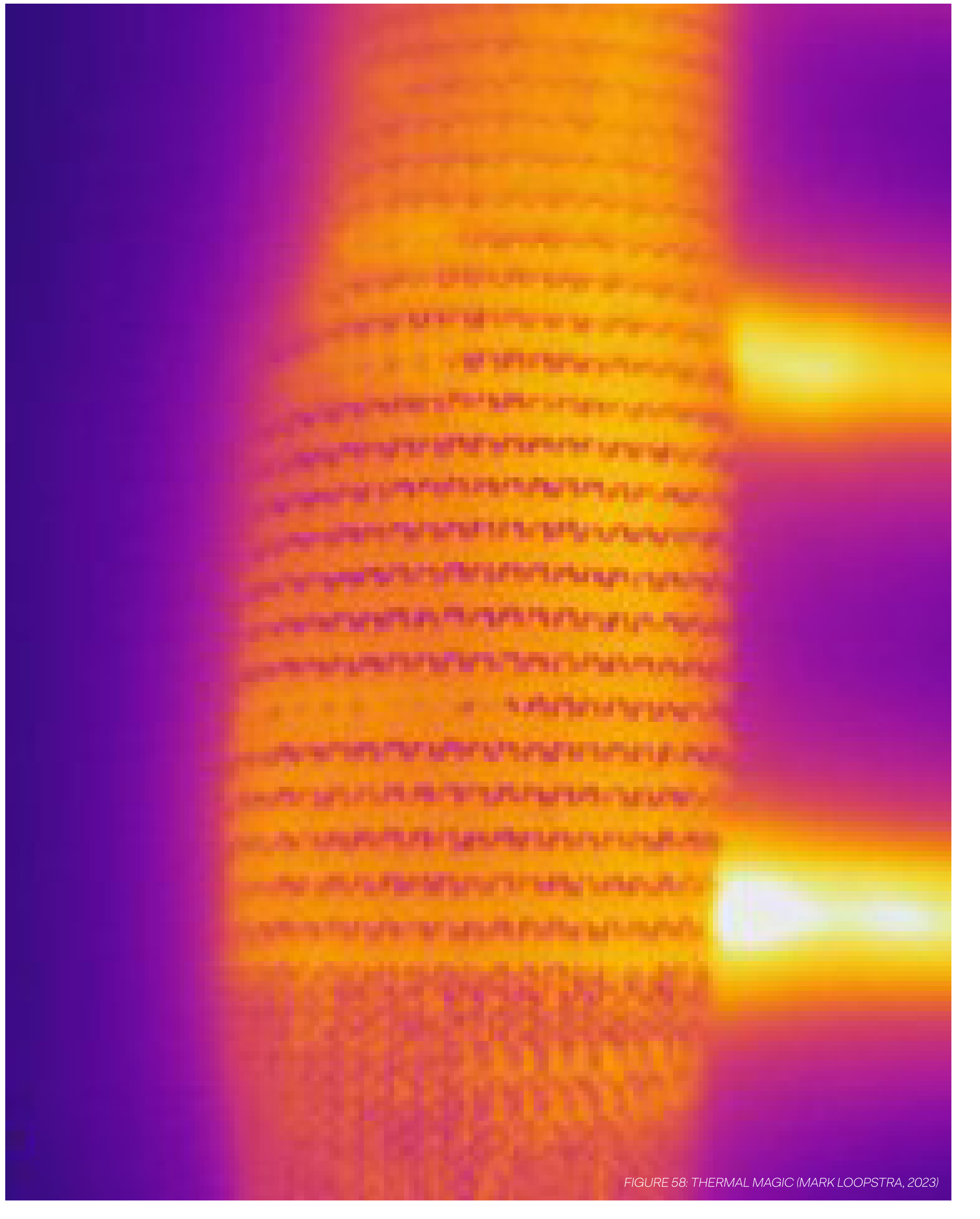


FIGURE 58: THERMAL MAGIC (MARK LOOPSTRA, 2023)

Three samples were produced: S10.1, S10.2 and S10.3. The samples are identical, except for the plating technique used in their leadwires:

S10.1

S10.1 (see figure E641A) is a DJ 'sandwiched' knit, with the conductive yarns of the leadwire being plated on the back of the frontside jersey. In this samples, the two jerseys are not connected in the conductive areas in order to maintain the sandwich (see chapter 2.5). As the conductive yarn is plated on the back, the yarn is not visible on the front (see figure E641B). The plating went almost perfect; From a distance, the conductive yarn is not visible, but when looked at with a microscope (see figure E641C), some conductive yarn can be seen on the outside.

- DJ Plated
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Plating yarn: N1
- Back Jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl = 2-26 courses
- date of knitting: 01/06/2023

S10.2

S10.2 (see figure E642A) is also a DJ 'sandwiched' knit, but now the two jerseys are connected with an additional, elastic yarn. This resulted in altering behaviour for the plating, which is explained in the discussion after Chapter 2.4. For one stitch the conductive yarn is on the outside, for the other it is on the inside (see figure E642c). Therefore, the conductive yarn is not actually sandwiched anymore (only half of the time).

- DJ Plated
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Plating yarn: N1
- Back Jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl = 2-26 courses
- date of knitting: 01/06/2023

S10.3

S10.3 (see figure E643A) Is a DJ knit with the conductive yarn plated on the front side of the front jersey. Therefore, the conductive yarns of the leadwire are fully visible on the outside of the sample. As for S10.1, the plating is almost perfect, when zoomed in with a microscope (see figure E643C), the non-conductive yarn is slightly visible.

- DJ Plated
- Conductive yarn 1: C1
- Conductive yarn 2: C2
- Plating yarn: N1
- Back Jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl = 2-26 courses
- date of knitting: 01/06/2023

In order to take the influence of stretch on the resistance of the heaters into account, S6.1.2 (Sample 6.1, the part that is 2 courses wide) was also subjected to the tensile machine, and was tested under the same conditions as mentioned later. As this sample is much smaller (20mm), it was harder to accurately stretch it. Nevertheless, valuable results were derived.

S10.1 **S10.2** **S10.3**

FIGURE E641A: SAMPLE S10.1

FIGURE E642A: SAMPLE S10.2

FIGURE E643A: SAMPLE S10.3

FIGURE E641B: CLOSE-UP OF SAMPLE S10.1

FIGURE E642B: CLOSE-UP OF SAMPLE S10.2

FIGURE E643B: CLOSE-UP OF SAMPLE S10.3

FIGURE E641C: MICROSCOPE IMAGE OF SAMPLE S10.1, FRONT SIDE

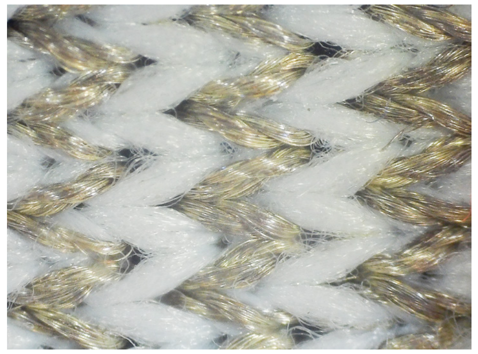


FIGURE E642C: MICROSCOPE IMAGE OF SAMPLE S10.2, FRONT SIDE

FIGURE E643C: MICROSCOPE IMAGE OF SAMPLE S10.3, FRONT SIDE

FIGURE E641D: MICROSCOPE IMAGE OF SAMPLE S10.1, BACK SIDE

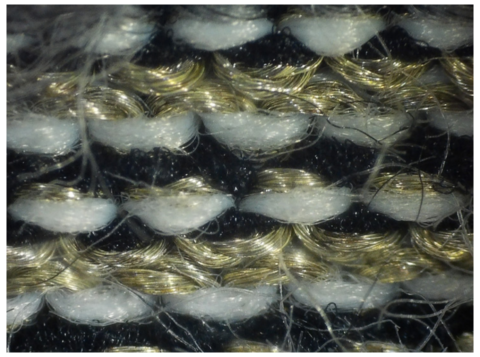


FIGURE E642D: MICROSCOPE IMAGE OF SAMPLE S10.2, BACK SIDE

FIGURE E643D: MICROSCOPE IMAGE OF SAMPLE S10.3, BACK SIDE

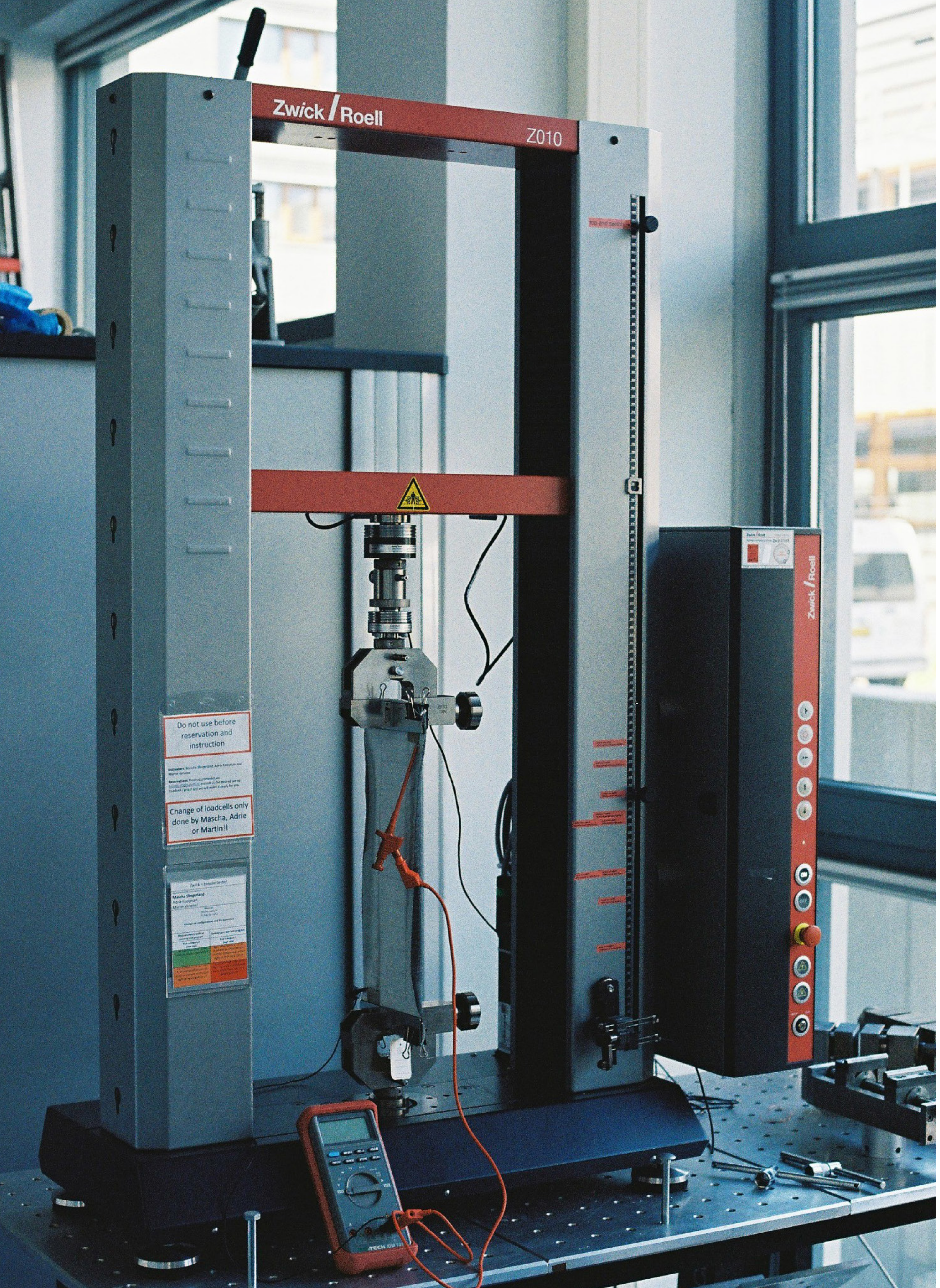


FIGURE 59: A SAMPLE PLACED IN THE TENSILE TEST SETUP
(MARK LOOPSTRA, 2023)

SETUP

Date: 14/06/2023

Although it was a warm and sunny day, the temperature inside was kept cool with air-conditioning and was measured at 20.5 degrees.

The three samples were, one after each other, placed in the Zwick/Roell Z010 Tensile strength tester. To make sure that samples were stretched over their entire width, custom clamps were made from steel sheets with rubber attached to it. The rubber also serves as isolation between the samples and the machine, so that no extra conductivity is measured through the machine. The clamps were attached to both sides of the samples with simple clips. Before measuring the actual resistances, the samples were pre-stretched by repeatedly stretching them from 0% to 15%, and back to 0%. After that, the samples were left to rest for 2 hours.

The samples were then put back in the tensile test machine and a multimeter was attached to the electrodes with small hook-like clamps. The resistance through the samples was measured in a resting position, and with 5, 10 and 15% stretch. When stretched to a certain value, the resistance was measured after 180 seconds, in order to give the sample some time to relax. After these three minutes, the resistance through the samples had reached an equilibrium. The resting position was chosen at the point where the samples were all perfectly verticle, but no surface tension could be felt in the fabric. The Tensile force at this point was measured at 2-3N.

FIGURE 60: CLOSE-UP OF S10.1 PLACED IN THE TENSILE TEST SETUP
(MARK LOOPSTRA, 2023)

RESULTS

Whereas the resistances of S10.1 and S10.3 in non-stretched positions are relatively equal, being 25 Ohms and 22 Ohms respectively, S10.2's resistance is about 40 percent lower: 15 Ohms.

Besides that, S10.1 shows a clear correlation between stretch and resistance: The more it is stretched, the lower the resistance gets, with the largest impact happening in the first few percentages of stretch: When stretched to 5%, resistance was measured to be 31% lower. This is in line with what was observed during Experiment 6.2, when determining the c-value for the leadwire: With little stretch, the resistance would drop drastically. To quantify this, S8.0 was also placed in the aforementioned test setup and was tested accordingly. Its results can be seen in figure E6454.

S10.2, on the other hand, shows a more stable resistance when being stretched. When stretched to 15% however, it shows a slight resistance decrease of 14%.

The resistance of S10.3 seems to slightly increase during the first 15% of stretch, but after that severely drops.

DISCUSSION

As the three tested samples are identical, apart from the plating technique in the leadwires, the different Rtot for every sample indicates that the plating technique in the leadwires significantly influences their resistances. As for their sensitivity to stretch, it can be seen that S10.2 shows the most stable behaviour. However, as the heaters show a decrease in resistance in a stretched position, it could be that the leadwire is actually not as stable as it seems, but just outweighs the resistance change in the heaters. In further research, the relative influence of stretch on heaters and leadwires should be investigated. Nevertheless it can be said that **the plating technique used in S10.1 is the most stretch-sensitive option**.

Looking at figures E641E-E643E, the resistance values can be somewhat explained.

In E641E, representing S10.1, it can be seen that the conductive yarn (illustrated as the golden yarn) **is often being blocked by the non-conductive yarn in making contact with itself**. The only spots where they actually touch are on the sides. One can imagine that this contact area and pressure increases when the structure is being stretched.

In E642E, representing S10.2, it can be seen that the conductive yarn, unlike in S10.1, **makes good contact with itself in every second loop**. At these spots, two conductive loops are really pulled against each other. This could explain the decreased resistance in this sample, and the increased stability when stretched.

In E643E, representing S10.3, the loops of conductive yarns do, similar to S10.1, not make much contact with itself, only on the sides. When stretched, it is likely that this contact area even decreases as the conductive yarn will in that case make place for the non-conductive one.

As the leadwire resistance is desired to be as low as possible, from a conductivity-point of view, an alternating plating structure such as in S10.2 would be most suitable. This plating structure was earlier in the project however seen as a mistake, as it does not successfully 'sandwich' the conductive yarn between two layers of jersey. When designing a knitted heater, these two desires should be weighed against each other.

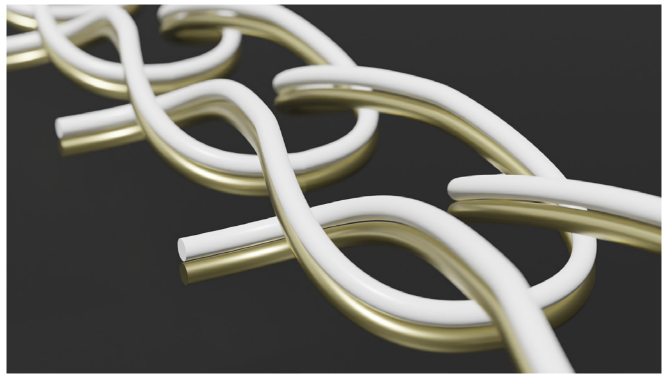


FIGURE E641E: VISUALISATION OF CORRESPONDING PLATING TECHNIQUE

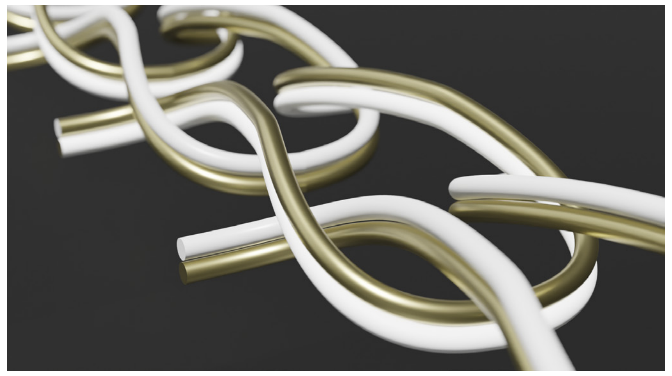


FIGURE E642E: VISUALISATION OF CORRESPONDING PLATING TECHNIQUE

FIGURE E643E: VISUALISATION OF CORRESPONDING PLATING TECHNIQUE

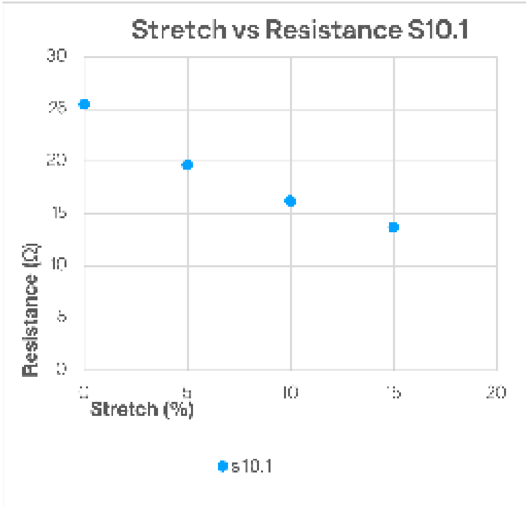


FIGURE E6451: STRETCH VS RESISTANCE SCATTER S10.1

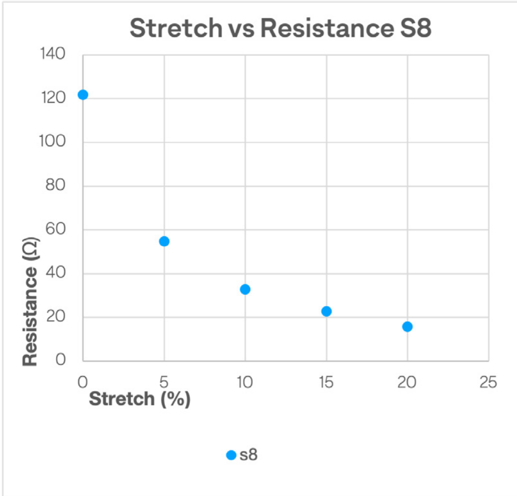


FIGURE E6454: STRETCH VS RESISTANCE SCATTER S8

FIGURE E6452: STRETCH VS RESISTANCE SCATTER S10.2

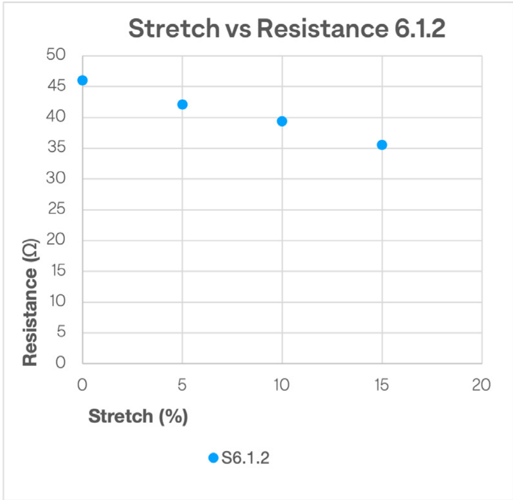


FIGURE E6455: STRETCH VS RESISTANCE SCATTER S6.1.2

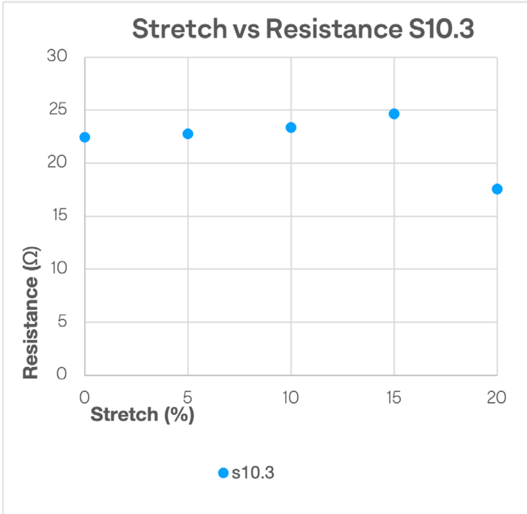


FIGURE E6453: STRETCH VS RESISTANCE SCATTER S10.3

EXPERIMENT 6

DESIGNING AN EVEN HEAT DISTRIBUTION

When designing an EHG that covers a large heating area, it can be assumed that it is desired to keep the heat generation constant and symmetrical over the entire heating area.
As can be seen on the images at the right, this does not happen naturally in our previous configurations. Figures 61-64 show the thermal images of 4 samples that were heated with 7V for 60 seconds. In S5.2 (figure 63), the heat generation differences were most severe: 26,4 °C versus 6,4 °C, making the hottest area more than 4 times hotter than the least heated area.

The reason this occurs is because of leadwire resistance; **if the leadwires would have infinite conductivity, the current would flow equally through the heating courses closeby as through the ones far away from the electrodes.** However, as the leadwires do have some resistance, the current prefers flowing through the courses closer by, making them heat up severly more than the others.

Besides the differences in heat generation through the heating areas, **the leadwires themselves also show a clear gradual decrease moving further away from the electrodes.** As resistant heating occurs in the leadwires as well, they will unavoidably become part of the heating element. This is not necessarily a bad thing, but it should be taken into account when designing configurations for knitted heaters.

This chapter is dedicated to designing a knit configuration that resolves this issue of uneven heating, approaching it from two different angles.

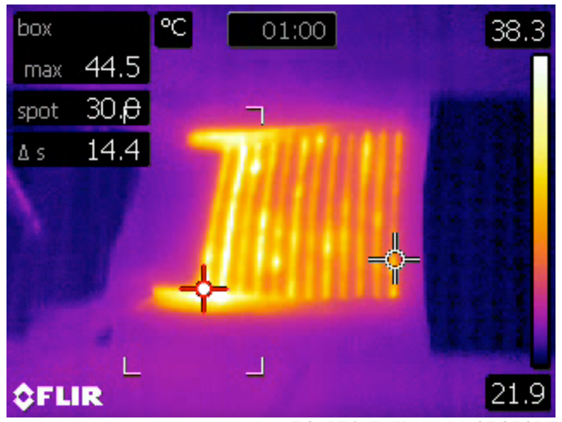


FIGURE 61: THERMAL IMAGE OF S5.1F

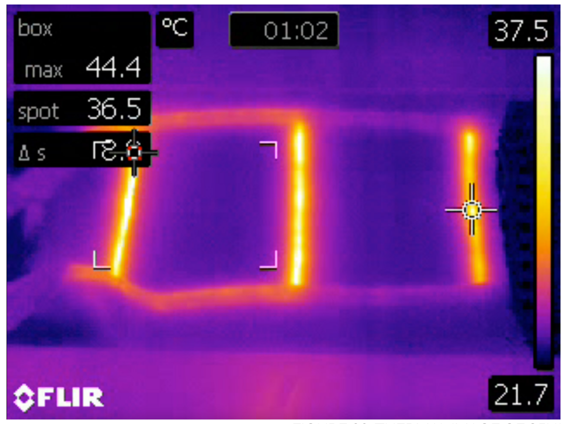


FIGURE 62: THERMAL IMAGE OF S5H1

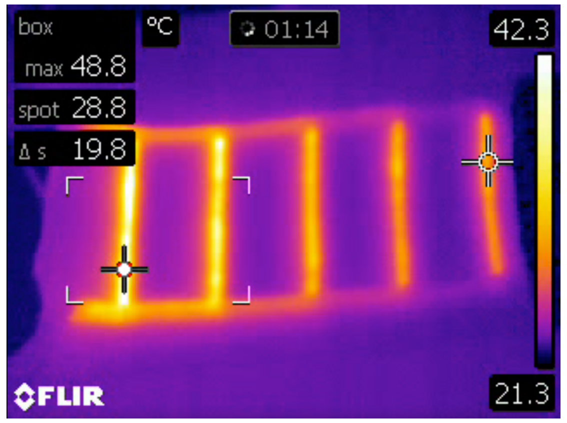


FIGURE 63: THERMAL IMAGE OF S5H2

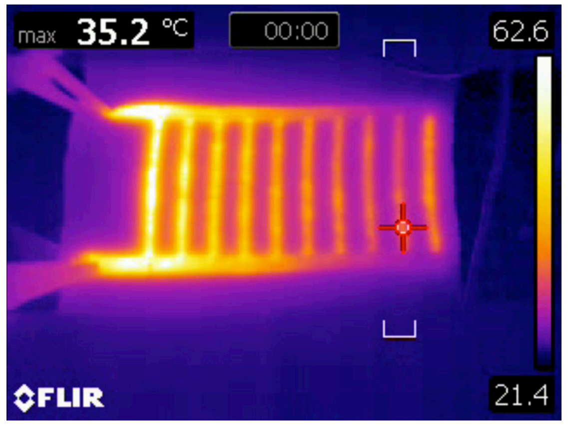


FIGURE 64: THERMAL IMAGE OF S5H3

Several principles were thought of that could potentially be used to design an even heating area. The goal of these solutions is to find a way for the current to flow equally through all horizontal areas. This can be obtained in two ways

- **by gradually altering the resistances through these heatable courses**
- **by changing the positions of the electrodes on the samples**

Figure 65 shows a bunch of configurations that make use of these principles. They are elaborated below.

C

status quo - the situation as it is now. The heat generation is higher at the electrodes than in the back.

C1

by gradually increasing the Ncourses towards the back, or decreasing them towards the beginning, resistances will show a gradual decrease following

$$R := \frac{c \cdot L}{W}$$

PRO

- Effective resistance control after manual testing
- Allows for large heating areas

CON

- Inaccurate increments as only a whole (or even two, considering ease of knitting) course(s) can be added or removed
- Need for increased material use
- Adding extra courses will increase heating area, making the temperature harder to actually rise
- Does not resolve gradient in leadwire temperature

C1A

same as C1, but with gradually decreasing leadwire thickness, which could resolve the gradient leadwire temperature.

C2/C2A

Instead of increasing the width, we now decrease the L towards the end, making the resistance show a gradual decrease following R = c x L/W +b.

PRO

- More incremential accuracy as Nstitches is altered instead of Ncourse. A stitch is severely smaller than a whole course, as there is 67 stitches in the courses knitted in previous examples.
- No increase of needed material

CON

- only allows for trapezium or triangular shaped structured. This could however be resolved by altering the shape inversely with itself, which can be seen in **C2A1**. Then again, that would mean that you need a more complex structure of different electrical circuits.
- Diagonal leadwires could increase resistance through less contact between stitches.

C3/C3A

C3 and C3A show a configuration where instead of gradually altering the resistance through the heaters, the positition of the electrodes is changed for the current to flow equally throughout the entire sample. By making the current flow diagonally, the resistance it gets will be equal for every path. Combining this with a gradual leadwire resistance could potentially offer an elegant way of designing an element with even heat distribution.

PRO

- No extra material needed
- Exact heat distribution
- Will work the same for different knit structures, yarns and other parameters
- Proven to work in other industries (see experiment 6.1)

CON

- Diagonal configuration places the electrodes on opposite sides of the heating area, making a connection with the battery or other power source more complicated. This could however be resolved by making a circular-shaped EHG, as can be seen in **V3A** and **V3A1**. **D3A** and **D3A1** show what the configurations would look like when the examples are flat.

Analyzing the pro's and cons, **it is decided to continue C3A,** in order to make a heater with an exact heat distribution. As knit structures are generally used in a circular shape anyway (e.g. in garments), this could be an interesting challenge to design with. If it is desired to knit a garment with a flat shape, an extra conductive path should be knitted to get the electrodes at the desired position.

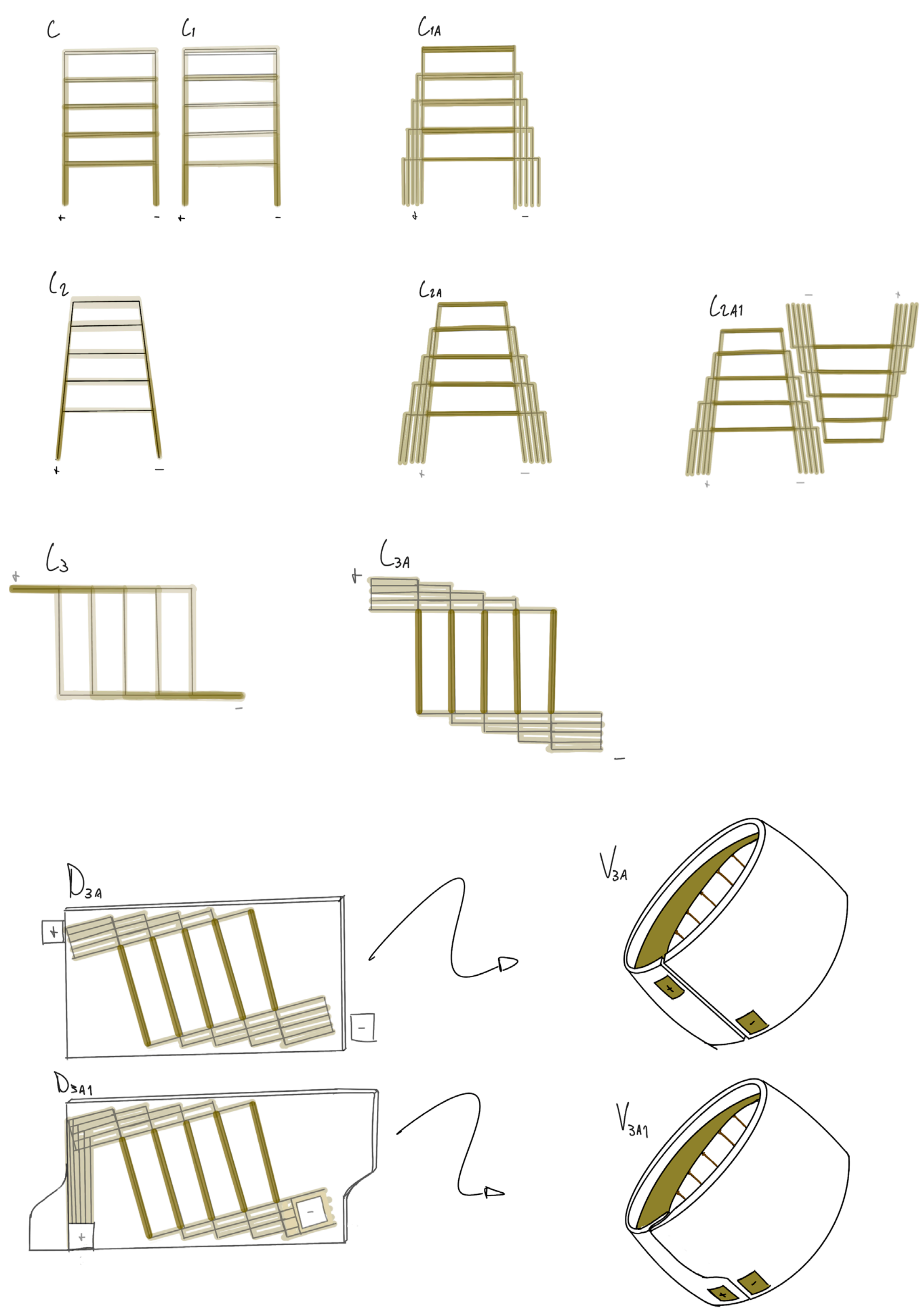


FIGURE 65: OVERVIEW OF POSSIBLE WAYS TO DESIGN FOR EVEN HEAT DISTRIBUTION

EXPERIMENT 6.1: DESIGNING AN EVEN HEAT DISTRIBUTION THROUGH DIAGONAL CONFIGURATION

As mentioned in the previous section of this series of experiments, a diagonal configuration could results in an equally distributed heating area, as the paths that the current travels will be equally resistant. This sample principle is already being implemented in other industries. A clear example of this can be seen in figure 66. The diagonal configuration in an intercooler air flow system makes the air flow equally through every path, as every path has an equal length (and thus resistance). A less obvious but also interesting example of a similar principle is the equal length exhaust header (figure 67).

As an initial test, samples 5H1 and 5H2, that are also discussed at the beginning of this chapter, have been powered with the same voltage, but by letting the current flow diagonally by using a thin multimeter clamp (see figure 70), making sure it is in contact with the conductive yarn network. The position of the clamps can be seen on the thermal image of S5H2 (figure 68).

Comparing the heat generation of S5H2 with a diagonal configuration versus the earlier configuration, we see that the coldest hot spot is the horizontal heating element in the middle. It differs 7.8 °C from the hottest hot spot, making the difference between dTmax and dTmin 78 %. This is a significant increase compared to the 412 % in the previous configuration. Besides that, as the hottest elements are now across from each other, there is a symmetrical heating pattern, which is likely to be experienced as more homogenous. Nevertheless, 78 % is still a too high value. In later samples, this percentage is attempted to be reduced through gradual leadwire resistance.

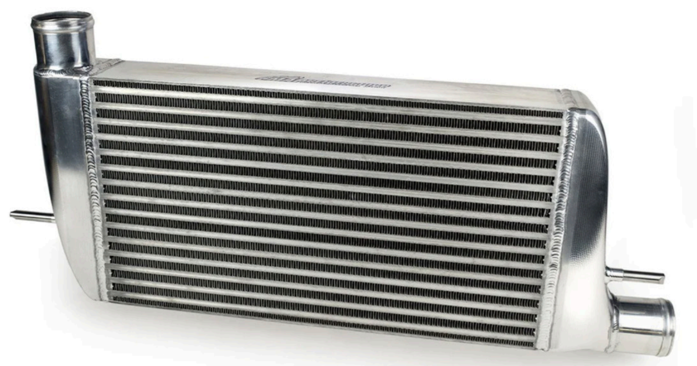


FIGURE 66: INTERCOOLER AIR FLOW SYSTEM
PARKAUTO MOTOR SPORTS, N.D.

FIGURE 67: EQUAL LENGTH EXHAUST HEADER
JBS POWERCENTRE, N.D.

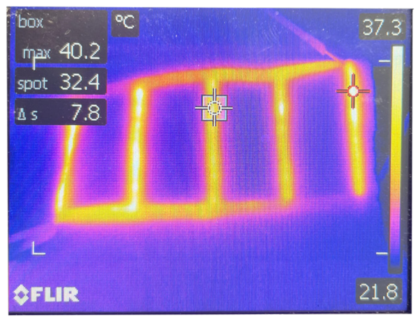


FIGURE 68:
THERMAL IMAGE OF S5H2 DIAGONAL CONFIGURATION

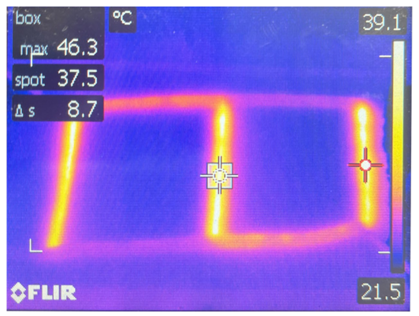


FIGURE 69:
THERMAL IMAGE OF S5H1 DIAGONAL CONFIGURATION

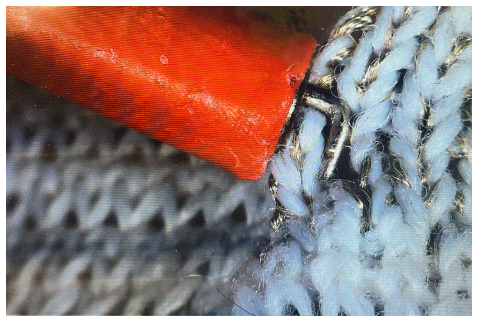


FIGURE 70: MICROSCOPE PHOTO OF ELECTRODE CONNECTION HOOK

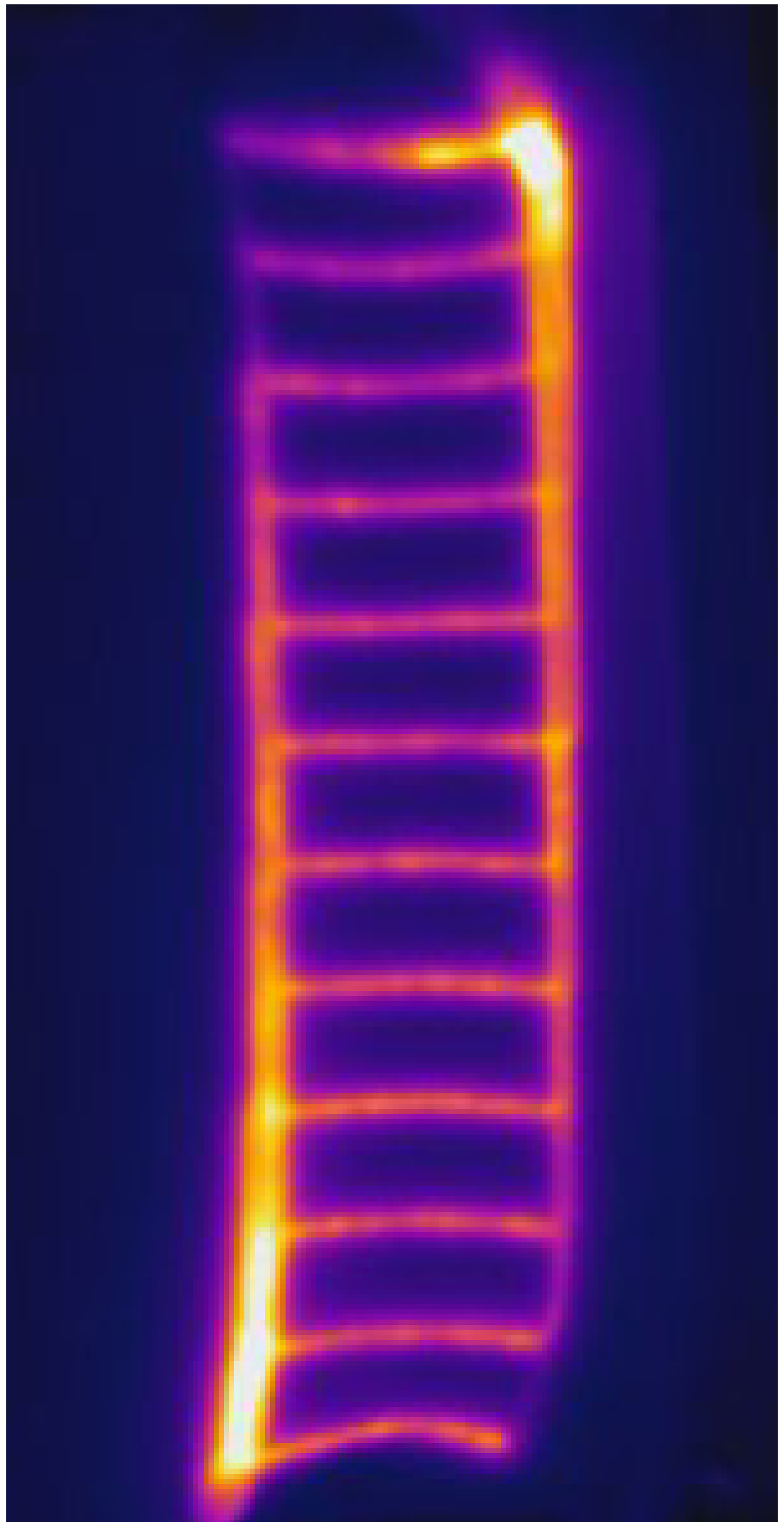


FIGURE 71: THERMAL IMAGE THAT SHOWS OVERHEATING IN THE LEADWIRE AREAS.

INTRO

Sample 7.1 was knitted as a first large area-covering heater with a diagonal configuration, and with gradual width-decreasing leadwires. As in previous samples, the diagonal configuration is made possible with backwards plated electrodes, knitted at the opposite sides of the sample, that are connected to the electrical circuit. For the width-decreasing leadwires, it was decided to decrease Wl with 2 wales at a time, keeping it at least 2 wales wide, as this has proven to result in more stable resistances.

$$2 \leq Wl$$

It was hypothesized that the gradual decrease in the leadwires would result in a more evenly distributed heating image throughout these conductors.

SETUP

In Experiment E6.1, sample 7.1 was heated with 10V for 15 minutes. After this time, the temperature had stabilised and the heat was measured in every resistance with the FLIR thermal camera. The heating elements in these samples are knitted in the course-direction, so they come horizontally out of the knitting machine.

Sample 7.1

- Heater yarn 1: C1
- Leadwire yarn 2: C2
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 2 courses
- Lh = 67 wales
- Lw = 6/4/2 wales
- date of knitting: 23/05/2023

RESULTS

The heatmap derived form the thermal camera measurements can be seen in figure 72. The figure shows the dT in every resistance of the heating element. The two outer columns represent the leadwires, whereas the column in the middle represents the heaters. The results show that there is indeed a roughly equivalent dissipation of heat over the individual heaters. However, the heat dissipation in the leadwires turned out to be a lot higher than expected, exceeding the values of the heaters. The upper heating element deviates, but this was later explained by an extra bit of yarn that was tucked on the backside of the sample, making contact with that heater. There is some varying dT visible between the heaters, showing a rising trend towards the outer top and bottom of the sample.

57.6	28.6	5.6
42.6	18.6	11.6
38.6	15.6	14.6
37.6	13.6	24.6
37.6	11.6	24.6
28.6	13.6	32.6
31.6	13.6	35.6
23.6	13.6	28.6
13.6	12.6	35.6
7.6	13.6	37.6
5.6	14.6	49.6
5.6	18.6	49.6

FIGURE 72: HEATMAP OF THE TEMPERATURE DIFFERENCES IN EVERY RESISTANCE

DISCUSSION

The diagonal configuration has proved to be able to dissipate heat equally over the heaters. The upper heating element deviates, but this was later explained by an extra bit of yarn that was tucked on the backside of the sample, which made contact with that specific heater. However, a new challenge has risen to the surface: the severe dT in the leadwires. The hypothesis that this would be prevented by gradually decreasing their resistances can therefore not (yet) be confirmed.
An explanation of this occurance is discussed in the next section.

THE RELATIONSHIP BETWEEN THE AMOUNT OF HEATERS AND THE RESISTANCE VALUES OF THE LEADWIRES

As is known from basic physics, in a series-configured electrical circuit the current through the resistors will be equal. In a parallel circuit, however, the current will divide proportionally over the resistances. The tested sample, with a diagonal configuration, deals with a combination of series and parralel connections. As the resistances of the invididual heaters are designed to be equal, it is assumed that the current running through them is equal like so. Figure 73 shows a hypothetical heatmap of current running through an alike sample with 12 heaters.

In this parallel circuit, the total current is the sum of all currents running through the heaters:

$$Itot = I1 + I2 + I3 \,..$$

Which, if all heaters have equal resistances, can also be written as:

$$Itot = Nh \cdot Ih$$

With Nh being the amount of heaters, and Ih being the current running through one heater.

Besides that, the input current is equal to the output current, which are equal to the total current.

$$Itot = Iin = Iout$$

This means that the total current, and thus also the in- and output currents, will the N times as high as the current through a heater. At first sight, it seems logical for the heat to be N times higher in these areas than in the heaters. However, in resistive heating, the heat is not determined by the current running through a resistance but by the power.

$$P = I^2 \cdot R$$

As current has a quadratical relationship with power, the resistance of the leadwire has to be much lower than the resistance of the heater, in a configuration with multiple heaters. To put this more precisely: **For the maximum power generation through the leadwire to be similar or smaller than the heat generation in the heaters, the ratio of their resistances has to be equal or higher to the the amount of heaters squared**.

for

$$Pa \leq Pb$$

:

$$\frac{Rb}{Ra} = Nh^2$$

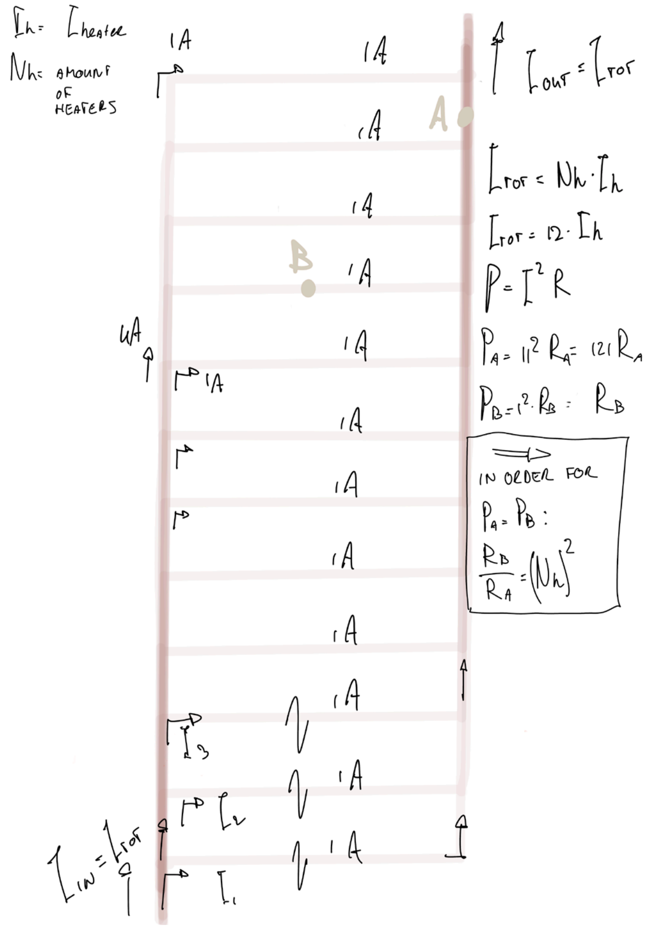


FIGURE 73: ILLUSTRATION OF THE POWER BEHAVIOUR IN A DIAGONAL PARALLEL CIRCUIT

Therefore, designing an evenly-dissipating knitted heater with this configuration can be challenging when many heaters are desired. In the previous design, in order to make the power running through the heaters equal to the maximum power running through the leadwire sections, the leadwire resistance would have to be decreased with about a factor 4.5 (this is calculated in chapter 6.3.1). As the formula for the resistance of the leadwire reads:

$$Rl = \frac{Cl \cdot Ll}{Wl}$$

There are a couplt of things that can be done to achieve this required conductivity ratio increase:

- Using a 4.5 times more conductive yarn for the leadwires, which will decrease the Cl-value.
- Making a 4.5 times shorter heating element, which will decrease the Ll-value.
- Using a 4.5 times less conductive yarn as the heater, which will increase the Ch-value.
- Making the heating element 4.5 times wider, which will increase the Wl-value

or a combination of the above.

Each of the aforementioned options come with their own disadvantages, as the goal of this research is to design an energy- and material-efficient knitted heater that covers a large heating area, that can be supplied with a low-voltage battery. Enwidening the leadwires means increased material use, as for using a more conductive silver-plated yarn, as those will also just have more conductive silver in them. Using a different material yarn would be an option, but does not lay within the scope of this research. Besides, super-conductive yarns are supposedly hard to knit with. Though, more and more conductive yarns that are suitable for knitting are being developed, making this a possible way out for future designers.

Alternative approaches are to either decrease the amount of heaters, or increase the resistances through the heaters. As the width of the heaters is already at a minimum, however, this can not simply be done be removing conductive yarn from the heaters. Besides that, removing resistances or increasing the resistances through the heaters will also increase the overall resistance, making it harder to supply the heater of sufficient power with a low-voltage battery.

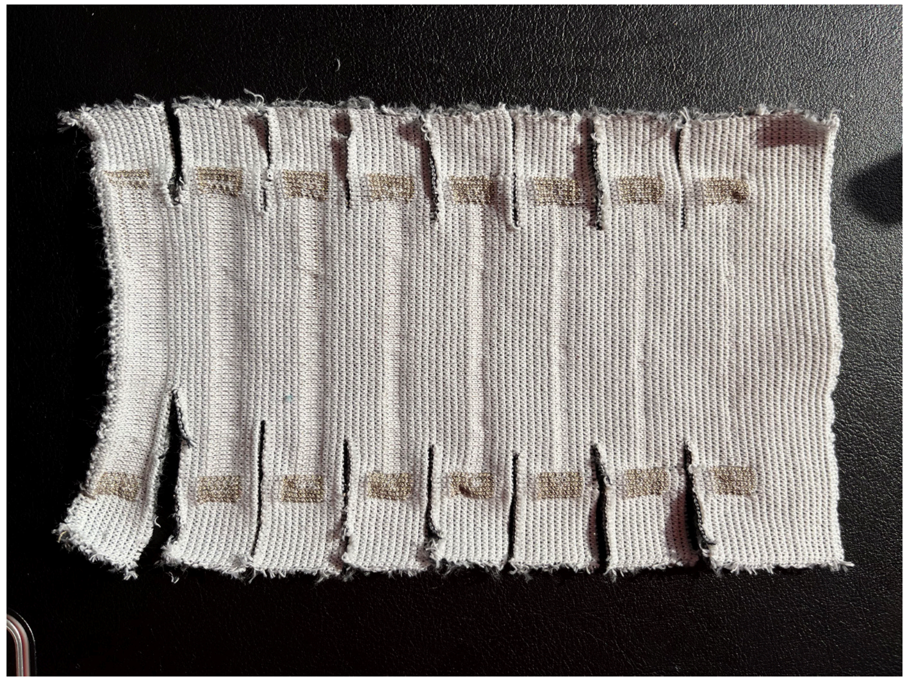
OPTIMISATION MODEL

A Matlab model was developed as a tool to balance out these dilemmas. It predicts the power running through the resistors of a diagonally-configured knitted heater, and will give you an array of optimised leadwire widths after filling in several values.

The model, which is elaborated in experiment 6.3 and of which the code can be found in Appendix 4.4, is designed for a diagonally configured heater with equally resistant heaters. The model allows you to fill in several values that it needs in order to do its calculations. These values should, prior to using the model, be derived from a test sample.

EXPERIMENT 6.2

DETERMINING THE C-VALUES OF HEATERS AND LEADWIRES.



FIGURES 74 AND 75: PHOTOS OF SAMPELS S6.1 AND S8.1

To determine the c-values of both the knitted leadwires as the heaters in a double jersey+plated sandwich configuration, samples S6.1 and S8.1 were developed.

SETUP

S6.1 contains 8 individual electrical circuits that have similar electrodes, but varying heater widths. the widths, determined by the amount of courses, are 12, 8, 6, 5, 4, 3, 2 and 1 from left to right respectively.
The samples was, after knitting, cut halfway through in order to break the electrical connections that were still present between the different circuits. This is necessary, as the measured resistance values will otherwise not be genuine.

S8.1 is a single large leadwire, which gradually increasing widths, that is also sandwiched between plating and a double jersey. The amount of wales in the heater are 12, 8, 6, 4 and 2, from left to right respectively.

The resistances through the samples were measured at varying widths and lengths with an ISO-TECH IDM 101 multimeter. For S6.1, the resistances were measured by putting the clams of the multimeter on the designated electrodes. As these are not present in S8.1, the resistances were in that sample measured by sticking thin clams through the jersey, making sure it properly contacts the conductive circuit.

It should be mentioned that S8.1 showed some unexpected behaviour during the resistance tests; When it was slightly stretched, the resistance would suddenly drop by about half. Stretching it further would however not influence the resistance; there was a clear treshold. It was chosen to measure the slightly stretched values, as a knitted product like this is likely to be stretched during use. The corresponding heat tests will therefore also be conducted in a stretched position. More information about the influence of stretch on the resistance of plated structures can be found in chapter 2.5.

Sample 6.1

- Heater yarn : C1
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Nh = 8
- Wh = 1/2/4/5/6/8/10/12
- date of knitting: 12/05/2023

Sample 8.1

- Leadwire yarn 2: C2
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Wl = 2/4/6/8/12 wales
- date of knitting: 12/05/2023

RESULTS

After measuring the resistances at different lengths and widths of the samples, figures 77 and 78 were derived from the data to show the correlation between the L/W ratio and the resistance. The graphs show approximate linear shapes, and trendlines have been drawn through each data set to derive an cx+b type formula out of it. To determine the general c-values for the heaters and leadwires, the average value of all trendlines have been calculated for both the heater as the leadwire:

c-value heater:	**c(C1) = 2.14**
c-value leadwire	**c(C2) = 0.179**

DISCUSSION

From the experiments it is conducted that the ratio Ch:Cl is about 12. The c-value directly proportionally influences the resistances of the heaters and leadwires. In a configuration like this, the ratio is desired to be as high as possible. If it is not possible to get the ratio high due to the absence of super-conductive yarns (like in the examplary experiment), leadwire resistances will have to be decreased through width increase.

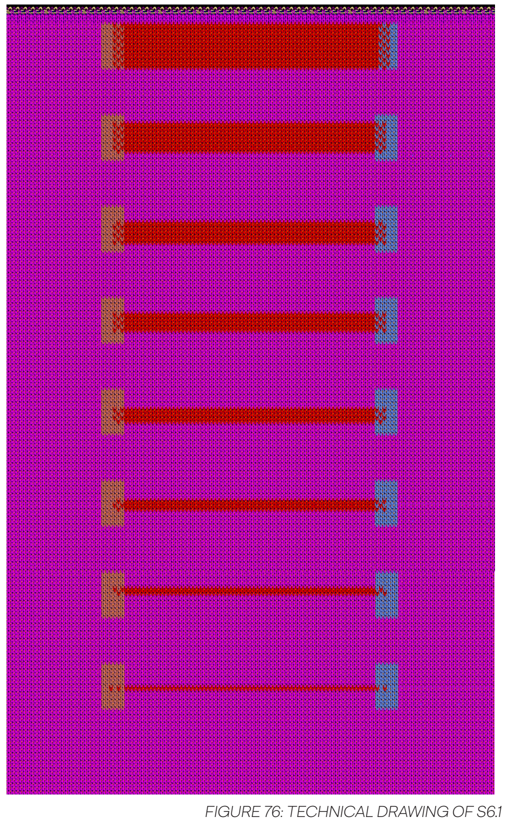


FIGURE 76: TECHNICAL DRAWING OF S6.1

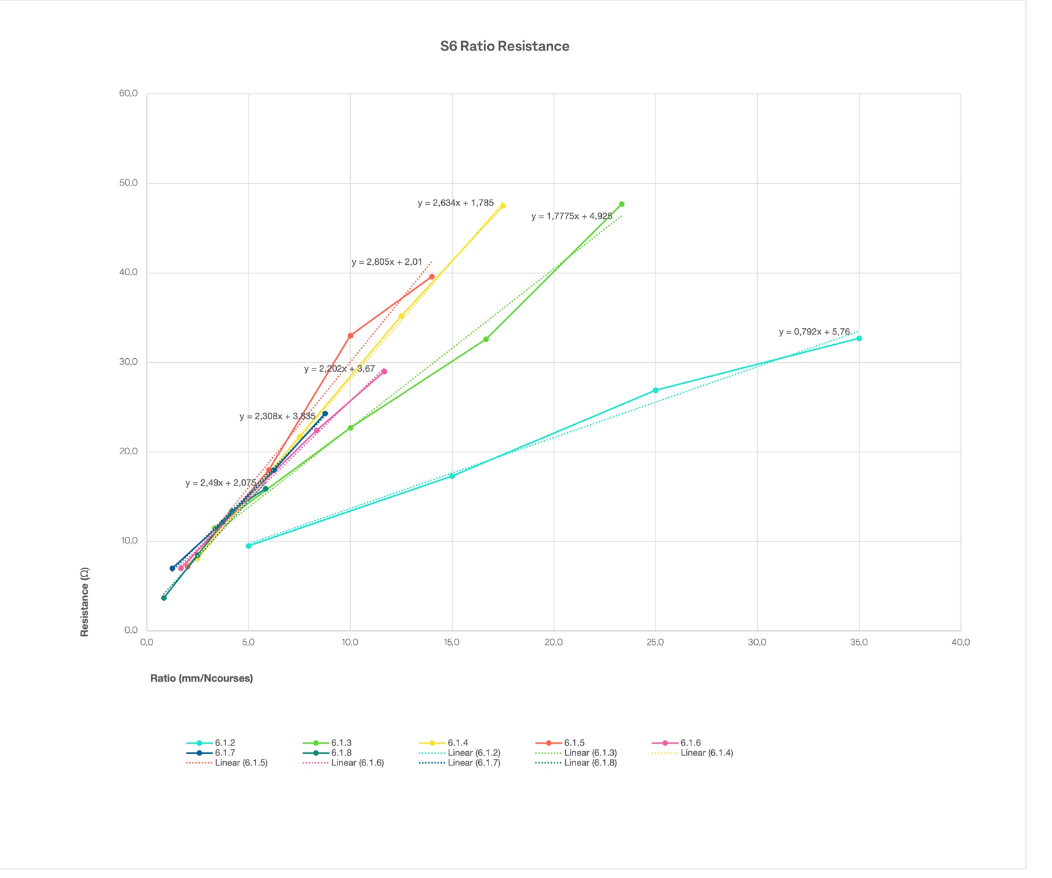


FIGURE 77: RATIO VS RESISTANCE GRAPH OF SAMPLE 6.1

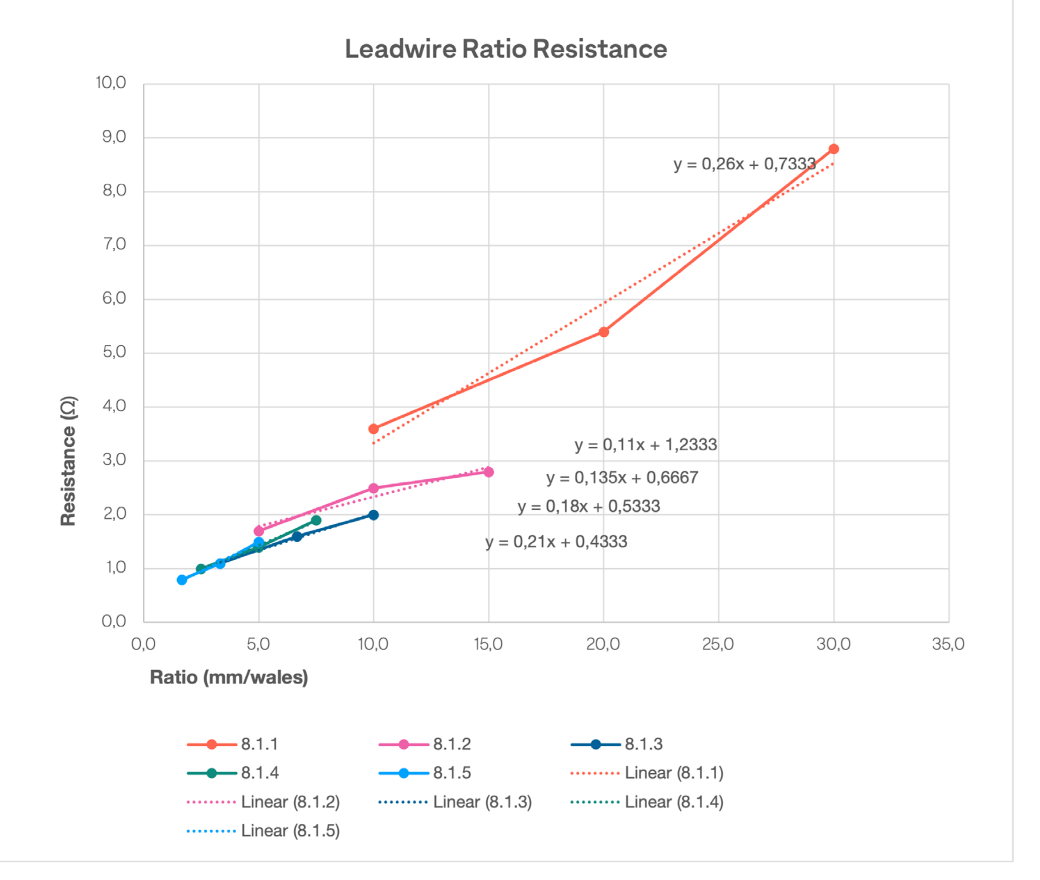


FIGURE 78: RATIO VS RESISTANCE GRAPH OF LEADWIRE SAMPLE S8.1

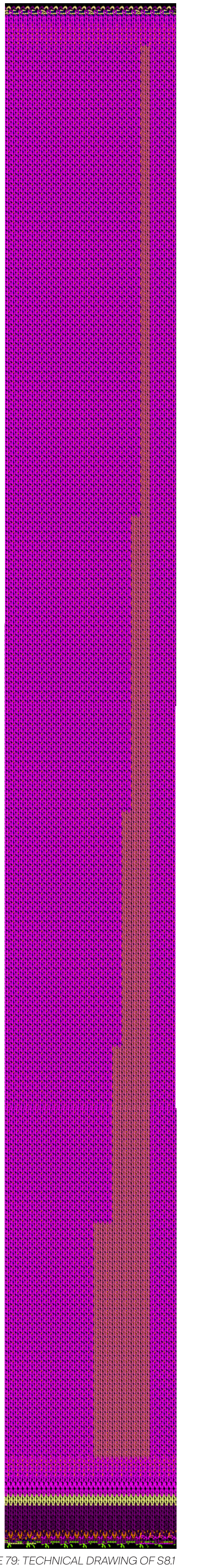


FIGURE 79: TECHNICAL DRAWING OF S8.1

EXPERIMENT 6.2B

Determining the c-values for a more resistant yarn.

As one solution for a better heat-dissipated knit is increasing the resistance of the heaters, as described in chapter E6.2, the c-value is also determined for a more resistant yarn. This is also a Shieldex yarn (See Appendix: Yarns, C5), and has an approximately 6 times higher resistance than the one used in the previous experiment.

The average c-value of this more resistant yarn is calculated at

c(C5)= 22,8

This value is approximately 11 times higher than c(C1), and would be appropriate to use as a heater for a parrallel configuration as it has a significant higher resistance (and thus c-value) than the leadwire. **From a material-saving point of view, using a more resistant yarn for the heaters makes much sense.** Not only do resistant yarns often contain less silver (as silver is what makes them conductive), but it will also result in less needed material for the leadwires: With very resistant heaters, the leadwire resistance can be higher as well.

However, it is chosen not to continue with this yarn as it would drastically increase the total resistance of the heater, making it hard to power with a low-voltage battery (see chapter 1.3 Power input).

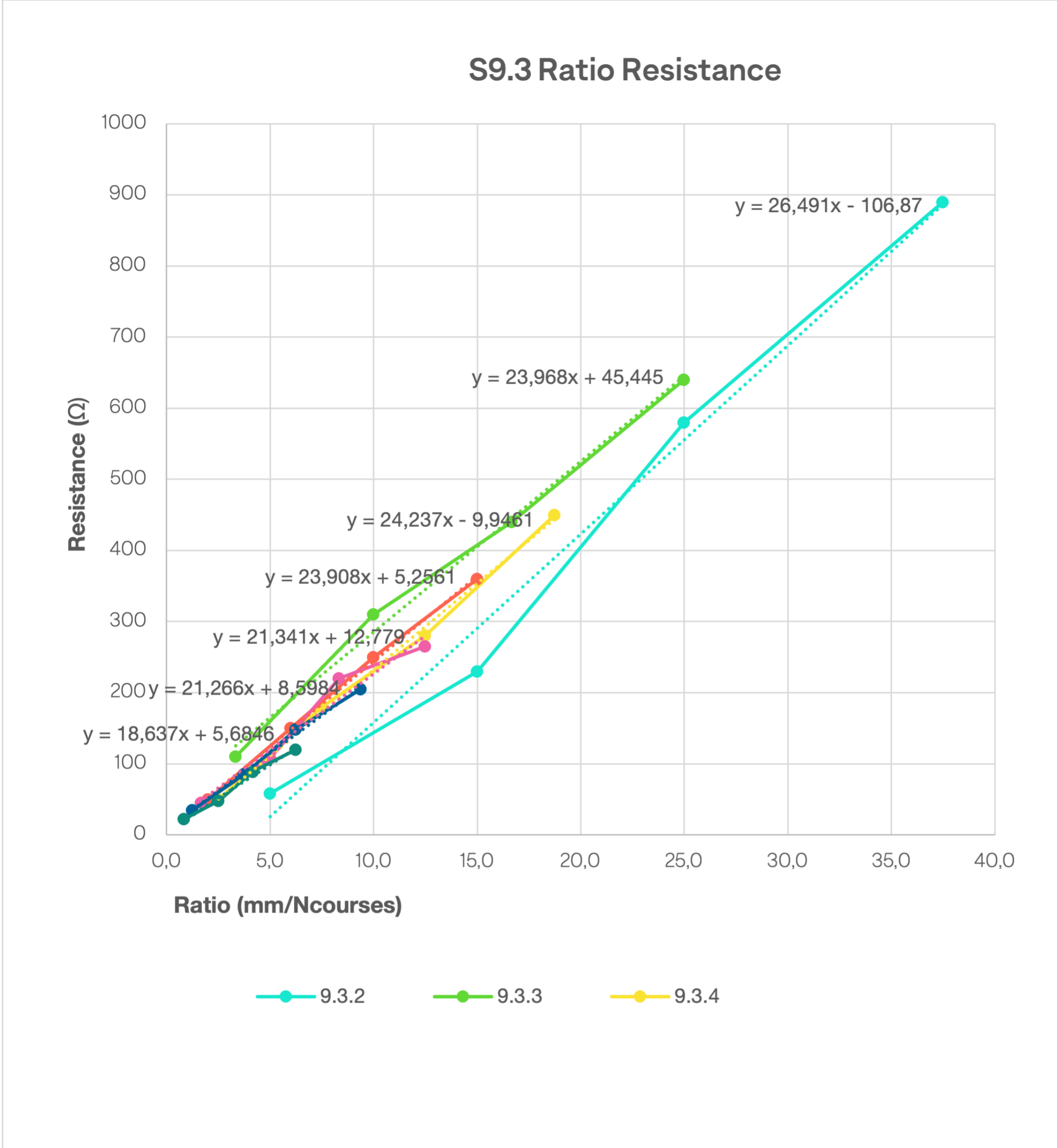


FIGURE 80: RATIO VS RESISTANCE GRAPH OF SAMPLE S9.3

EXPERIMENT 6.3: PREDICTING ENERGY FLOW WITH A DIGITAL MODEL

As mentioned earlier, a Matlab model was developed as a tool to balance out several dilemmas. The tool is designed to help designers and engineers predict the power running through resistors, and eventually the temperature through the resistors of a diagonally-configured knitted heater. The goal of the model is to be able to configure an energy- and material efficient, large-area knitted heater that allows for an equal heat distribution: it should not have hotspots and should use as little material as possible.

There are two approaches:

- **Approach 1:** Calculating the optimised leadwire width so that the **power** running through every resistance is equal

  The power is determined by $P = I^2 \cdot R$ and has Watt as the unit.

- **Approach 2:** Calculating the optimised leadwire width so that the **surface power density** running through every resistance is equal

  The surface power density is determined by $SPD = \frac{P}{A}$ and has Watt per Square Meter or Watt per Nstitches as the unit.

The model can give you an array of optimised leadwire widths after filling in several values:

U0	Voltage of the battery
Itot	Desired input current
Ltot	Length of the heating element
N	Amount of heaters
Wh	Width of the heaters in wales
Lh	Length of the heaters in courses
Cl	c-value of leadwire
Ch	c-value of heater

In-depth explanation of what the model does is done by means of an example study. The goal is to redesign sample S7.1 in a way that the leadwires do not become hotter than the heaters.

The c-values derived from experiment 6.2 are used as the input values, as S7.1 was knitted with the same knit structure. For the c-value of the heater, it was chosen to fill in the actual measured c-value of a 2-course heater rather than the general c-value, as it is chosen to make all heaters this specific width.

U0	7
Itot	1
Ltot	310
N	12
Wh	2
Lh	67
Cl	0.159
Ch	0.792

EXPERIMENT 6.3.1: APPROACH 1

After filling in the values and running the model, Matlab generates 6 images:

- **Figure E6311: current array**
  This figure shows the current that runs through every individual resistance. As can be seen, this current is much higher in the leadwires, especially nearing the electrodes.

- **Figure E6312: desired resistance array**
  This figures shows the required resistances that the leadwires need compared to the heaters in order to counter these current differences. With these resistances, the power running through every resistance will be equal (see chapter 6.1 for the mathematical explanation behind this)

- **Figure E6313: desired power array**
  This figure visually confirms that the power will be equal, following P=I^2 *R.

- **Figure E6314A (left): desired width array**
  This figure shows the required widths in wales of the leadwires that will make them reach the resistance they need, following R=c*L/W.

- **Figure E6314B (Right): actual width array**
  As we can only knit entire wales or courses, this array shows the closest possible width that can be knitted in the leadwire. It will always give a minimum of 2 wales, and only outputs even numbers for ease of knit programming purposes. It will always round up, as the leadwires should stay colder than the heaters.

- **Figure E6315: actual power array**
  This figure shows the actual power array with the actual leadwire widths. As can be seen in the figure, the leadwire sections far away from the electrodes show a clearly lower power generation. This is because these leadwires have the largest relative difference between the desired width and the actual width. The powers of the other sections are close to the powers in the heaters.

	1	2	3
1	0.08333	0.08333	1
2	0.1667	0.08333	0.9167
3	0.25	0.08333	0.8333
4	0.3333	0.08333	0.75
5	0.4167	0.08333	0.6667
6	0.5	0.08333	0.5833
7	0.5833	0.08333	0.5
8	0.6667	0.08333	0.4167
9	0.75	0.08333	0.3333
10	0.8333	0.08333	0.25
11	0.9167	0.08333	0.1667
12	1	0.08333	0.08333

FIGURE E6311: CURRENT ARRAY

	1	2	3
1	26.53	26.53	0.1842
2	6.633	26.53	0.2193
3	2.948	26.53	0.2653
4	1.658	26.53	0.3276
5	1.061	26.53	0.4146
6	0.737	26.53	0.5415
7	0.5415	26.53	0.737
8	0.4146	26.53	1.061
9	0.3276	26.53	1.658
10	0.2653	26.53	2.948
11	0.2193	26.53	6.633
12	0.1842	26.53	26.53

FIGURE E6312: DESIRED RESISTANCE ARRAY

	1	2	3
1	0.1842	0.1842	0.1842
2	0.1842	0.1842	0.1842
3	0.1842	0.1842	0.1842
4	0.1842	0.1842	0.1842
5	0.1842	0.1842	0.1842
6	0.1842	0.1842	0.1842
7	0.1842	0.1842	0.1842
8	0.1842	0.1842	0.1842
9	0.1842	0.1842	0.1842
10	0.1842	0.1842	0.1842
11	0.1842	0.1842	0.1842
12	0.1842	0.1842	0.1842

FIGURE E6313: DESIRED POWER ARRAY

	1	2	3
1	0.01556	0.1842	0.1723
2	0.06223	0.1842	0.1711
3	0.14	0.1842	0.1729
4	0.1245	0.1842	0.18
5	0.1297	0.1842	0.166
6	0.14	0.1842	0.1525
7	0.1525	0.1842	0.14
8	0.166	0.1842	0.1297
9	0.18	0.1842	0.1245
10	0.1729	0.1842	0.14
11	0.1711	0.1842	0.06223
12	0.1723	0.1842	0.01556

FIGURE E6315: ACTUAL POWER ARRAY

	1
1	0.1689
2	0.6755
3	1.52
4	2.702
5	4.222
6	6.08
7	8.275
8	10.81
9	13.68
10	16.89
11	20.44
12	24.32

	1
1	2
2	2
3	2
4	4
5	6
6	8
7	10
8	12
9	14
10	18
11	22
12	26

FIGURE E6314A (LEFT): DESIRED WIDTH ARRAY
FIGURE E6314B (RIGHT): ACTUAL WIDTH ARRAY

DISCUSSION

Summarised, 'Figure E6314B (Right): actual width array', shows you the data for the leadwire widths that is required to get as close as possible to an even power distribution over the resistances. It can be seen in the figure that these width range from 2 to 26 wales. If we compare these values to the widths used in S7.1, the leadwire will be 4.5 times wider.

However, the generated temperature is not only determined by the power that runs through a resistance, but also by the size of that resistance; One can imagine that 1W running through a 1 square meter area will heat that area up less than 1W running through a 1 square centimeter area.

Therefore, the Surface Power Density was calculated for every redesigned resistance. As can be seen from the results in figure E6316, the SPD of all leadwire sections is (far) below that of the heaters, except for 2 sections. The SPD of these sections is almost twice as high of the one of the heaters.

A sample was knitted with the power-optimised leadwire widths to find out to what extent SPD actually influences the temperature.

	1	2	3
1	0.276	1.375	0.2352
2	1.104	1.375	0.276
3	2.484	1.375	0.3408
4	1.104	1.375	0.4563
5	0.7668	1.375	0.4907
6	0.6211	1.375	0.541
7	0.541	1.375	0.6211
8	0.4907	1.375	0.7668
9	0.4563	1.375	1.104
10	0.3408	1.375	2.484
11	0.276	1.375	1.104
12	0.2352	1.375	0.276

FIGURE E6316: SURFACE POWER DENSITY

EXPERIMENT 6.3.1B

To prove the actual correlation between area and temperature, and to find out how termperature acts other than predicted, a sample with the configuration calculated in experiment 6.3.1

SETUP

S9.1 is similar to S7.1, containing 12 x 2 courses, but has a power-optimised leadwire array, which can be seen in figure E6314B. It should be noticed that the leadwire has, especially in the wide parts, the tendency to blow up a bit in the z-direction. This can be explained by the way it is knitted: As is explained in the discussion after chapter 2.4: Knitting a sandwich, it is chosen for the conductive parts not to connect them to to the backside jersey with a connecting yarn, as this will mess up the plating structure. As the conductive yarns are a lot thicker than the other yarns, however, it takes more space and therefore expands outwards. It is chosen to take this phenomenon for granted, as this is only an experiment and we want to keep all parameters equal to earlier experiments.

Sample 9.1

- Heater yarn 1: C1
- Leadwire yarn 2: C2
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 2 courses
- Lh = 67 wales
- Wl = 2-26 wales
- date of knitting: 01/06/2023

As the c-value of the leadwire was determined in a stretched position, the heating experiment was also conducted in a stretched position. The sample was placed in the Zwick/Roell Z010 testing system and was stretched 10%. After 3 minutes of stretching, a 12V adapter with connected alligator clamps was attached to the electrodes of the sample. In this experiment, the relative values of the heat generation are investigated. Therefore, the difference in power source does not influence the interpretation of the results.

RESULTS

The results show that optimising power distribution over individual heaters as a way to achieve well-distributed heat generation comes close to what happens in practice. Comparing figure 81 (heatmap) to figures E6316: SPD and E6315: Actual Power Array, it can be concluded that the heatmap derived from the experiment is much more similar to E6315 than to E6316:

- There are no hotspots in the third leadwire, which was predicted with the SPD-optimised array.
- Heat generation in the leadwires is generally a bit lower than in the heaters. This was predicted by both models.

	1	2	3
1	18.9	29.6	6.2
2	20.8	33.1	9.4
3	26.2	46.6	21.7
4	23.7	32.2	21
5	23.2	28	24
6	23.8	33.6	24
7	23.1	35.9	21.8
8	22.4	27.7	22.9
9	27.4	29.7	23
10	20.6	25	19
11	11.5	27.2	20.9
12	7.4	30.6	17.1

FIGURE 81: MEASURED HEATING BEHAVIOUR IN SAMPLE S9.1

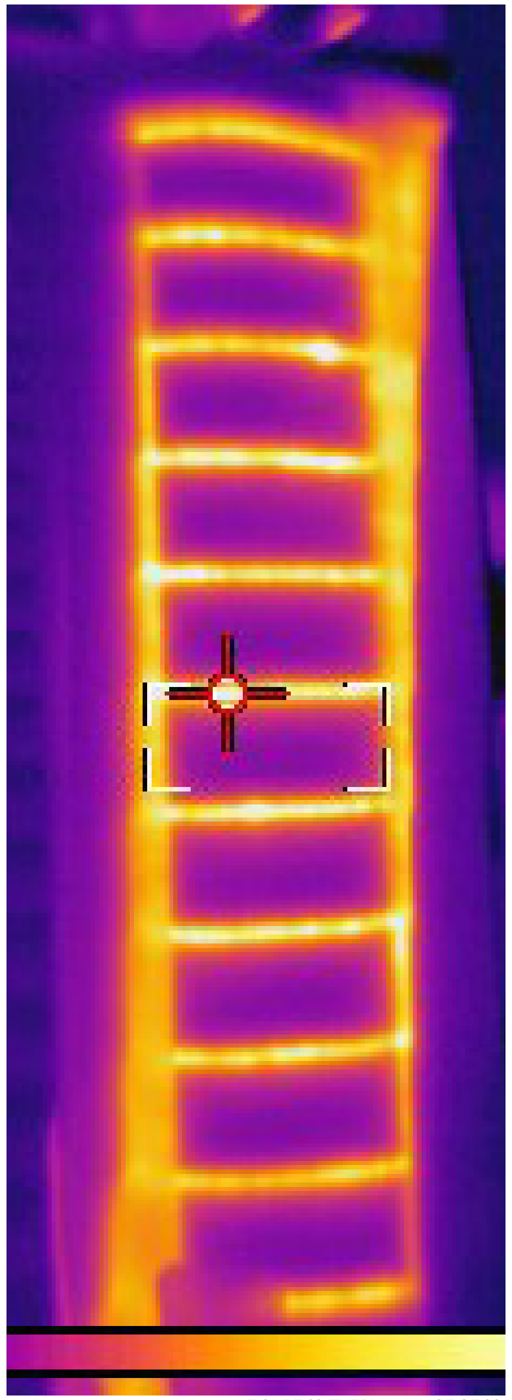


FIGURE 82: THERMAL IMAGE OF S9.1

The SPD-optimised model predicted the heat generation to be about 3 times lower in the leadwires than in the heaters. However, these differences are not that severe, and look much more like the relative differences that were shown in the power-optimised model.

General remarks:

- There is only one leadwire temperature difference (27.4 degrees) that is measured to be higher than in any of the heaters, and this temperature is still below the average heat generation in the heaters (about 32 degrees).
- The heat generation in the heaters is close to even, but has some hotspots that rise far above the other measured values.

DISCUSSION

Although much can still be gained concerning the optimisation of even heat distribution and material use, the power-optimised model proves to be a good first step towards predicting heat generation. It successfully keeps the heat generation in the leadwires lower than in the heaters. However, with the average heat generation in the leadwires being about 21 degrees versus 32 degrees in the heaters, the heat generation seems to be about a third as low. The leadwire-widths should be optimised in such a way that their heat generation remains lower than in the actual heaters, but gets as close as possible (to minimise conductive material use). With this in mind, it seems like they could have been a bit smaller. In the following experiment (E6.3.2B), the SPD-optimised sample is being heated, to see how this behaves. It is however expected that this will not be a perfect prediction, as the thermal behaviour in E6.3.1B proved the SPD-array wrong.

EXPERIMENT 6.3.2: APPROACH 2

A second model was developed that optimises the SPD of every resistance, rather than the power. Besides making sure that no single leadwire-SPD surpasses the heaterSPD, the model optimises the leadwire widths in a way that their SPD gets as close as possible to the heater-SPD, while staying under it. This is done so that **as little conductive material as possible** is used in the leadwires.

After filling in the values and running the model, Matlab generates 4 images:

- **Figure E6321: current array**
  This figure shows, similar to E6311, the current that runs through the heating element.

- **Figure E6322: optimised SPD**
  This figure shows the optimised SPD for the heater with the pre-filled values. The model first calculates the leadwire widths in the same way as the first approach: by making the power than runs through them equal as in the heaters. After that, it puts these values into a loop that measures the SPD-values. If a leadwire-SPD turns out to be higher than the accompanyinng heater value, it increases the width (again with 2 wales at a time) until it falls under the heater-SPD. Simeltaneously, if a leadwire-SPD value is lower than its accompanying heater value, the leadwire width is being decrease by 2 wales at a time until its SPD surpasses the heater-SPD. In this way, material use is minimised while keeping the heat generation well-divided over the entire element.
- **Figure E6323: actual power array**
  Figure E6323 shows the power than runs through every resistance. It should be noticed that the power running through the leadwires is, in some places, higher than the power running through the actual heaters. This is explained by the fact that the leadwire in those places occupy a larger area than the heaters, making their SPD's drop.
- **Figure E6324: actual width array**
  This figure shows the actual width of the leadwires that should be knitted for the optimised spd and actual power array to, theoretically, turn out as they are presented.

DISCUSSION

Figure E6324 is the only output array that is needed to start knitting. It should be noticed that the widths the program recommends to you are smaller than it does with the first approach. Therefore, the heatmap of the heater knitted with the second approach will definitely show more heat generated in the leadwires, something they were not originally intended for. However, integrating the leadwires as a part of the heater allows for material reduction. Whether or not the SPD indeed determines the temperature generation in a knitted heater is tested in the following experiment.

	1	2	3
1	0.08333	0.08333	1
2	0.1667	0.08333	0.9167
3	0.25	0.08333	0.8333
4	0.3333	0.08333	0.75
5	0.4167	0.08333	0.6667
6	0.5	0.08333	0.5833
7	0.5833	0.08333	0.5
8	0.6667	0.08333	0.4167
9	0.75	0.08333	0.3333
10	0.8333	0.08333	0.25
11	0.9167	0.08333	0.1667
12	1	0.08333	0.08333

FIGURE E6321: CURRENT ARRAY

	1	2	3
1	0.276	1.375	1.104
2	1.104	1.375	1.336
3	0.6211	1.375	1.104
4	1.104	1.375	0.8944
5	0.7668	1.375	1.104
6	1.104	1.375	0.8454
7	0.8454	1.375	1.104
8	1.104	1.375	0.7668
9	0.8944	1.375	1.104
10	1.104	1.375	0.6211
11	1.336	1.375	1.104
12	1.104	1.375	0.276

FIGURE E6322: OPTIMISED SPD

	1	2	3
1	0.01556	0.1842	0.3734
2	0.06223	0.1842	0.3765
3	0.07001	0.1842	0.3112
4	0.1245	0.1842	0.2521
5	0.1297	0.1842	0.2489
6	0.1867	0.1842	0.1906
7	0.1906	0.1842	0.1867
8	0.2489	0.1842	0.1297
9	0.2521	0.1842	0.1245
10	0.3112	0.1842	0.07001
11	0.3765	0.1842	0.06223
12	0.3734	0.1842	0.01556

FIGURE E6323: ACTUAL POWER ARRAY

	1
1	2
2	2
3	4
4	4
5	6
6	6
7	8
8	8
9	10
10	10
11	10
12	12

FIGURE E6323: ACTUAL WIDTH ARRAY

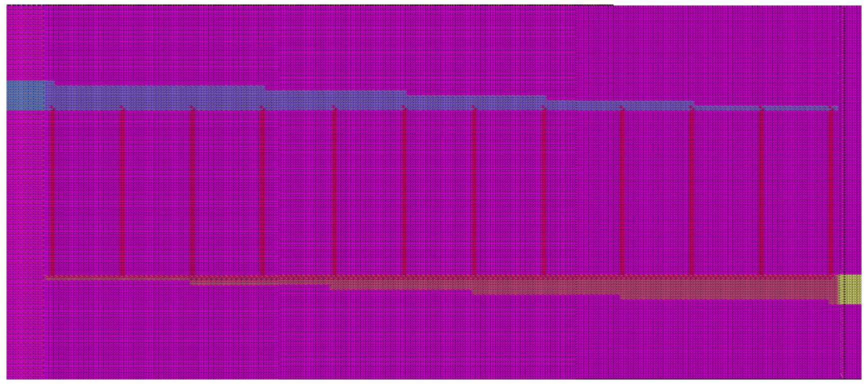


FIGURE E632B6: TECHNICAL DRAWING OF S9.2

EXPERIMENT 6.3.2B

Similar to experiment 6.3.1B, Sample S9.2.1 was knitted to prove the correlation between SPD and temperature. The sample has the leadwire configuration that correlates with the optimised outcome of Experiment 6.3.2.

SETUP

S9.2 is similar to S9.1, containing 12 x 2 courses, but has a SPD-optimised leadwire array, which can be seen in figure E6323. As with S9.1, It should be noticed that the leadwire has, especially in the wide parts, the tendency to blow up a bit in the z-direction. This is fortunately less severe than in S9.1. It is chosen to take this phenomenon for granted, as this is only an experiment and we want to keep all parameters equal to earlier experiments.

Sample 9.1

- Heater yarn 1: C1
- Leadwire yarn 2: C2
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 2 courses
- Lh = 67 wales
- Wl = 2-12 wales
- date of knitting: 01/06/2023

Similar to E6.3.1B, As the c-value of the leadwire was determined in a stretched position, the heating experiment was conducted in a stretched position. The sample was placed in the Zwick/Roell Z010 testing system and was stretched 10%. After 3 minutes of stretching, a 12V adapter with connected alligator clamps was attached to the electrodes of the sample. In this experiment, the relative values of the heat generation are investigated. Therefore, the difference in power source does not influence the interpretation of the results.

RESULTS

As expected, the heat distribution of S9.2.1 is much better than what was observed for sample S7.1: The relative heat generation in the heaters is about twice as high. The heat generation in the leadwires is also more evenly distributed than in S7.1. However, the hottests areas are still in the leadwires, close to the electrodes.

DISCUSSION

Although showing improved heating behaviour compared to S7.1, which is heated in E6.1, The digital model for optimised SPD does, in practice, not suffice for the realisation of an equal heat distribution. The thermal images that can be seen in figures E632B3, E632B4 and E632B5 give a possible solution to this. Some remarks that can be derived from the thermal

	1	2	3
1	17.4	33.3	7.7
2	47.5	26.3	10.9
3	41.7	25.8	19.5
4	32.4	24	23.3
5	33.8	23.2	27.3
6	31.9	21.6	30.7
7	31.3	22.6	30.9
8	26.8	23	34.1
9	25	24.9	34.1
10	20	23.7	40.9
11	12.1	24.6	45.7
12	7.4	27.6	16.9

FIGURE E632B1: HEATMAP OF S9.2

images:

- As can be seen in figure E632B4, hotspots can be seen at the intersections of the leadwires and heaters. These regions where multiple paths intersect act as junction points where electrical currents combine. If one path carries a higher current, the junction point may experience an increased concentration of electrical current, leading to localized heating or hotspots.

- As can be seen in figure E632B5, the heat distribution within one area is not equal. It seems like the center of a heated area is the hottest, and the temperature gradually decreases near the edges. This can be explained by heat clustering. Heat naturally tends to cluster or concentrate in certain regions rather than spreading uniformly. It is a fundamental behavior of heat propagation.

- As can be seen in figure E632B3, one of the outer heaters has an unexpected heating pattern; it does not heat up much, until it gets near the electrode. This could be explained by the thermal conductivity of the silver yarns, as it is unlikely that the current travels halfway into a heater only to realise that a different route is probably easier.

- As can be seen in figure E632B3, the electrodes only start getting really hot when plating switches to the back. This indicates that the resistance is much lower in the areas where the conductive yarns are plated on the front side. As increased conductivity is desired in the leadwires in order to save material, this phenomenon should be investigated.

Comparing E6.3.1B with E6.3.2B, it can be said that the first model (the one that optimises the power per heater), gets closest to predicting the actual heating behaviour in a knitted heater. However, the true heating behaviour lays somewhere in between the predictions of the models; This can be explained by the hotspots in the junction points, or by the phenomenon of heat clustering.
A third model should be developed that is a combination of both models. In order to do this, their relative impacts should

FIGURE E632B2: THERMAL IMAGE OF S9.2, STRETCHED

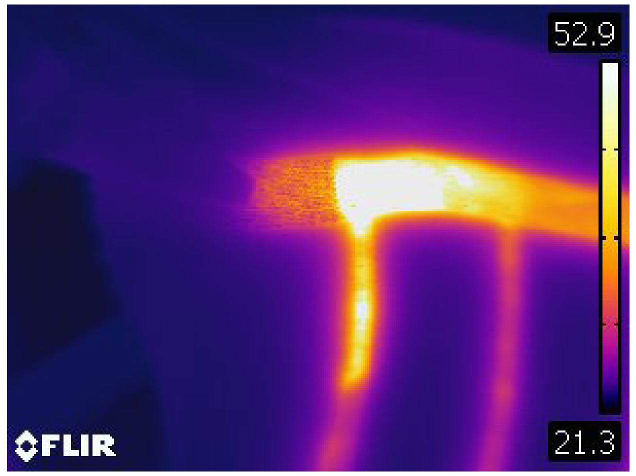


FIGURE E632B3: THERMAL IMAGE SHOWING HEAT GENERATION DIFFERENCE BETWEEN ELECTRODE AND FIRST LEADWIRE SECTION

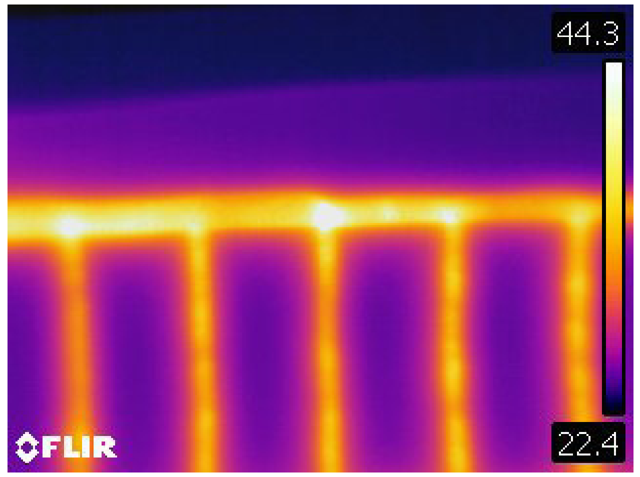


FIGURE E632B4: THERMAL IMAGE SHOWING HOTSPOTS AT INTERSECTION POINTS

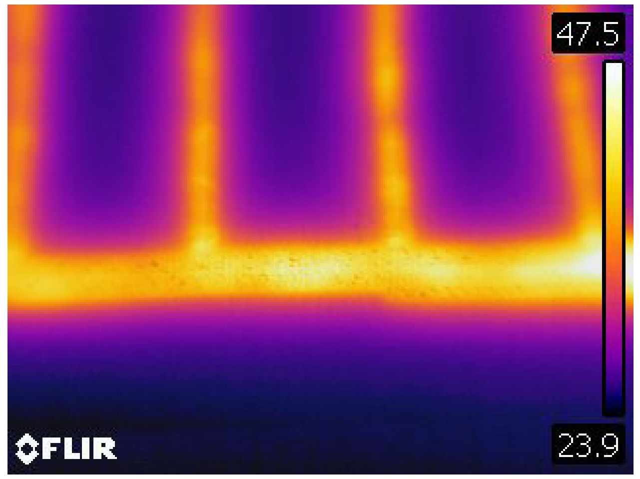


FIGURE E632B5: THERMAL IMAGE SHOWING HEAT CLUSTERING

EXPERIMENT 6.5

COMPARING THEORY WITH PRACTICE

EXPERIMENT 6.5.1
RETROSPECTIVELY DETERMINING A C-VALUE

In E6.4.2, the c-values of samples S10.1-S10.3 were derived from resistance measurements. To do a proper c-value calculation, a sample should be knitted that is just a single leadwire, without any heaters attached to it. Otherwise, conductivity will increase as current has extra ways to flow from point to point. However, this extra conductivity is relatively low as the resistance through the heaters is much higher than through the leadwires.

For this experiment we only had S10.1 - S10.3, and it was not desired to cut them. Therefore, the c-value was derived from the sample with heaters still attached to it. In order to find out the relative impact that this would have in comparison to a loose leadwire, S9.2.2 was used as a guinea pig. The c-value of this sample was first measured with the heaters attached to it. Afterwards, the heaters were cut and the c-value was remeasured. The results can be seen in figures 86 and 87: the c-value derived from the sample with the heaters still attached is slightly higher than the one with the leadwires cut loose. As theoretically the c-value of the 'attached' sample should be lower, in the following experiment the effects of conductivity through the heaters neglected during determination of the leadwire c-value. In figure 88, the c-values of the S10 samples can be seen.

FIGURE 83: SAMPLE S9.2.2

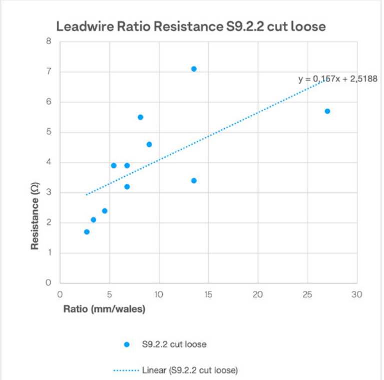


FIGURE 86 : LEADWIRE RATIO RESISTANCE OF S9.2.2, CUT LOOSE

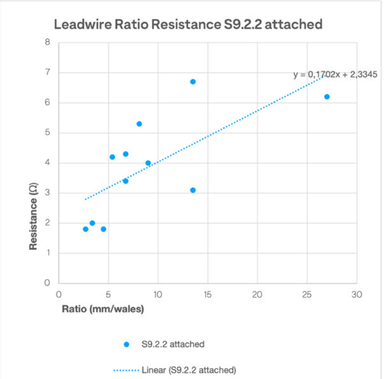


FIGURE 87 : LEADWIRE RATIO RESISTANCE OF S9.2.2, ATTACHED

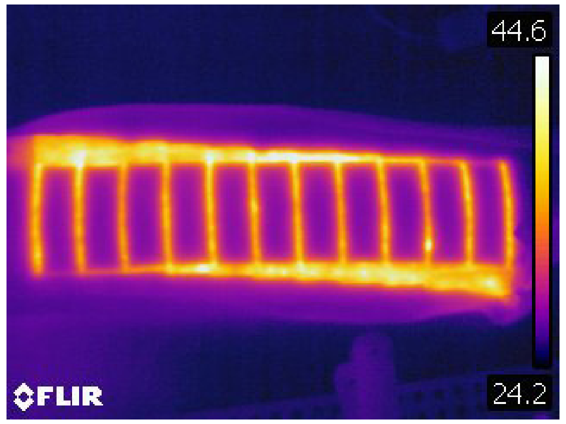


FIGURE 84: THERMAL IMAGE OF SAMPLE S10.1 HEATED WITH 5.5W

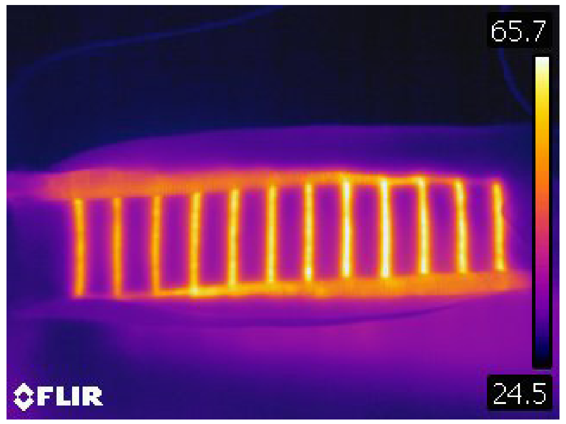


FIGURE 85: THERMAL IMAGE OF SAMPLE S10.2 HEATED WITH 5.5W

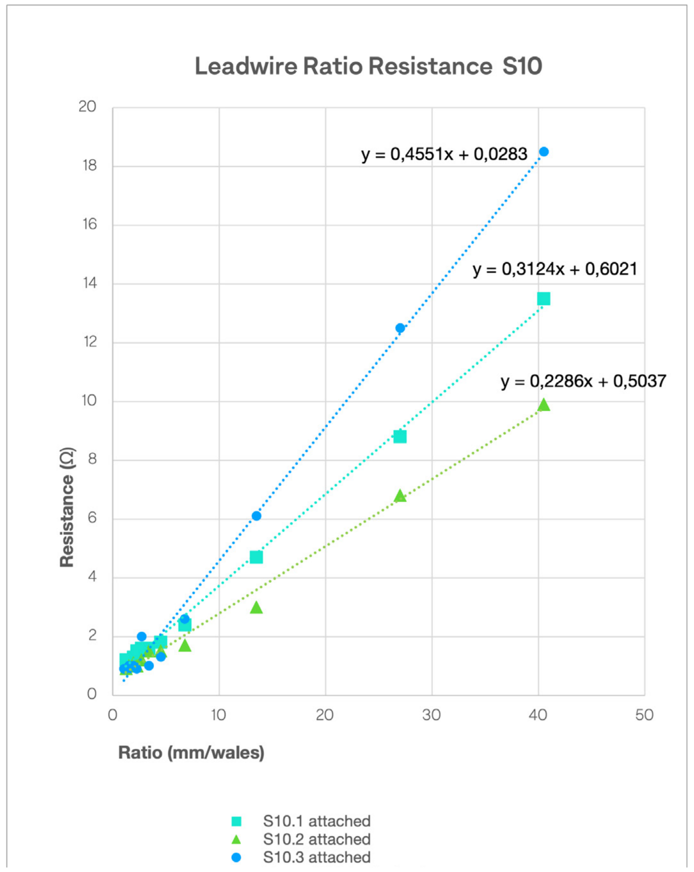


FIGURE 88 : LEADWIRE RATIO RESISTANCE OF S10

COMPARING HEATING BEHAVIOUR WITH CORRESPONDING SPD AND POWER ARRAYS

S10.1 and S10.2 were heated for 10 minutes with a power of 5,5W, in the regular test setup. As the resistances of the samples varies, input voltage was adjusted accordingly in order to maintain the same input power. The temperatures through every resistance of both samples were carefully measured with the thermal camera, and temperature differences were normalized to better visualise their relative differences.

As can be seen in the thermal images and their corresponding heatmaps, S10.2, which has a lower leadwire c-value than S10.1, shows an overall better heat distribution with relatively more heat being generated by the heaters compared to the leadwires.

To quantify the relative influence of Power and Surface Power Density on heat generation, the power and SPD arrays of the samples were both generated by manually filling in the c-value and leadwire widths of the samples in . These arrays were normalized and can be seen in figures 91, 92, 95, 96.

1	13.2	23	6.2
2	18.4	23.6	10
3	22.1	18.2	16.7
4	20.7	19.6	30.3
5	20.2	21.3	21
6	21	22.1	28.1
7	27	20.8	25.1
8	28.3	22	29.1
9	25.2	20.9	25.9
10	19.8	30.9	24
11	13.3	23.6	24.6
12	6.8	23.4	15.2

FIGURE 89: HEAT GENERATION ARRAY OF SAMPLE S10.1

1	0.4272	0.7443	0.2006
2	0.5955	0.7638	0.3236
3	0.7152	0.589	0.5405
4	0.6699	0.6343	0.9806
5	0.6537	0.6893	0.6796
6	0.6796	0.7152	0.9094
7	0.8738	0.6731	0.8123
8	0.9159	0.712	0.9417
9	0.8155	0.6764	0.8382
10	0.6408	1	0.7767
11	0.4304	0.7638	0.7961
12	0.2201	0.7573	0.4919

FIGURE 90: NORMALIZED HEAT GENERATION ARRAY OF SAMPLE S10.1

1	0.08642	0.5249	0.9573
2	0.3457	0.5249	0.9506
3	0.7778	0.5249	0.9602
4	0.6914	0.5249	1
5	0.7202	0.5249	0.9218
6	0.7778	0.5249	0.8469
7	0.8469	0.5249	0.7778
8	0.9218	0.5249	0.7202
9	1	0.5249	0.6914
10	0.9602	0.5249	0.7778
11	0.9506	0.5249	0.3457
12	0.9573	0.5249	0.08642

FIGURE 91: NORMALIZED POWER ARRAY FOR SAMPLE S10.1

0.1111	0.2839	0.09467
0.4444	0.2839	0.1111
1	0.2839	0.1372
0.4444	0.2839	0.1837
0.3086	0.2839	0.1975
0.25	0.2839	0.2178
0.2178	0.2839	0.25
0.1975	0.2839	0.3086
0.1837	0.2839	0.4444
0.1372	0.2839	1
0.1111	0.2839	0.4444
0.09467	0.2839	0.1111

FIGURE 92: NORMALIZED SPD ARRAY FOR SAMPLE S10.1

1	11.6	22.6	8.2
2	15.6	22.2	10.7
3	14.6	21.3	20.8
4	15.8	24.8	24.1
5	16.1	26.6	19.6
6	16.1	26.7	20
7	15.7	27.8	19.4
8	17.9	34.2	17.2
9	21.8	34.6	19.4
10	22	29.1	16.9
11	7.6	27.6	16.2
12	14.9	24.7	15.7

FIGURE 93: HEAT GENERATION ARRAY OF SAMPLE S10.2

1	0.3353	0.6532	0.237
2	0.4509	0.6416	0.3092
3	0.422	0.6156	0.6012
4	0.4566	0.7168	0.6965
5	0.4653	0.7688	0.5665
6	0.4653	0.7717	0.578
7	0.4538	0.8035	0.5607
8	0.5173	0.9884	0.4971
9	0.6301	1	0.5607
10	0.6358	0.841	0.4884
11	0.2197	0.7977	0.4682
12	0.4306	0.7139	0.4538

FIGURE 94: NORMALIZED HEAT GENERATION ARRAY OF SAMPLE S10.2

1	0.08642	0.7075	0.9573
2	0.3457	0.7075	0.9506
3	0.7778	0.7075	0.9602
4	0.6914	0.7075	1
5	0.7202	0.7075	0.9218
6	0.7778	0.7075	0.8469
7	0.8469	0.7075	0.7778
8	0.9218	0.7075	0.7202
9	1	0.7075	0.6914
10	0.9602	0.7075	0.7778
11	0.9506	0.7075	0.3457
12	0.9573	0.7075	0.08642

FIGURE 95: NORMALIZED POWER ARRAY FOR SAMPLE S10.2

0.1111	0.3826	0.09467
0.4444	0.3826	0.1111
1	0.3826	0.1372
0.4444	0.3826	0.1837
0.3086	0.3826	0.1975
0.25	0.3826	0.2178
0.2178	0.3826	0.25
0.1975	0.3826	0.3086
0.1837	0.3826	0.4444
0.1372	0.3826	1
0.1111	0.3826	0.4444
0.09467	0.3826	0.1111

FIGURE 96: NORMALIZED SPD ARRAY FOR SAMPLE S10.2

ABSOLUTE DIFFERENCES

The **absolute percentual differences** between the measured heat generation and the predicted power (top) and SPD (bottom) generation were calculated for both samples. The differences per value can be seen in figures 97-100.

DISCUSSION

Judging the figures, it can be said that the generated power arrays are better in prediciting the heating behaviour of a knitted heater than the SPD arrays. It is remarkable that the power generally does a relatively good job, but seems to be completely lost in translation for the resistors at the outside of the heater. These areas seem to heat up more than expected. This can be explained by two things:

- They are relatively small, which gives them a high SPD. The SPD array scores therefore slightly better in these parts.
- It is likely that some heat generated by other resistances is conducted to this area, as the heater is not so big.
- At both sides of these resistors are hot heaters. During the measurements, it is possible that some of their heat was actually measured, as the thermal camera captures the hottest temperature.

1	395	42	80
2	73	46	66
3	9	13	44
4	4	21	2
5	10	32	27
6	13	37	8
7	4	29	5
8	1	36	31
9	19	29	22
10	34	91	1
11	55	46	131
12	78	45	470

FIGURE 97: PERCENTUAL ABSOLUTE DIFFERENCE BETWEEN MEASURED HEAT AND POWER ARRAY OF SAMPLE S10.1

1	289	8	76
2	31	10	68
3	46	13	38
4	34	2	31
5	36	9	39
6	41	10	32
7	47	14	28
8	44	40	31
9	37	42	19
10	34	19	38
11	77	13	36
12	56	1	426

FIGURE 98: PERCENTUAL ABSOLUTE DIFFERENCE BETWEEN MEASURED HEAT AND POWER ARRAY OF SAMPLE S10.2

1	285	163	112
2	34	170	192
3	29	108	295
4	51	124	434
5	112	143	245
6	172	152	318
7	302	138	225
8	364	151	206
9	344	139	89
10	368	253	23
11	288	170	80
12	133	167	343

FIGURE 99: PERCENTUAL ABSOLUTE DIFFERENCE BETWEEN MEASURED HEAT AND SPD ARRAY OF SAMPLE S10.1

1	202	96	151
2	2	92	179
3	58	83	339
4	3	118	280
5	51	137	187
6	87	138	166
7	109	149	125
8	162	214	62
9	244	218	27
10	364	162	52
11	98	147	6
12	355	117	309

FIGURE 100: PERCENTUAL ABSOLUTE DIFFERENCE BETWEEN MEASURED HEAT AND SPD ARRAY OF SAMPLE S10.2

DISCUSSION E6

The goal of this series of experiments was to develop a well-distributed heating area. First of all, a diagonal parrallel configuration, despite its inconvenient electrode positions, has proven to be an elegant and simple way to divide the heat well over the heaters. Besides, adjusting leadwire width has turned out to be a succesful way to balance out the power.
The power behaviour in a likewise configuration, which has been reasoned with electro engineering principles, has opened up the opportunity to make first step towards heat behaviour prediction. The SPD-optimised model and the power-optimised model both have some say in the matter, but are not complete yet.

During all the experiments, the thermal camera was set to measure the hottest point within its given boundaries. Therefore, it makes sense that the heater does not seem to correlate well with the predicted behaviour of the SPD array. Increasing the area of a knitted heater apparantly does not have a linear relationship with the measured maximum temperature. This does however not automatically mean that it is worse at predicting the heating behaviour than the power-optimising model. It is more likely that other factors, such as heat clustering and heat intersection points, influence the maximum heat in an area as well, that are also dependent on the heated area. For the power array, it is likely that these factors somewhat balance out against the deficiencies of its prediction.

It was noticed during the experiments that the heating behaviour in a knit is actually rather hard to accurately predict; besides the possible explanations mentioned earlier, there are often unexplainable hot- and coldspots. In future research, a more accurate and advanced measuring method than simply measuring the hottest value should be looked into: The heat in every location within the resistance should be measured. Judging figure E632B5, it can be expected that the heat pattern will look like a bell curve, being the hottest in the middel. Besides, in order to prevent hotspots, the intersection points between resistors, that now tend to heat up easily, should be redesigned in a way that they have more space to conduct their heat to.

Despite not being able to predict heating behaviour super accuretely in a knit yet, the heat generation in samples S10.1 and S10.2 is better distributed than in any previous sample. To predict heating behaviour and to design a knitted heater, it can be said that for now, the power-optimised model does the best job in generating a well-distributed heating area. Before shifting to another approach, more research should be done on heat clustering, and more accurate heat measuring methods should be used. Besides, it should be investigated to what extent hotspots are actually noticed by users, when knitted heat is integrated into a wearable piece of fabric.

In the design phase of this project, a heater will be knitted using the power-optimised model to determine leadwire width. During user tests with this prototype, it will be tested whether hotspots can be noticed, and if so, to what extent that is undesirable.

EXPERIMENT 7

THE INFLUENCE OF TEMPERATURE ON THE ELECTRICAL RESISTANCE A DJ KNIT

Literature has taught us (see chapter 1.8 'Resistive heating') that when we heat knitted conductive yarns, an interesting phenomenon will occur: When electrical current is applied, the resistance of a sample will show a short rise, followed by a gradual drop. It is likely that this resistance drop is correlated with the rise in temperature. This experiment was conducted to find out how the resistance behaves when yarns are heating in a DJ sandwiched knit structure.

SETUP

12/05/2023

Sample S5.1.1 was placed in a Memmert industrial oven (see figure 102) in such a way that the conductive parts are only in contact with air (see figure 101A). The fan of the oven was turned off. The resistance was measured with a multimeter, of which the wires were pressed inbetween the oven and its door. The sample was heated to approximately 25, 30, 40, 50 and 60 degrees and was kept 45 minutes at the same temperature before the resistance was measured.

FIGURE 101A: S5.1.1 IN THE OVEN

RESULTS & DISCUSSION

As can be seen in figure 101B, there is a clear linear correlation between temperature and conductivity, meaning that the resistance will drop when it heats up. This phenomenon has also been observed in the other heat tests during this project: The current output was always higher at t=60s than at t=0s.

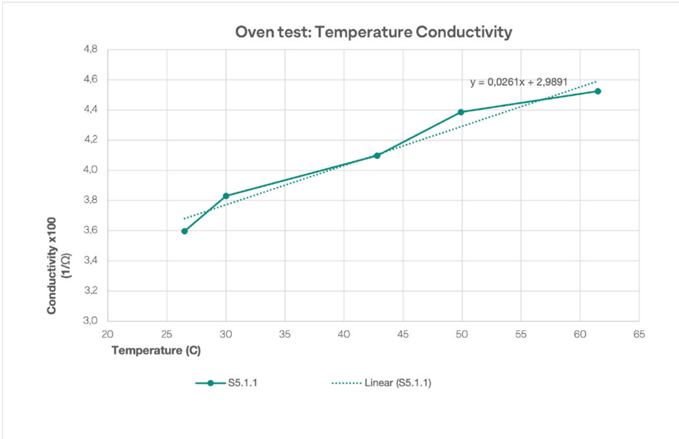


FIGURE 101B: TEMPERATURE VS CONDUCTIVITY GRAPH OF S5.1.1.

The results from this oven test prove that it is the heat, and not the current that influences the resistance in a heater. No visible difference could be seen in the yarn structure, even with a microscope. Therefore, it is assumed that the resistance drop has to do something with the material characteristics of the yarn. Despite the cause, the phenomenon of these resistance drops opens up design opportunities: It could for example be used to design a temperature sensor with a single, carefully knitted SPCY.

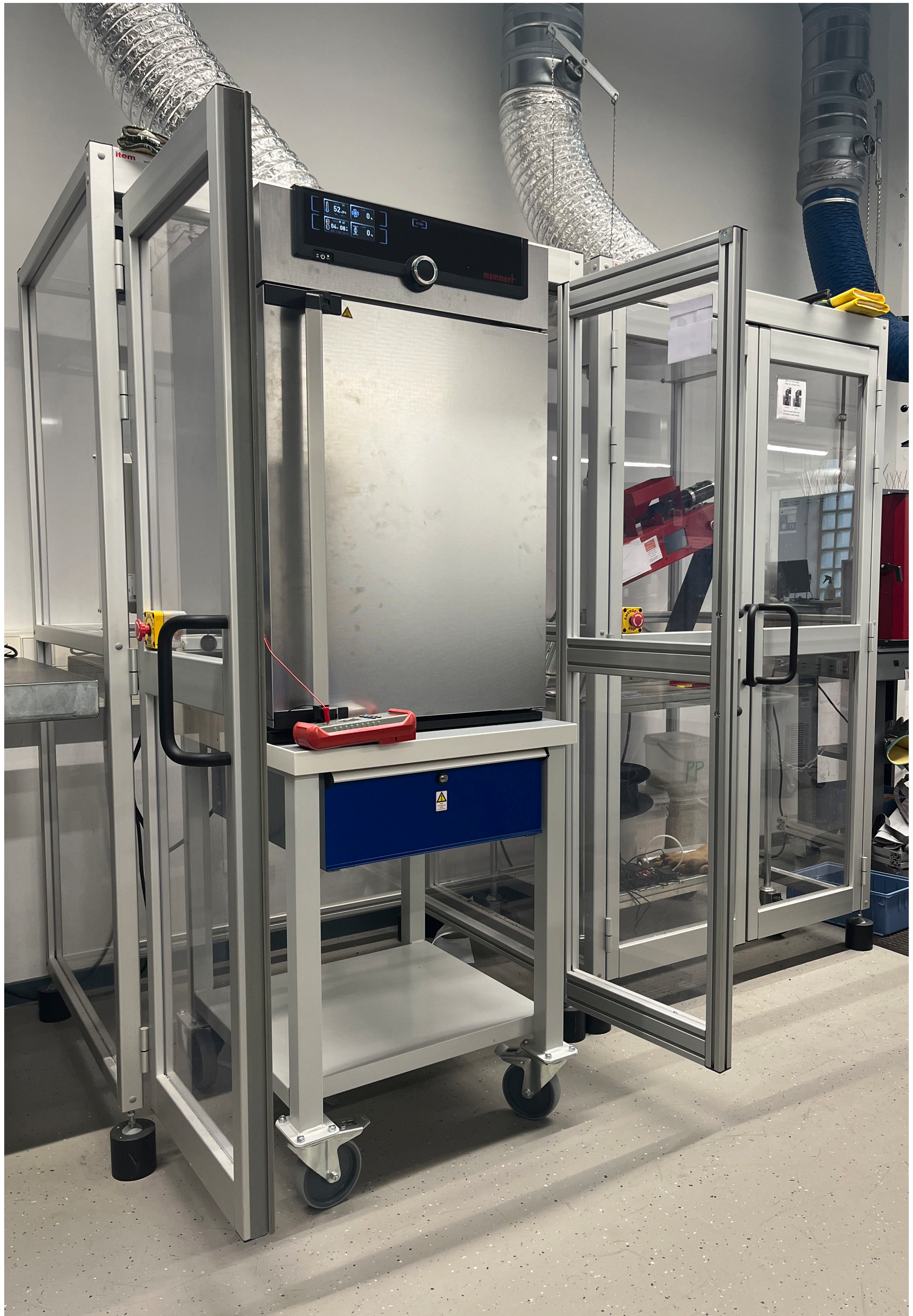
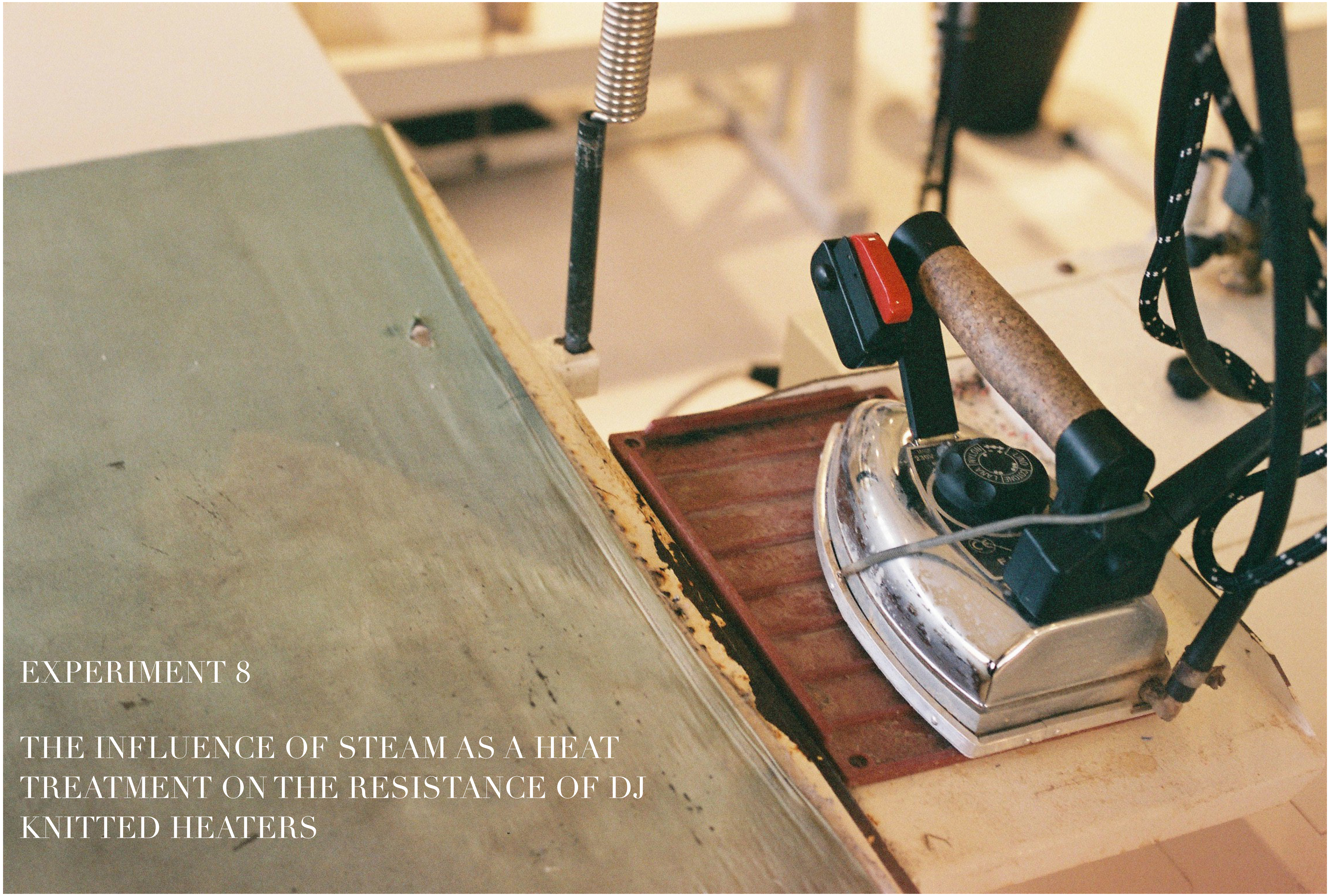


FIGURE 102: THE OVEN (MARK LOOPSTRA, 2023)



EXPERIMENT 8

THE INFLUENCE OF STEAM AS A HEAT TREATMENT ON THE RESISTANCE OF DJ KNITTED HEATERS

FIGURE 103: IRON AT BYBORRE KNITLAB (MARK LOOPSTRA, 2023)

Fabrics are often finished with a heating treatment after their manufacturing. Heating knit fabrics will make it shrink, which is why garments often say 'pre-shrunk'. Shrinkage influences the density of a fabric, and therefore influences the contact area and pressure between individual stitches. To find out what the influence of this shrinkage has on the conductivity through conductive fabric, an experiment was conducted that compares two identical knit samples, where one was steamed with a hot iron and one was not. Steaming is often used at Byborre as a quick method to visualise the end product, rather than the raw fabric that comes out of the machine (Byborre knit technician Joao, 2023).

SETUP

2 samples were investigated: S4.1.1 and S4.1.2, that are both double jersey samples with the conductive yarns plated on the backside of the polyamide yarn (sandwiched).

Sample 4.1.1

- DJ plated
- Heater yarn 1: C1
- Leadwire yarn 2: C2
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl =6 wales
- date of knitting: 30/03/2023

Sample 4.1.2

- DJ plated
- Heater yarn 1: C1
- Leadwire yarn 2: C2
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl =6 wales
- date of knitting: 30/03/2023

PROCEDURE

S4.1.1 and S4.1.2 are identical samples, knitted with the same yarns on the same date, shortly after each other on the same machine. After coming out of the machine, S4.1.2 was immediately steamed with an 800W F.lli Casoli iron for ten seconds (see figure 103).
Voltages of 5 and 7V were run through the samples and their resistance was measured at t=60s.

RESULTS

The results show that for both voltages, there is a clear difference between the resistance of the steamed sample versus the 'raw' sample: The resistance of S4.1.2 is 42% lower than that of S4.1.1.

The dimensions of the steamed sample are slightly smaller; a decrease of 2,1 % in its width (courses) and 2,2% in its length (wales) direction (see figure 106)

DISCUSSION

It can be concluded from the experiment that steaming has a significant influence on the density and thus the resistivity of the samples. Therefore, it should be chosen beforehand whether or not the final design will be steamed. If it will be, samples that are knitted to determine the c-values should be steamed as well.

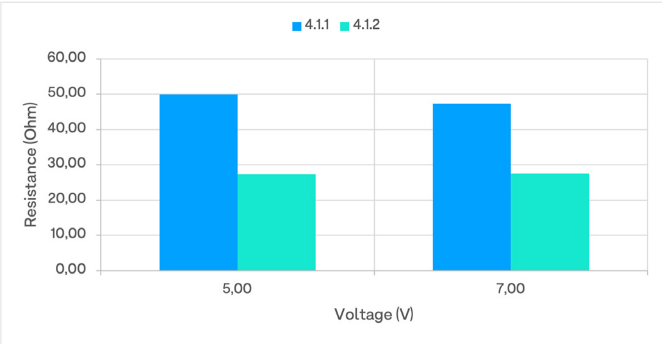


FIGURE 104: RESISTANCES OF S4.1.1 AND S4.1.2

FIGURE 105: STEAMING THE SAMPLE

FIGURE 106: THE SAMPLES AFTER S4.1.2 (BOTTOM) WAS STEAMED

EXPERIMENT 9:
THE INFLUENCE OF SWEAT ON THE PERFORMANCE OF A KNITTED HEATER

Not only will skin conductivity lower the resistance, but sweat could also cause a direct connection from one electrode to the other. It is hypothesized that shortcuts can be prevented by isolating the conductive yarns with a different layer of knitted fabric. Experiment 9 will show the results.

SETUP

3 samples have been investigated, of which one is single jersey fabric, one is single jersey plated fabric, and 1 is 'sandwiched' double jersey fabrics with the conductive yarns plated on the back side of the layer that is supposed to be worn in contact with the skin. The samples are placed in a test setup so that the conductive part is in contact with only air. The test was conducted at the Technical University of Delft, with an inside temperature of 21 degrees Celcius.

Samples with measured resistances:

Sample 3.2
- SJ
- Heater yarn 1: C1
- Leadwire yarn 2: C2
- non-conductive yarn : N1
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl =6 wales
- date of knitting: 23/03/2023

Sample 3.3
- SJ plated
- Heater yarn 1: C1
- Leadwire yarn 2: C2
- Plating yarn : N1
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl =6 wales
- date of knitting: 23/03/2023

Sample 5.1F
- DJ plated
- Heater yarn 1: C1
- Leadwire yarn 2: C2
- Plating yarn : N1
- Backside jersey yarn: N2
- Tucking yarn: N3
- Nh = 12
- Wh = 1 course
- Lh = 67 wales
- Wl =6 wales
- date of knitting: 14/04/2023


FIGURE 107: SAMPLE 3.2


FIGURE 108: SAMPLE 3.3


FIGURE 109: SAMPLE 5.1F

PROCEDURE

A voltage of 7V is run through all the individual samples. After three minutes, when the sample has roughly reached equilibrium temperature, one spray (= 0,8 ml) of room temperature water with 10g/L (Lara et al., 2015) NaCl is being sprayed on the top side of the sample, from a distance of 15 cm. The spray diverges in such a way that it covers the entire sample with hydro drops.

After 5 additional minutes, an extra 4 sprays are sprayed onto the sample. The resistance is measured for another 5 minutes.

The experiment is repeated for each sample. After letting dry the samples for 2 hours, the experiments are repeated with the other side up (backside)

RESULTS

It can be seen in figure 111 that shortly after the first spray of water was applied to the sample, a small increase in resistance occurs in the sample. After 480 seconds, when the 4 additional sprays are sprayed on the sample, the resistance starts to heavily increase, with fluctuating values. 5 minutes after the appliance last 4 sprays, the measurement was stopped.

Comparing the thermal images of the samples before and after the experiment shows that all samples have lost part of, or all their connection between the two electrodes. Conduction through the lead wires remained unchanged.

DISCUSSION

From the experiment it can be concluded that artificial sweat, and thus sweat, has a strongly negative influence on the conductivity of these silver-plated yarns. Instead of decreasing resistance through additional electrical connections between both electrodes, the resistance increases heavily due to yarn breakage.

Sample 5.1F, in which the yarns are plated behind a polyamide yarn, has less damage, but still lost connection of 9 of the 12 yarns. After the four sprays of salted water, the samples were actually soaked, which is unlikely to happen in an everyday situation as the wearer would probably take the product off before having generated this amount of sweat. However, a more hydrophobic material and structure should be considered to be used in an EHG with silver coated yarns, in order to protect the product from yarn breakage. Even better would it be to find a yarn which is resistant to sweat. For different yarns, similar experiments should be conducted.

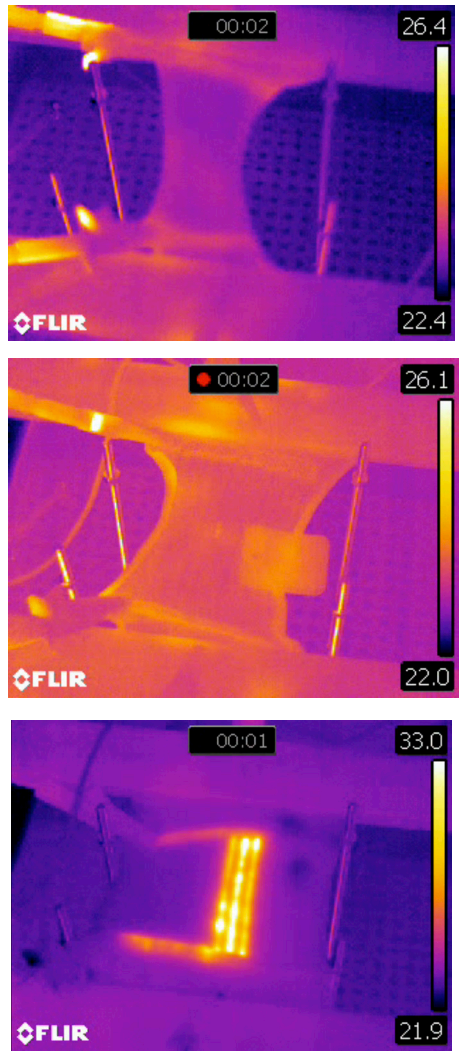


FIGURE 110: THERMAL IMAGES OF TESTED SAMPLES

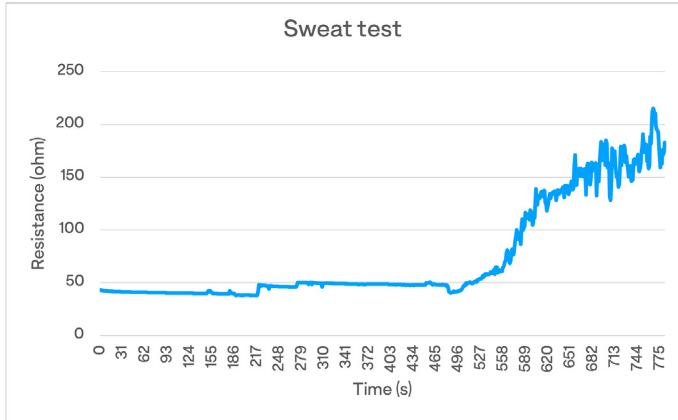


FIGURE 111: RESISTANCE VS TIME GRAPH

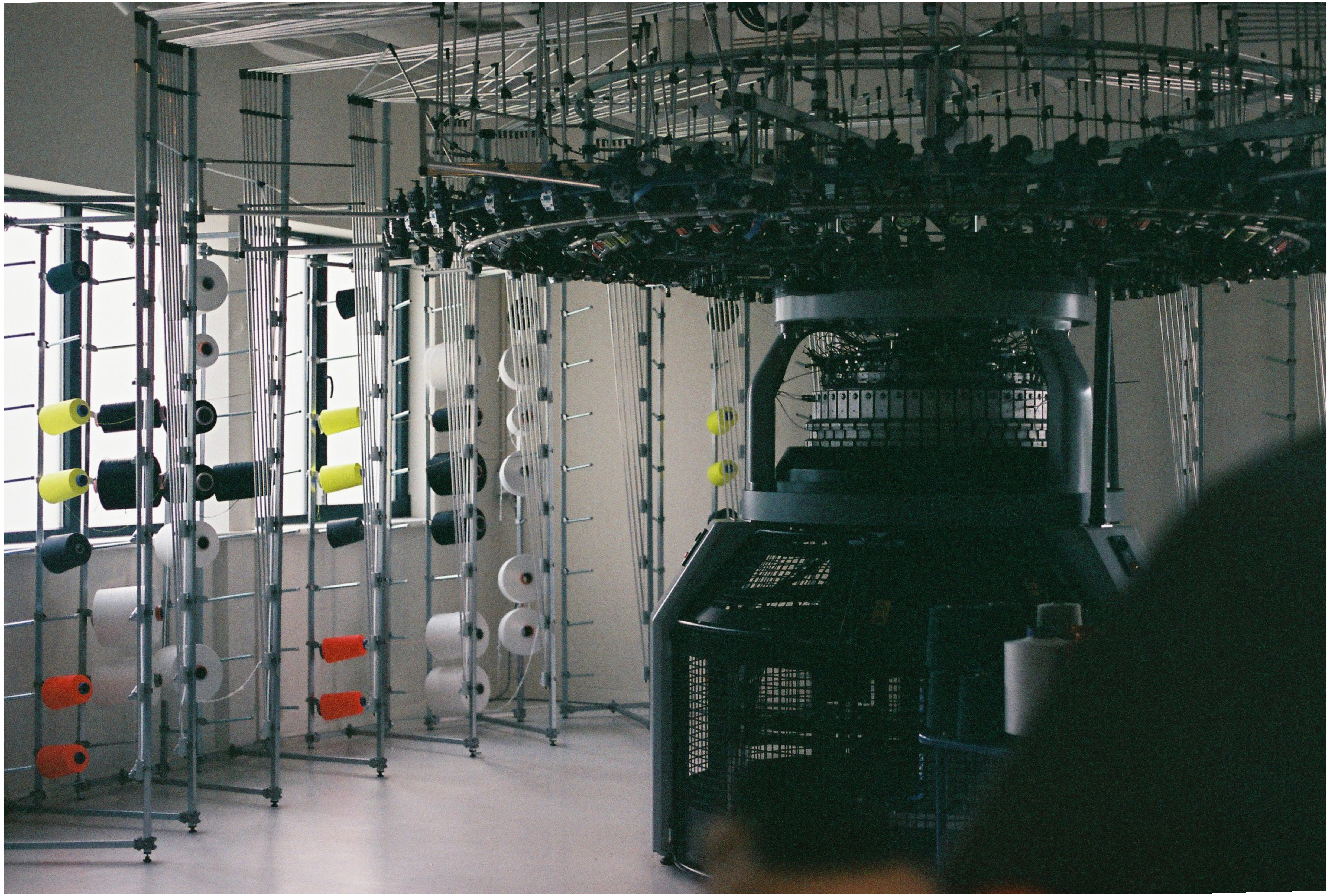


FIGURE 112: CIRCULAR KNITTING MACHINE AT BYBORRE (MARK LOOPSTRA, 2023)

FIGURE 113: SAMPLES AT BYBORRE (MARK LOOPSTRA, 2023)

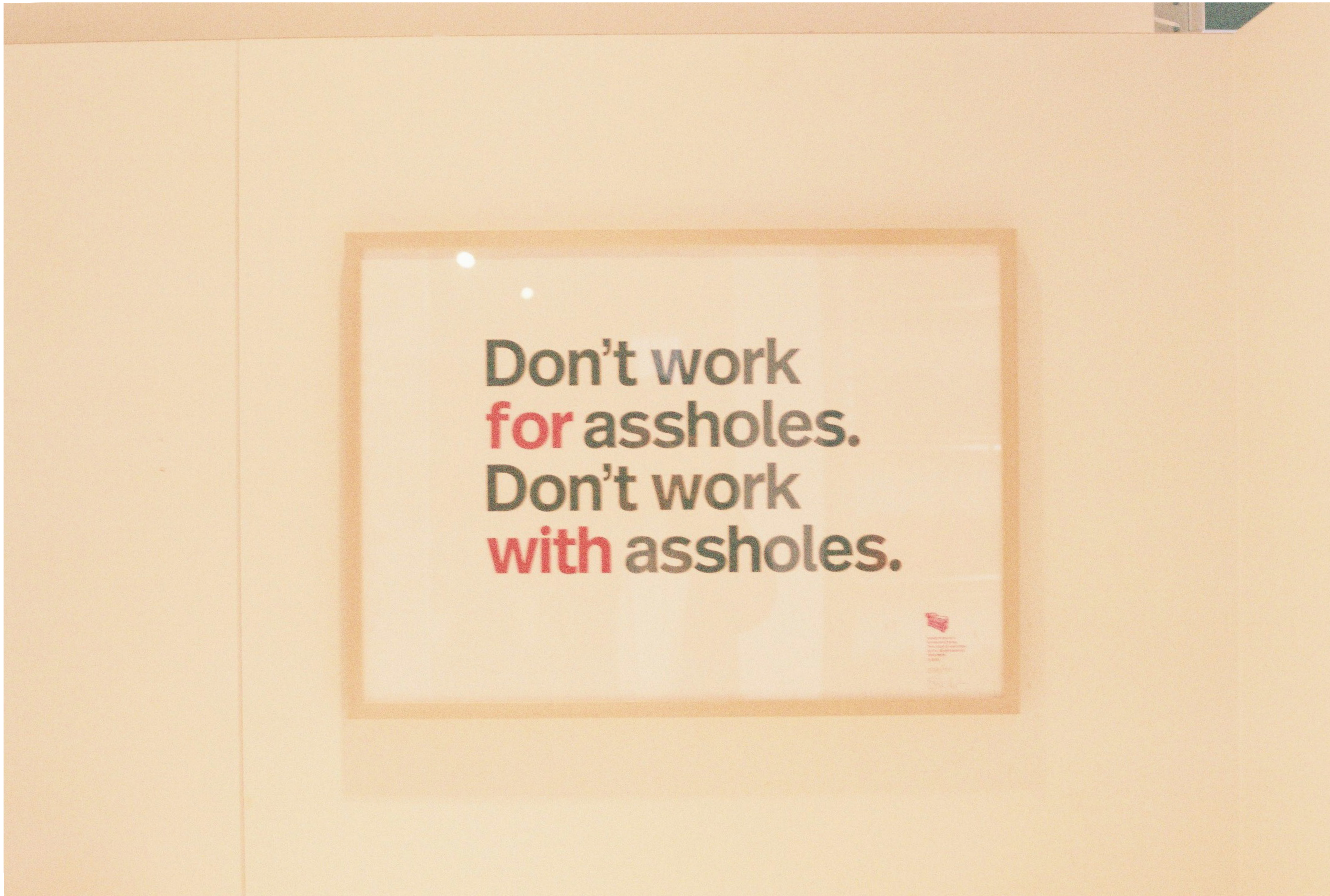


FIGURE 114: ASSHOLE SIGN AT BYBORRE (MARK LOOPSTRA, 2023)

DISCUSSION: DESIGNING A RELIABLE WEFT-KNITTED HEATER

In this project, the challenges and possibilities associated with weft-knitting silver-coated conductive yarns for creating weft-knitted heaters were explored. SCCY have proven to contain some unique characteristics, that can be challenging to work with. However, the knitting difficulties that come with their high friction and dtex do not outweigh the amazing possibilities that they offer within the (smart) textile realm; The samples produced in the experiments of this project are a total game-changer for the concept of 'heat'. Suddenly, heat can be felt in a stretchable, soft, and elegant piece of fabric. The use of resistive heating in a knitted heater demonstrated a clear correspondence with theoretical principles: Heat generation seems to be mainly dependant on the resistances in an electrical circuit. By sticking to some of the guidelines pointed out throughout this report, these resistances can be better controlled.
However, the conducted experiments have turned out that heating behaviour of a knitted heater is hard to accurately predict. t
The resistances in a knitted fabric are dependant on many knitting parameters, and we can only try to get close to controlling them. Some parameters are easily adjustable, such as the length and the width of a heater, and the conductivity of the yarns that are used. Other parameters are hard to adjust and should better be kept constant, as they can severly influence the resistance (such as steaming). Nevertheless, bundling all uncontrollable parameters in one c-value, and adjusting only length and width to get a desired resistance, has proven to be a valid way for basic R-predictions. After future research into the influence of other parameters, the c-value can be further dissected. Determining the c-value with a sample knitted beforehand is a good way to get insights in the resistance of your specific knit, though the knitted c-sample should contain many measuring points in order to get a reliable value.

Despite showing a slight heat-increasing trend towards the central heaters, using a diagonal parallel configuration is a simple and functional way to obtain equal heat distribution over every heater, making the equal heat distribution-challenge a lot simpler compared to a regular parallel configuration. It could however be said that making a series configuration would be even more simple, as the power through every resistor is naturally equal in a likewise electrical circuit. However, a series-configured circuit surely comes with its own challenges. By smartly integrating the leadwires as a part of the heater, material can be saved and the heating area will increase. As only the length and width parameters were changed in the design process, this can be done by adjusting the leadwire width accordingly. It should however be mentioned that by increasing the amount of heaters, the resistance of the leadwires has to drop exponantially. In absence of a big difference between the conductivity of multiple yarns, it should be mentioned that this might result in very wide leadwires. This is not necessarily a problem, but may not be everyone's aesthetic preference.

Predicting heating behaviour with a model that levels the power through every resistor has, for now, proven to be the the most accurate way. However, as mentioned in the discussion of Experiment 6, this method has its deficiencies. For small or large areas, it will not make an accurate prediction. For such extremities, surface power density should be taken into account. It should also be mentioned that the way in which heat generation was measured, is probably not very reliable. Hotspots occur not only at intersection points of multiple heaters, but also in the centers of individual resistors. Therefore, measuring the maximum heat over an area will not represent a realistic reflection of the actual heating behaviour. For future research, in order to truly understand heating behaviour, it is advised to use more advanced thermal measurement equipment, that can detect and store a detailed heatmap of a single heated resistor. In addition, it should be tested how these hotspots are actually being perceived by the human body.

Single Jersey heated knitters were decided to be too floppy to continue with. Plating the conductive yarn, especially in combination with a Double Jersey, has shown to be a good way to obtain proper samples with a professional feel. The heating behaviour of sandwiched yarn also has not disappointed. However, plating severly influences the resistance of a conductive knit, generally detoriating conductivity through a lack of contact points between individual stitches. Besides, some ways of plating have turned out to result in resistances that are very prone to respond to stretch. As fluctuating resistances in resistive heating will result in fluctuating heat generation, this should be carefully considered.

Unfortunately, the silver-coated yarns have some deficiencies; They are very fragile towards external factors, such as washing, sweat, and mechanical abrasion. For implementation of knitted heat into society, it is therefore important that more research is conducted on developing a bare conductive yarn with the same comfort that SCCY can offer, but without the vulnerabilities. If that is realised, knitted heat will become attractive for mass-production. As the research conducted in this project can be extrapolated to every type of bare conductive yarn, it can offer valuable insights to future designers that want to work with, for example, carbon-based yarns.

In conclusion, this project has formulated guidelines and tools for future designers to work with weft-knitted heaters. Through this project, BYBORRE has made an introduction into the realm of combining textile with electro-engineering, and has felt the heat through a self-made elegant piece of weft-knitted fabric. It is hoped that they will retain the energy to, in the future, further develop their knowlegde on this topic and combine it with their expertise to develop smart, wearable heat.

DISCUSSION: DETERMINING QUANTITIVE HEAT GENERATION IN A DIAGONAL PARALLEL CONFIGURATION

The determination of the equivalent resistance in knitted electrically heated garments can be a complex task, particularly when the heater is configured in a diagonal parallel pattern. This arrangement allows for uniform heat distribution across the garment. However, due to the diagonal flow, the effective resistance of the heater becomes more difficult to determine using conventional methods. However, understanding the total resistance is of large importance as it directly influences the power consumption and heat generation of the garment.

In this report and in the corresponding MATLAB model, there is no established method that calculates the total resistance of a diagonal parallel configuration. While various modeling techniques and simulations can help visualize the current flow and analyze the electrical behavior of the garment, there is a need for further research to develop an approach that accurately determines the total resistance. Numerical methods and simulations can be employed to simulate the electrical behavior of the garment and explore the effects of various factors on the equivalent resistance. By integrating advanced computational techniques with experimental data, researchers can develop more sophisticated models to estimate the total resistance in diagonal parallel configurations.

Nevertheless, the heat generation of a knitted heater can be optimized through not only adjusting the resistance but also by considering two additional factors: adjusting the input voltage and utilizing pulse width modulation (PWM).

By smartly choosing the output voltage of the batteries, which can be adjusted by connecting batteries in series, the power supplied to the heater can be adjusted accordingly. This flexibility enables fine-tuning of the power output of the garment to meet specific heating requirements. In the context of the prototype which is elaborated in the next chapter, an 11.1V battery was chosen by connecting 3 LiPo 3.7V batteries to each other. This was done in order to reach the estimated desired output power of 5-10W. Note that the desired output power differs for every single garment and should be determined beforehand.

Furthermore, pulse width modulation (PWM) can play a crucial role in temperature control and optimizing heat generation. PWM is a technique where the heating element is rapidly switched on and off at a controlled duty cycle. By adjusting the duty cycle, which represents the proportion of time the heating element is switched on relative to the total cycle time, the effective power delivered to the garment can be controlled. This enables precise temperature regulation and efficient energy utilization. Even if the total resistance of the knitted heater is slightly lower than calculated, the PWM control can compensate for it by appropriately adjusting the duty cycle to achieve the desired temperature.

In summary, optimizing the heat generation of a knitted heater involves multiple factors. Adjusting the resistance, input voltage, and utilizing pulse width modulation are essential considerations. While the determination of the exact equivalent resistance in a diagonal parallel configuration may pose complexity and require further research, the use of PWM control offers flexibility in compensating for resistance variations. Additionally, adjusting the input voltage through battery configuration allows for fine-tuning the power output of the garment. By considering these factors, designers can effectively optimize the heat generation and temperature control of knitted electrically heated garments, enhancing user comfort and energy efficiency.

3 DESIGN

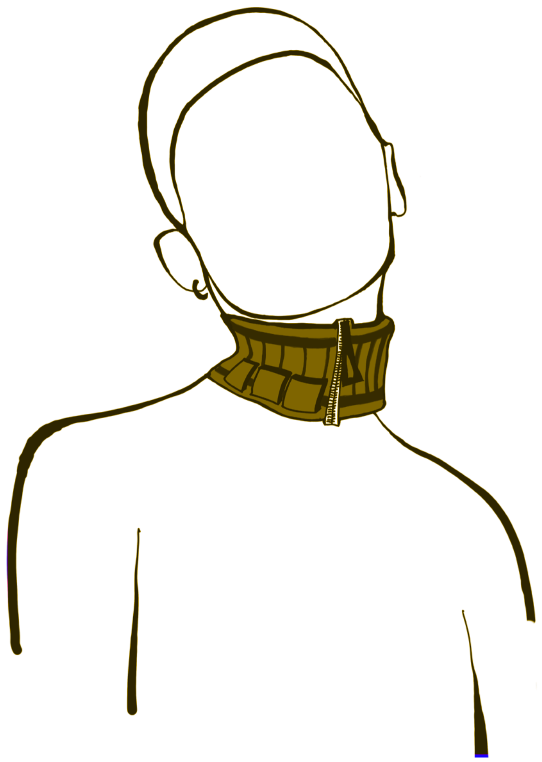
FIGURE 115: MODELS WEARING THE DEMONSTRATOR DESIGN (MARK LOOPSTRA, 2023)

INTRODUCTION

In this chapter, a design showcase is presented featuring a prototype that serves as a demonstrator, highlighting the possibilities and potential of knitted heat. The development of this demonstrator serves as a pivotal moment in the thesis, encapsulating the culmination of research efforts by showcasing a tangible prototype that embodies the findings outlined in the previous chapters.

The key objective of the demonstrator is to inspire and motivate future researchers, designers, and industry professionals to further explore and refine knitted heat. The prototype is developed to act as a catalyst, stimulating interest in the field. The prototype was kept as simple as possible to emphasize the feel of the heat in combination with the feel of the knit fabric, without being distracted by other design elements.

The demonstrator is a col, a scarf-like product that fits around the neck. It was knitted at BYBORRE studio on july 13th, 2023.



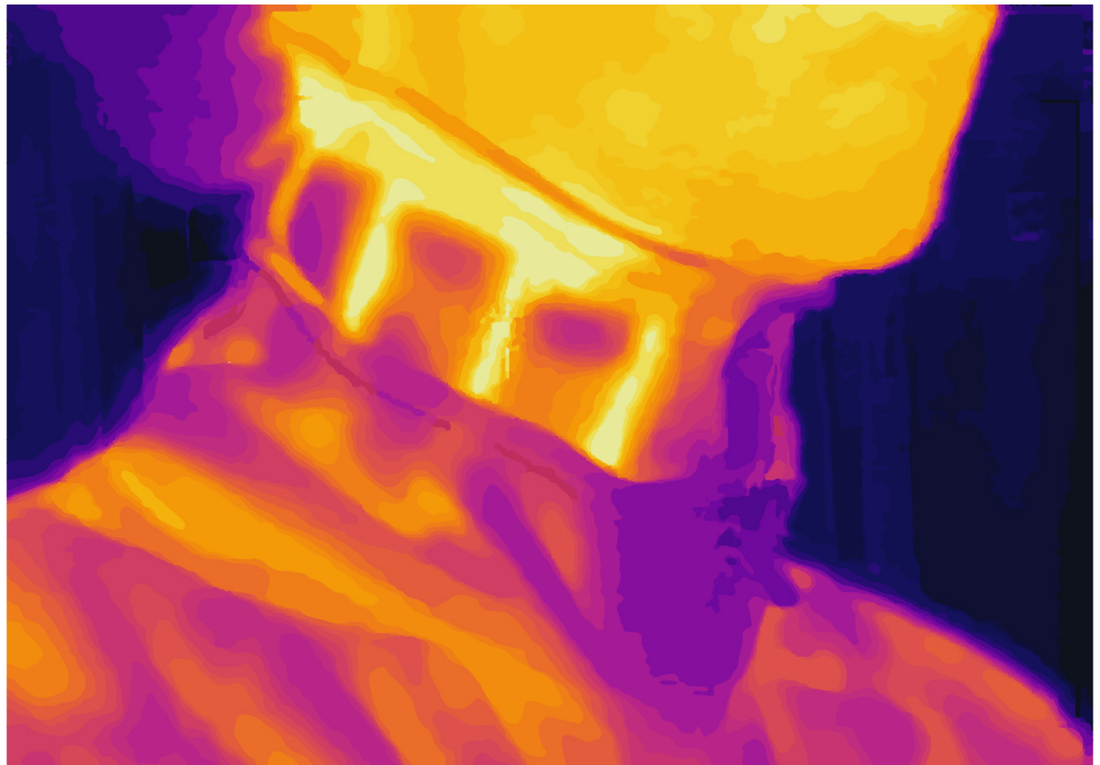


FIGURE 116: THERMAL IMAGE OF PERSON WEARING THE DEMONSTRATOR (MARK LOOPSTRA, 2023)

THE DESIGN

THE COL
The design of the prototype, a scarf-like 'col', was chosen for its simplicity and ease of demonstration. As a practical and widely recognized garment, the col serves as a suitable platform to showcase the capabilities of implemented knitted heat. Besides that, as scarves are already highly associated with cold, the product well fits the experience it intends to convey.

BATTERIES
Based on experiences during previous experiments, and for the sake of demonstrating, it was decided that a desirable output power range for the batteries in the prototype is between 5 to 10 watts. To achieve this power range, considerations were made regarding the expected resistance of the product, estimated to be approximately 15 ohms (similar to sample S10.2). Taking into account Ohm's Law, a voltage of 11 volts was chosen to ensure the desired power output falls within the desired range. Therefore three LiPo (Lithium Polymer) 3.7V 500 mAh single-cell batteries were configured in series. By connecting the batteries in series, the voltage from each cell adds up, resulting in a total voltage of 11.1V.

BATTERY POUCH
The design includes a knitted pouch specifically designed to hold the batteries (see figure 117). This pouch allows for easy insertion and removal of the batteries, facilitated by custom-made buttons that securely hold them in place. This design choice enables convenient replacement of the batteries as needed. The pouch is placed in the neck area, with the opening positioned on the inside of the col. This choice is motivated by observations in other industries, like football, where the neck region is commonly utilized for smart garment battery placement. By locating the pouch in the the neck, it provides convenient discreetness while ensuring a comfortable, dangle-free fit for the wearer.

CONNECTION WIRES
To establish the electrical connection from battery to electrodes, wires are configured through 'tunnels' that lead the wires to the corresponding electrode. As the prototype is designed with a diagonal parallel configuration, it should be noted that one of the wires has to cross to the other side of the circuit.

ALTERNATING PLATING PATTERN
As an alternating plating pattern proved to be the most conductive and stable option, it was chosen to use this in the demonstrator as well. It is important to note that the demonstrator is not intended for actual long-term use as a heated garment, as its primary purpose is to showcase the capabilities and potential of knitted heat. Therefore, considerations regarding durability and resistance to external factors such as washing, sweating, and rain, have not been fully addressed in this prototype.

YARNS
It was chosen to work with the same yarns as usual to keep control of resistances, but to choose a different, thicker second-jersey yarn in order to make the knit get some more body and make it feel more like an actual product. During preliminary knit tests, it was discovered that this thicker yarn however resulted in a much wider knit, as the stitches were thicker. It was therefore eventually chosen to decrease the amount of heater stitches slightly

LEADWIRES
The leadwire widths were optimised with the earlier presented MATLAB model (power-optimised). As this model failed at accurately predicting heat generation in the extreme width-leadwire parts, these values were slightly adjusted: The width in the widest areas was decreased by 20%.
The leadwires were also configured with the flat side pointed outwards, in order to make the circuit fit well within a rectangular area.

CLOSURE
The product needs some kind of closure to enable being worn around the neck. The first idea was to do this with a zipper, which could act as an on/off switch as it could complete the electrical circuit when one zipper-part made contact with the zipper part across from it. Eventually it was chosen not to continue with this idea as it required some very accurate sewing and knitting and was very prone to break. The closure was therefore realised with some simple, hidden buttons.

ON/OFF SWITCH
The demonstrator is turned on and off simply by connecting the battery to both buttons that lead to the electrodes, thus creating a full electrical circuit. If it is desired to turn the demonstrator off while keeping the battery in its pouch, It can be done so by disconnecting one of the buttons and placing the button part connected to battery in the big pouch, while keeping the button part connected to the wire in its own small pouch so that they will not be able to make contact.
It is chosen not to include an additional on/off switch in order to keep the prototype as simple as possible. As the demonstrator is not supposed to be used in daily life, it does not have to be turned on and off all the time. During a demonstration, the prototype will be turned on, and will most probably stay on until the demonstration is over. After the demonstration, the battery should be taken out to be recharged, which automatically turns the heater 'off'.

TEMPERATURE CONTROL
After the demonstrator was knitted, it was heated with 11V and heat generation was observed. As the heat generation was not as high as expected (as the resistance turned out to be higher), it was chosen not to include an additional PWM-based temperature control, as this can only decrease heat generation. Leaving it out would again make the demonstrator simpler.

FIGURE 117: DEMONSTRATOR SKETCH

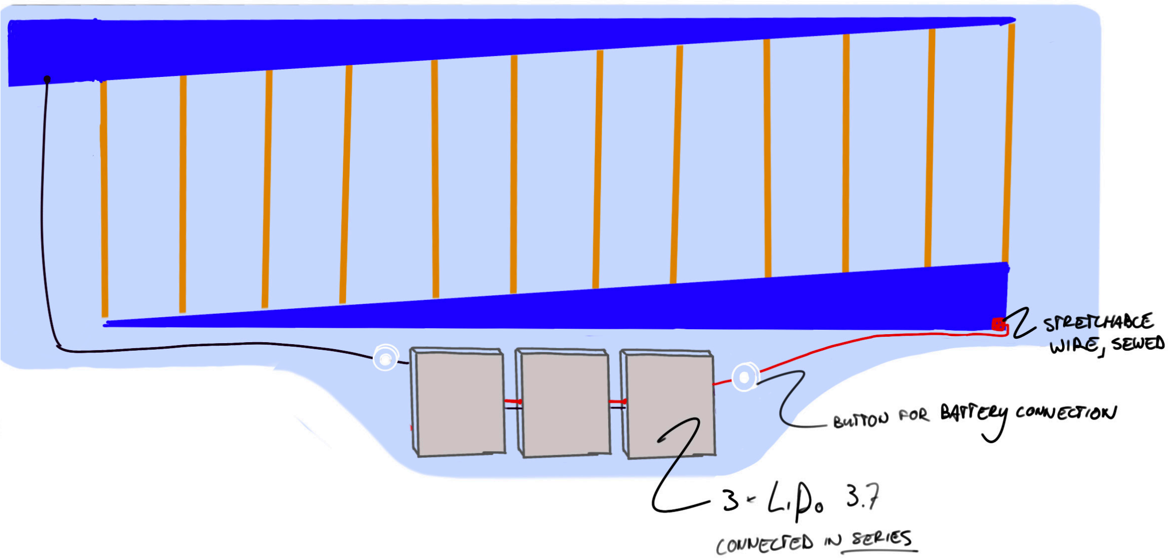


FIGURE 118: DEMONSTRATOR ELECTRICAL CONFIGURATION

RESULTS

THE KNIT RESULT

After having the necessary dimension tests, the demonstrator was knitted with conductive yarns on the 13th of July, 2023, from 4 till 4.30 pm. Except for a minor flaw in one of the battery pockets, the knit came out as expected.

RESISTANCE

The resistance was measured to be 27 Ohms. This is a bit higher than expected, as S10.2, which has a similar configuration, gave a value of approximately 15 Ohms. Therefore, the battery output and thus the heat generation will be a bit lower than estimated. The increased resistance can only be explained by the use of a different second jersey yarn, as the rest stayed constant. It was expected that this would not severly influence the resistance as this yarn does not touch the electric circuit. It can however be said that with a product like this, where the heat is very close to skin, not much heat generation is needed to keep the wearer comfortable. However, for the sake of demonstrating, a lower resistance was preferred.

EXTRA WIRES

After being knit, the additional electric wires were laced through the knitted tunnels and, after partly stripping the wire of its plastic coating, sewed on the tips of the leadwires (see figure underneath). The wires were intentionally cut off slightly bigger than the tunnel length, to allow for stretch.

THERMAL BEHAVIOUR

The thermal behavior of the demonstrator prototype can be described as effective, with generally well-distributed heat. However, some hotspots were observed in the middle of the lead wires. Besides, it can be seen that the connecting buttons also tend to heat up. As their heat generation is not higher than the that generated in the knit, this is however not really a problem.

FIGURE 119:DETAIL OF ELECTRICAL WIRE CONFIGURATION

FIGURE 120: THE DEMONSTRATOR, CLOSED

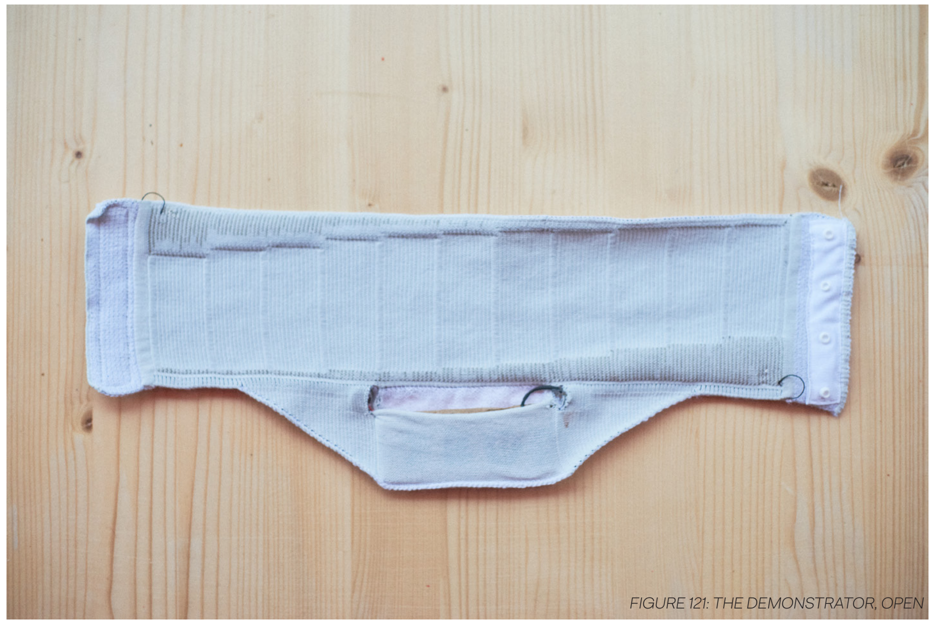


FIGURE 121: THE DEMONSTRATOR, OPEN

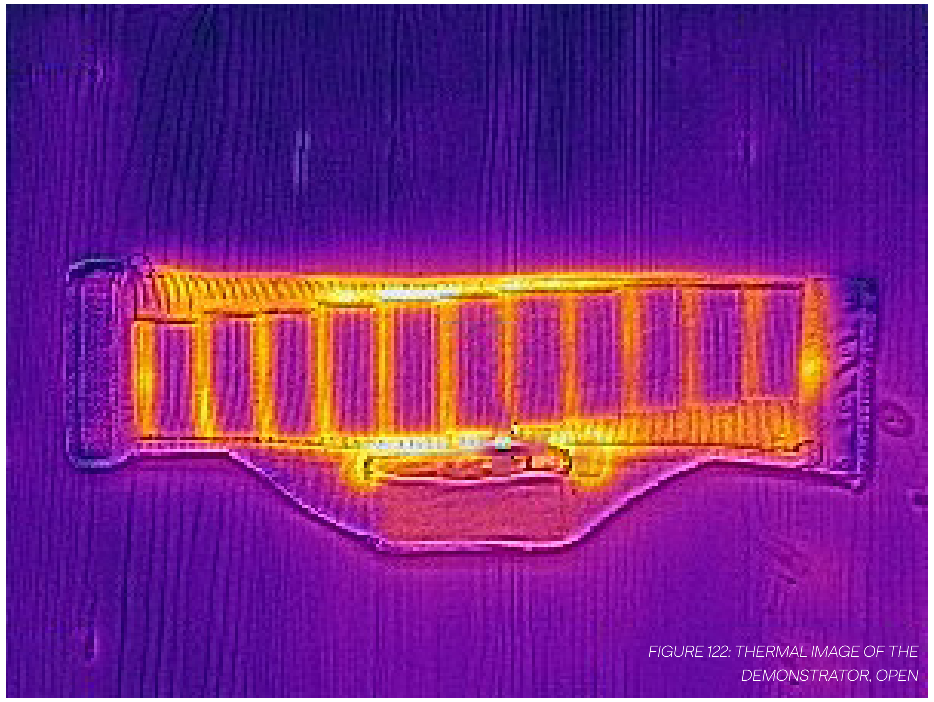


FIGURE 122: THERMAL IMAGE OF THE DEMONSTRATOR, OPEN

FIGURE 123: PHOTO OF A POSSIBLE FUTURE INDOOR WINTER SCENARIO: EITHER WEARING A BLANKET OR SOME SMART KNITTED HEAT

FEEDBACK

During a presentation at BYBORRE studio, some general feedback from the audience was asked and collected. The audience consisted of about 25 people, ageing 21-45. Their feedback is arranged in several clusters:

LOOK & FEEL
The audience was rather positive about both the appearance as the feel of the warm piece of fabric. They were mostly amazed by how it can heat up while feeling just like regular fabric. Some quotes read:

*'**This is cool**, imagine having a whole shirt made with this!'*

*'This fabric feels incredibly soft. I can imagine myself using it as **a cozy accessory** during chilly days.'*

*'The battery is **well-integrated**. I can imagine that you really don't notice it being there'*

*'It feels like a **warm hug** around my neck'*

DESIRABILITY
Whereas some people had a somewhat sceptical attitude, some expressed their desire for a likewise product.

*'I don't like wearing stuff around my neck **in general**'*

*'I think this will be **way too hot**. It's probably already warm enough without the electricity in it'*

*'Wow, **I'd wear this** in the winter'*

FUTURE DEVELOPMENT
A lot of questions rose concerning future development. People wondered how this can be further developed and what it still needs to be ready for market.

SAFETY CONCERNS
Many expressed safety concerns: not only about being electrocuted, but also about being set on fire.

DURABILITY CONCERNS
There were some questionmarks about the durability and thus sustainability of a likewise product, mainly regarding washing.

DISCUSSION: THE DEMONSTRATOR

The design chapter of this thesis provides a comprehensive exploration of a knitted heated garment prototype, highlighting both successful aspects and opportunities for improvement. By critically examining the design process, we can identify what went right and wrong, in order to write recommendations for future designers.

One notable achievement of the design phase was the selection of a scarf-like col as the product. This choice effectively demonstrated the practicality and versatility of the knitted heating technique in a familiar and wearable garment. The design provided an excellent platform for showcasing the capabilities of the technology, while being not much more complicated than the samples that were already there. Additionally, the integration of a knitted pouch to hold the batteries, along with custom-made buttons for easy insertion and removal, exemplified a user-centric approach. This consideration of user convenience and accessibility enhanced the overall experience of interacting with the prototype. The addition of electrical wire to connect the battery to the electrodes, even in a diagonal configuration, can be elegantly addressed by knitting tunnels. By omitting the connecting yarn at specific points in the double jersey knit, a seamless solution can be achieved.

While the design chapter showcases several successes, there are areas that could have been improved upon; To maintain predictable resistances, it was crucial to keep all parameters constant. However, the use of a different double jersey yarn in the demonstrator, chosen for enhanced sturdiness, likely affected the equivalent resistance, necessitating further investigation.

The durability of the prototype, particularly regarding resistance to washing, sweating, and rain, was identified as a general concern, and was hard to defend. Future designs should incoorporate alternative yarn options, such as carbon-based yarns, which offer promising durability characteristics.
Besides, the safety of the prototype emerged as a significant concern. Feedback from the audience emphasized worries about potential electrical hazards, such as shocks or fire risks. Future designs should prioritize implementing robust safety features, such as insulation, temperature regulation, and automatic shut-off mechanisms. Ensuring compliance with safety standards and obtaining relevant certifications will be critical for gaining user trust and market readiness. During the design process of a knitted heater, these safety-concerns should be taken into account from both a functional and an aesthetic point of view: How could we make a knitted heater *appear* more safe?.

Collaboration emerged as an interesting recommendation for future work. Involving experts from various disciplines, such as materials science, electrical engineering, fashion design, and user experience, could contribute to comprehensive and innovative advancements. Collaborative efforts should focus on addressing the identified limitations, improving performance, and refining the design of the heated garments.

To summarize, constant parameter maintenance, addressing safety concerns through temperature control and enhanced safety features, considering alternative yarn options, ensuring battery and MATLAB compatibility, and utilizing knitting techniques for wire integration are essential considerations for future design iterations. By addressing these recommendations, future projects can enhance the functionality, safety, and durability of heated garments, paving the way for new innovation in the field.

In conclusion, while the demonstrator has its limitations, it successfully serves as a springboard for future exploration, driving interest and pushing the boundaries of what can be achieved with knitted heat. By addressing the identified areas for improvement and building upon the successes observed, the path is paved for the development of reliable, safe, and durable heated garments that meet the needs and expectations of users. With continued research, collaboration, and innovation, the future of knitted heating holds great promise, opening up new horizons for nerve disease control, comfort, and sustainability.

4. APPENDIX

4.1 YARN OVERVIEW

YARNS	Report name	Brand	Model	Resistivity manufacturer	Resistivity measured	Materials	yarn count
	C1	Shieldex	Shieldex 235/36 HCB	< 600 Ω/m		Polyamide core, 99.9% pure silver coating	295 +- 4%
	C2	Shieldex	Shieldex 235/36 dtex 2-ply	< 80 Ω/m	53 Ω/m	Polyamide core, 99.9% pure silver coating	605 +- 10 dtex
	C3	Silver-tech	Silver-tech 120 tex 28	< 530 Ω/m	454 Ω/m	Silver coated polyamide/polyester hybrid	28
	C4	Silver-tech	Silver-tech 30 tex 96	< 85 Ω/m	67 Ω/m	Silver coated polyamide/polyester hybrid	96
	C5	Shieldex	Shieldex 78/20 dtex Z 120	< 3500 Ω/m		Polyamide core, 99.9% pure silver coating	92f20 +- 3 dtex
	N1	Nylstar	Meryl Cotton66	n.a.	n.a.	50% recycled PA/50% PA	190f136
	N2	OTW Barone		n.a.	n.a.	60% WV / 40% PA	
	N3		elastane yarn				

4.2 SAMPLE OVERVIEW

SAMPLES OVERVIEW	REPORT NAME	KNITTING DATE	STITCH TYPE	YARNS	COMMENTS
	S0	08/06/2023	SJ	C2, N1	
	S1.1	23/02/2023	SJ	C1 C2 N1	
	S1.2	23/02/2023	SJ	C1 C2 N1	
	S1.3	23/02/2023	SJ	C1 C2 N1	
	S1.4	23/02/2023	SJ	C3 C4 N1	
	S2.1	09/03/2023	SJ	C1 C2 N1	
	S2.2	09/03/2023	SJ	C1 C2 N1	
	S2.3	09/03/2023	SJ	C1 C2 N1	
	S3.1	23/03/2023	SJ	C1 C2 N1	
	S3.2	23/03/2023	SJ	C1 C2 N1	broke during sweat test
	S3.3	23/03/2023	SJ Plated	C1 C2 N1	broke during sweat test
	S4.1.1	30/03/2023	DJ plated	C1 C2 N1 N2 N3	
	S4.1.2	30/03/2023	DJ plated	C1 C2 N1 N2 N3	steamed
	S4.2	30/03/2023	DJ plated	C1 C2 N1 N2 N3	
	S51F	14/04/2023	DJ plated	C1 C2 N1 N2 N3	broke during sweat test
	S5H2	14/04/2023	DJ plated	C1 C2 N1 N2 N3	
	S5H3	14/04/2023	DJ plated	C1 C2 N1 N2 N3	
	S6.1	12/05/2023	DJ plated	C1 C2 N1 N2 N3	
	S7.1	23/05/2023	DJ plated	C1 C2 N1 N2 N3	
	S7.2	23/05/2023	DJ plated	C1 C2 N1 N2 N3	
	S7.3	23/05/2023	DJ plated	C1 C2 N1 N2 N3	
	S8.1	23/05/2023	DJ plated	C1 C2 N1 N2 N3	connections cut with scissors
	S9.1	02/06/2023	DJ plated	C1 C2 N1 N2 N3	
	S9.2	02/06/2023	DJ plated	C1 C2 N1 N2 N3	
	S9.2.2	02/06/2023	DJ plated	C1 C2 N1 N2 N3	connections cut during experiment 6.5
	S9.3	02/06/2023	DJ plated	C5 C2 N1 N2 N3	
	S10.1	08/06/2023	DJ plated	C1 C2 N1 N2 N3	perfect plate
	S10.2	08/06/2023	DJ plated	C1 C2 N1 N2 N3	alternating plate
	S10.3	08/06/2023	DJ plated	C1 C2 N1 N2 N3	reversed plate

4.3 BENCHMARK OVERVIEW

Brand	Product Category	Product name	Voltage	Battery Capacity	Price june 2023	Link	target group	notes
Nordic Heat	Vest	Liner Vest Black	7.4	2600	245	https://nordic-heat.com/product/liner-vest-black/	not specified	
Nordic Heat	Thermo longsleeve	BaseLayer top	7.4	2600	175	https://nordic-heat.com/product/base-layer-top/	not specified	
Nordic Heat	Scarf	Heated head and neck wear 2in1	7.4	1800	135	https://nordic-heat.com/product/head-neck-wear/	not specified	
ActionHeat	Jacket	ActionHeat 5V Men's Softshell Battery Heated Jacket	5	6000	200$	https://actionheat.com/collections/all-mens/products/actionheat-5v-battery-heated-jacket-mens?variant=19690711810166	not specified	
ActionHeat	Gloves	ActionHeat 5V men's premium heated gloves	5	3000 x2	200$	https://actionheat.com/collections/all-mens/products/actionheat-5v-mens-premium-heated-gloves?variant=31075509141622	not specified	
Hogge	Bodywarmer	Høgge Verwarmde Dames Bodywarmer Gløde Zwart	5	10000-20000	140	https://glode.nl/products/glode-elektrisch-verwarmde-bodywarmer-dames-v2-0?variant=42700737249508&currency=EUR&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&gclid=CjwKCAjw4ZWkBhA4EiwAVJXwqbIssyDDVOORMTOpeJJURfrheh_qg97XOQ5PHIv34x-WPiXWESxBXhoCPzAQAvD_BwE	not specified	
Santi Heating	diving suit	Santi Heating System Flex 2.0 Verwarmd Onderpak Man	Not specified, but 110W	24000	650	https://www.sublub.nl/artikel/62693/santi-heating-system-flex-20-verwarmd-onderpak-man.html?utm_source=googleshopping&utm_campaign=googleshopping-Feed&gclid=CjwKCAjw4ZWkBhA4EiwAVJXwqXqh3KaoLZFJsoWWSMhB3ewqAmTTOYf8JAxW6PzhEkf_DFDyWbMcSBoCiy4QAvD_BwE	Deep diving	
Odlo	Thermo longsleeve	I-Thermic-basislaagtop voor heren	not specified	not specified	175	https://www.odlo.com/nl/nl/i-thermic-basislaagtop-voor-heren-7613361731327.html?gclid=CjwKCAjw4ZWkBhA4EiwAVJXwqZLvgBfsZVm5vvNG_6PTjQHh15Bx78MobVlg0yJVk09JBpQwbnQhZhoCEswQAvD_BwE&gclsrc=aw.ds	Winter Sport	smart! Has thermic sensors and responds to them.
AGU	Jacket	HEATED THERMOJACK ESSENTIAL HEREN LED	not specified	not specified	154	https://agu.com/heated-thermojack-essential-heren-led?color_variant=Black&kb=ga_shpsmtt_17785574785_&gclid=CjwKCAjw4ZWkBhA4EiwAVJXwqa-mEXBoBJ2oufnGyAD_57OdBsMxXFNjw8enPnPT1P846kuJKr2cCRoCJW8QAvD_BwE	Biking	It has a ledlight integrated
Duran	vest	Duran Outerwear Heated Down Vest	not specified	not specified	not specified	https://www.duranheat.com/duran-outerwear-heated-down-vest-1.html	not specified	This company claims to be the inventor of the first carbon fiber heated garment. However, they don't elaborate

4.4 MATLAB

PowerLeadwireWidth

```
% Calculating desired leadwire width in diagonal parallel + lead wire resistances
% For knitted heater
%                              markloopstra 26-05-2023
% edit June 2023 (V2): Output values are normalized. Option added to manually fill in Wl to derive corresponding P and SPD arrays.

clear all;

    %%knit sample and fill in values

Capacity = 2500 % fill in battery capacity in mA
U0= 7; % fill in voltage of battery
Itot = 1; % fill in desired input current
Ltot = 310; % fill in total amount of wales in the heater
N = 12; % fill in amount of heaters
Wh = 2; %fill in width of heater, in courses
Lh = 67* ones(N, 1) ; % fill in the length of the heater
Cl = 0.23; % fill in measured c-value of leadwire
Ch = 1.28; % fill in measured c-value of heater
RCl = 0.7 % contact resistance: fill in b-value of leadwire
RCh = 5.76 % contact resistance: fill in b-value of heater
Rhmeasured = 32,7; % fill in measured value. Assuming all heaters have the same R

  %%colormap and font
  goldColor = [152/255 138/255 94/255]; % RGB values for gold color
white = [1.0 246/255 239/255]; % RGB values for yellow color

% Define the number of colormap divisions
numDivisions = 256;

% Create the custom colormap
customColormap = zeros(numDivisions, 3);
for i = 1:numDivisions
  customColormap(i, :) = goldColor + (numDivisions-i) / (numDivisions-1) * (white - goldColor);
end
  fontname = 'Armin Grotesk';
%%

Ih = (Itot/N) * ones(N, 1);
%Ih = [1 1 1 1 1 1 1 1]; %alternative configuration of heaters: make sure
%configuration is symmetrical

ILa = ones(N, 1); % Initialize ILa array

% fill in end value first
ILa(N) = Itot;

for k = N-1:-1:1
  ILa(k) = ILa(k+1) - Ih(k+1); % Decrease current ILa by the corresponding current value from Ih
end

ILb = ILa(end:-1:1);        % Opposite lead wire, in reversed direction

I = [ILa Ih ILb]; % overall current array
```



```
figure('Name', 'Current Array')
  heatmap(I)
  colormap(customColormap);
  ax = gca;
set(ax, 'FontName', fontname);

Rh = (Ch*Lh/Wh);
%Rh = (Rhmeasured-RCh) * ones(N, 1); % Resistance for heaters, accurate approach
Rh = Rh(1) * ones(N, 1); % Resistance for heaters, general approach
%RLa = (Rh/N^2); % Max Resistance for the hottest leadwire to stay under Ph

% Manually change resistance values for each part of leadwires
% RLa = [1 1 1 1 1]'
RLa = [Rh(1) ./ (1:N).^2]'; % use R required for equal heat distribution

RLb = RLa(end:-1:1);
R = [RLa Rh RLb];
figure('Name', 'Desired Resistance Configuration')
  heatmap(R)
  colormap(customColormap);
  ax = gca;
set(ax, 'FontName', fontname);

Ph = Ih.^2 .* Rh; % Power for heaters
PLa = ILa.^2 .* RLa; % Power for ILa
PLb = PLa(end:-1:1);

P = [PLa Ph PLb]; % overall power array
figure('Name', 'Power Array')
  heatmap(P)
  colormap(customColormap);
  ax = gca;
set(ax, 'FontName', fontname);

Ll = Ltot/(N-1);


DesiredWidthLeadwire = (Cl*Ll)./RLa;

Wl = ceil((Cl*Ll)./RLa); % round up to whole numbers (naar boven afgerond)
Wl = max(2, ceil(Wl / 2) * 2); % make sure minimum is 2, and only output even numbers
Wl % Wl is Leadwire width to be knitted, in wales

%manually fill in Wl to get corresponding power and SPD array. Make sure to
%put them in the right order: the electrode should be at the end (right
%side) of the array.

%Wl = [2 2 2 4 6 8 10 12 14 18 22 26]';

figure('Name', 'Desired Width Configuration')
heatmap(DesiredWidthLeadwire(:, 1))
customColormap1 = [152/255 138/255 94/255];
colormap(customColormap1);
ax = gca;
set(ax, 'FontName', fontname);

figure('Name', 'Actual Width Configuration')
heatmap(Wl(:, 1))
customColormap1 = [152/255 138/255 94/255];
```

```
colormap(customColormap1);
ax = gca;
set(ax, 'FontName', fontname);


TrueRLa = (Cl*Ll)./(Wl);


PLaTrue = ILa.^2 .* TrueRLa; % Power for ILaTrue
PLbTrue = PLaTrue(end:-1:1);

% Find the maximum value of the two arrays
maxValueP = max([Ph; PLaTrue; PLbTrue]);
% Normalize values
PhN = Ph/maxValueP;
PLaTrueN = PLaTrue/maxValueP;
PLbTrueN = PLaTrueN(end:-1:1);

TruePowerArray = [PLaTrueN PhN PLbTrueN]
figure('Name', 'True Power Array')
  heatmap(TruePowerArray)
  colormap(customColormap);
ax = gca;
set(ax, 'FontName', fontname);

  Ptot = Itot* U0 %total power in watts
  Rtot = U0/Itot %total resistance in ohm
  BatteryLife = 0.9*Capacity/(1000*Itot) %battery life in hours %90 percent rendement

  Wtot = Lh(1)+sum((Wl)/N)
  Ah = Lh*Wh;    Al = Ll*Wl;    %area of individual heaters and leadwires
Atot = Ltot*Wtot;  %area of entire heating element (dimensionless or amount of stitches)

SPDh = Ph(1)/Ah(1); %surface power density of heaters
SPDl = PLaTrue./Al; %surface power density of leadwires
SPDtot = Ptot/Atot %surface power density of total unit

% Find the maximum value of the two arrays
maxValueSPD = max([SPDh; SPDl]);
% Normalize values
SPDlN = SPDl/maxValueSPD;
SPDhN = SPDh/maxValueSPD;


SPD= [SPDlN SPDhN*ones(N, 1) (SPDlN(end:-1:1))]
figure('Name', 'Surface Power Density')
    heatmap(SPD)
  colormap(customColormap);
ax = gca;
set(ax, 'FontName', fontname);
```


SPDLeadwireWidth

```
% Calculating desired current, power and resistance in diagonal parallel + lead wire resistances
% For knitted heater                                        markloopstra 26-05-2023

clear all;

  %%knit sample and fill in values

Capacity = 2500 % fill in battery capacity in mA
U0= 7; % fill in voltage of battery
Itot = 1; % fill in desired input current
Ltot = 310; % fill in total amount of wales in the heater
N = 12; % fill in amount of heaters
Wh = 2; %fill in width of heater (amount of courses)
Lh = 67* ones(N, 1) ; % fill in the length of the heater
Cl = 0.159; % fill in measured c-value of leadwire
Ch = 0.792; % fill in measured c-value of heater
RCl = 0.7 % contact resistance: fill in b-value of leadwire
RCh = 5.76 % contact resistance: fill in b-value of heater
Rhmeasured = 32.7; % fill in measured value. Assuming all heaters have the same R

  %%colormap and font
  goldColor = [152/255 138/255 94/255]; % RGB values for gold color
white = [1.0 246/255 239/255]; % RGB values for yellow color

% Define the number of colormap divisions
numDivisions = 256;

% Create the custom colormap
customColormap = zeros(numDivisions, 3);
for i = 1:numDivisions
  customColormap(i, :) = goldColor + (numDivisions-i) / (numDivisions-1) * (white - goldColor);
end
  fontname = 'Armin Grotesk';
%%

Ih = (Itot/N) * ones(N, 1);
%Ih = [1 1 1 1 1 1 1]; %alternative configuration of heaters: make sure
%configuration is symmetrical

ILa = ones(N, 1); % Initialize ILa array

% fill in end value first
ILa(N) = Itot;

for k = N-1:-1:1
  ILa(k) = ILa(k+1) - Ih(k+1); % Decrease current ILa by the corresponding current value from Ih
end

ILa % Display the updated ILA values

ILb = ILa(end:-1:1);         % Opposite lead wire, in reversed direction

I = [ILa Ih ILb]; % overall current array
figure('Name', 'Current Array')
  heatmap(I)
    colormap(customColormap);
ax = gca;
```

```
set(ax, 'FontName', fontname);


Rh = (Ch*Lh/Wh);
%Rh = Rhmeasured * ones(N, 1); % Resistance for heaters, accurate approach
Rh = Rh(1) * ones(N, 1); % Resistance for heaters, general approach
%RLa = (Rh/N^2); % Max Resistance for the hottest leadwire to stay under Ph

% Manually change resistance values for each part of leadwires
% RLa = [1 1 1 1 1]'
RLa = [Rh(1) ./ (1:N).^2]'; % use R required for equal heat distribution

RLb = RLa(end:-1:1);
R = [RLa Rh RLb];
%figure('Name', 'Desired Resistance Configuration')
 %   heatmap(R)

Ph = Ih.^2 .* Rh; % Power for heaters
PLa = ILa.^2 .* RLa; % Power for ILa
PLb = PLa(end:-1:1);

P = [PLa Ph PLb]; % overall power array
%figure('Name', 'Power Array')
 %   heatmap(P)

Ll = Ltot/(N-1);


% Initialize Wl with the initial values
%Wl = ceil((Cl * (Ltot / (N - 1))) ./ ((Rh(1) ./ (1:N).^2)')); % use R required for equal heat distribution
%Wl = max(2, ceil(Wl / 2) * 2); % make sure minimum is 2, and only output even numbers

%% SPD
%set primary value for Wl
Wl = ones(N, 1)*(2)

% Calculate initial SPDl and SPDh
TrueRLa = (Cl * (Ltot / (N - 1))) ./ Wl;
PLaTrue = ILa.^2 .* TrueRLa; % Power for ILaTrue
SPDl = 1000 * PLaTrue ./ (Wl * (Ltot / (N - 1))); % Surface power density of leadwires
SPDh = 1000 * (Ih(1) .^ 2) .* Rh(1) ./ (Wh * Lh(1)); % Surface power density of heaters



% Additional loop to decrease Wl

while any (SPDl < SPDh)

decreaseIndices = find (SPDl<SPDh);

Wl(decreaseIndices) = Wl(decreaseIndices)-2;

TrueRLa(decreaseIndices) = (Cl * (Ltot / (N - 1))) ./ Wl(decreaseIndices);
PLaTrue = ILa.^2 .* TrueRLa; % Power for ILaTrue
   SPDl = 1000 * PLaTrue ./ (Wl * (Ltot / (N - 1)));
end

% Additional loop to increase Wl
```



```
while any(SPDl > SPDh)
   increaseIndices = find(SPDl > SPDh); % Find indices where SPDl is greater than SPDh

   % Decrease Wl by 2 for the indices where SPDl > SPDh
   Wl(increaseIndices) = Wl(increaseIndices) + 2;

   % Recalculate TrueRLa, PLaTrue, SPDl
   TrueRLa(increaseIndices) = (Cl * (Ltot / (N - 1))) ./ Wl(increaseIndices);
   PLaTrue = ILa.^2 .* TrueRLa; % Power for ILaTrue
   SPDl = 1000 * PLaTrue ./ (Wl * (Ltot / (N - 1)));
end


%% figures


figure('Name', 'SPD optimised Width Configuration')
heatmap(Wl(:, 1))
customColormap1 = [152/255 138/255 94/255];
colormap(customColormap1);
ax = gca;
set(ax, 'FontName', fontname);


TrueRLa = (Cl*Ll)./(Wl);


PLaTrue = ILa.^2 .* TrueRLa; % Power for ILaTrue
PLbTrue = PLaTrue(end:-1:1);

TruePowerArray = [PLaTrue Ph PLbTrue];
figure('Name', 'True Power Array')
   heatmap(TruePowerArray)
      colormap(customColormap);
ax = gca;
set(ax, 'FontName', fontname);


   SPD= [SPDl SPDh*ones(N, 1) (SPDl(end:-1:1))];
figure('Name', 'Optimised Surface Power Density')
      heatmap(SPD)
         colormap(customColormap);
ax = gca;
set(ax, 'FontName', fontname);


%   Ptot = Itot* U0 %total power in watts
 %  Rtot = U0/Itot %total resistance in ohm
  %  BatteryLife = 0.9*Capacity/(1000*Itot) %battery life in hours %90 percent rendement


  % Wtot = Lh(1)+sum((WidthLeadwire)/N)
   %Ah = Lh*Wh;    Al = Ll*Wl;    %area of individual heaters and leadwires
%Atot = Ltot*Wtot;  %area of entire heating element (dimensionless or amount of stitches)
```

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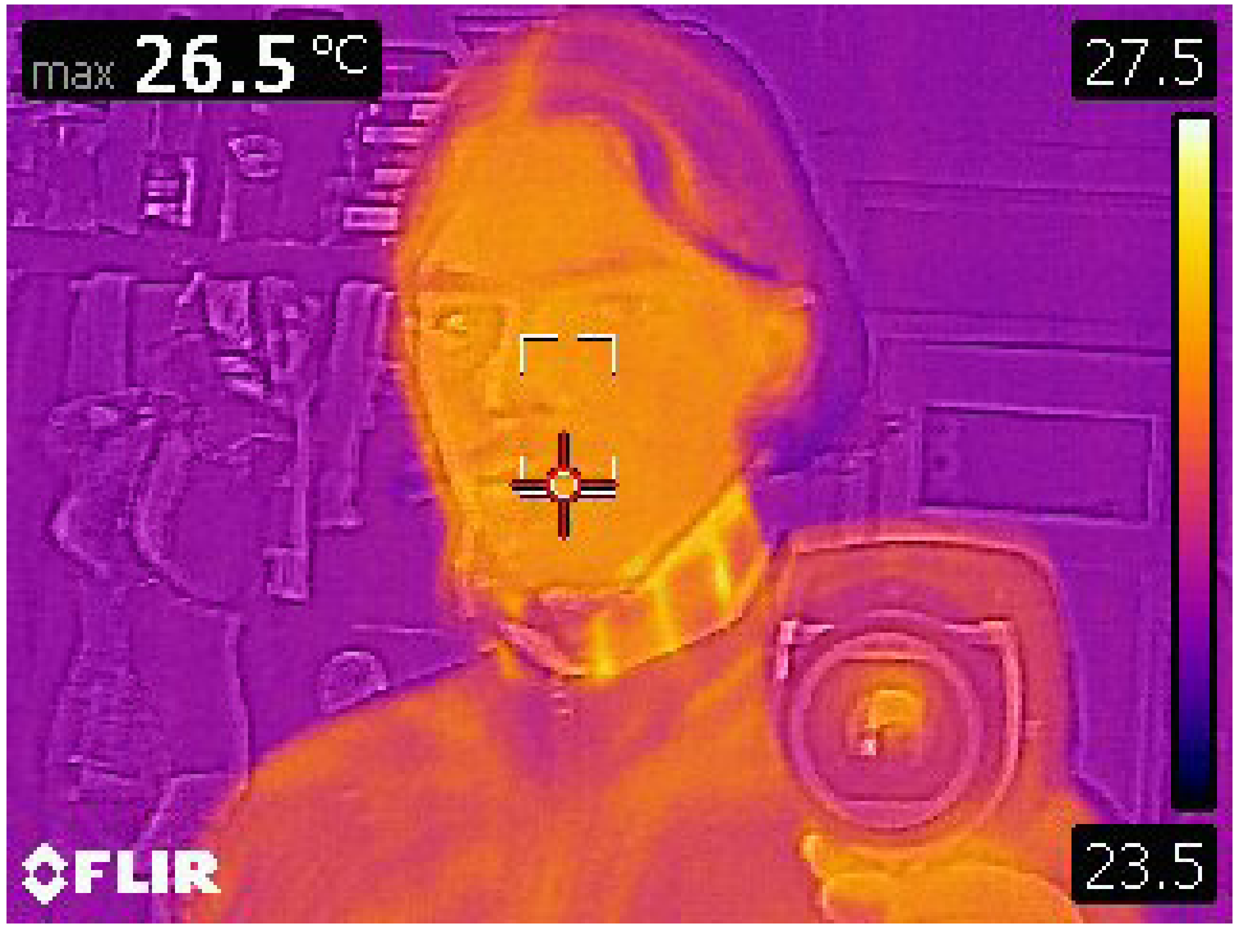

5.

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