Exploring the Possibilities of Graphene Textiles

- A Material-Driven Design Project to Develop Suitable Applications for Graphene Coated Textiles

Author: Louise Josefsson

Supervisors: Fredrik Henriksson and David Eklöf
Examiner: Renee Wever
Copyright

The publishers will keep this document online on the Internet – or its possible replacement – for a period of 25 years starting from the date of publication barring exceptional circumstances.

The online availability of the document implies permanent permission for anyone to read, to download, or to print out single copies for his/hers own use and to use it unchanged for non-commercial research and educational purpose. Subsequent transfers of copyright cannot revoke this permission. All other uses of the document are conditional upon the consent of the copyright owner. The publisher has taken technical and administrative measures to assure authenticity, security and accessibility.

According to intellectual property law the author has the right to be mentioned when his/her work is accessed as described above and to be protected against infringement.

For additional information about the Linköping University Electronic Press and its procedures for publication and for assurance of document integrity, please refer to its www home page: https://ep.liu.se/.
Abstract

Graphene is a two-dimensional carbon based material with unique properties, such as electrical and thermal conductivity. When a textile is coated with graphene, it becomes conductive, while remaining low weight, soft, breathable, flexible, and stretchable. The purpose of this thesis is to investigate what products are suitable to be made with graphene textiles, by using the method Material Driven Design (MDD). Reflections are also made to determine how this method is affected by being applied to a two-dimensional material. To help with this, three kinds of graphene textiles from the company Grafren AB are investigated; conductive textiles, heatable textiles, and textile sensors. The product goal is to develop a portfolio containing 5-8 conceptual products based on these graphene textiles.

The process includes conducting an investigation of the technical properties of the material, a user study, and a benchmarking study. This is done to understand the limitations and opportunities of the material, how it is perceived, and what similar materials there are on the market. After that, the material’s characteristics are reflected upon to establish a vision for how it should be used in future applications. Then, to follow that vision, a user study is conducted to investigate how people perceive different materials and products, in order to create design guidelines to ensure that the material and product are perceived as intended. Next, concepts are developed according to the previously determined guidelines. To achieve this, idea generating workshops are conducted, where 14 concepts are selected for further development. The portfolio is then created, meant to inspire further usage of the material. It contains the following seven concepts and can be seen at this website:

1. A heatable textile meant for cooking on camping trips.
2. A fabric containing sensors that can notify when it is damaged.
3. A keyboard made of fabric, for an easy and comfortable use and transportation.
4. A stroller with sensors and heaters, for a more comfortable and safe user experience.
5. A conductive jacket that can electrocute mosquitoes that come in contact with it.
6. Pressure sensors in a carpet that can keep track of the people inside and provide assistance in emergencies.
7. Gloves with sensors in them that can translate sign language live to text or speech.

Since MDD heavily focuses on the sensorial qualities and physical characteristics of the material, the method needs to be adapted to become useful when working with such a versatile two-dimensional material. Fortunately, most adaptations can be made fairly easily. The timing of each step should also be considered, to ensure that the vision and guidelines can be made specific enough to be useful.

Keywords: Material Driven Design, MDD, Graphene, E-textiles, Wearable technology, Graphene coated textiles, Graphene textiles, Conductive textiles, Heatable textiles, Textile sensors.
Acknowledgements

Thank you to everyone who helped me throughout the project. First I want to thank my supervisors, Fredrik Henriksson and David Eklöf, who have offered amazing support throughout the thesis, and for helping me formulate the research topic. I want to thank my opponents, Victoria Drewek and Ida Ritzman, for a great collaboration and for being available to answer questions when I needed. And thank you to the lecturers at Linköping University who took the time to help discuss various matters with me.

I want to thank everyone at Grafren AB for initiating the partnership, offering great feedback, taking the time to explain the technical aspects of the material and answered my many questions about it, as well as for participating in the idea generating workshop with great enthusiasm.

I also want to thank Ida, Natalie, David, Jana, Matilda, and Moa, who participated in the first user study to help me gather impressions of the material. Thank you to everyone who answered the anonymous questionnaire for the second user study. And thank you to Jana, Matilda, Moa, David, Anna, Saga, and Katja, who participated in the workshop and helped me generate many amazing ideas.

I want to thank Rebecca, Saga, Anna, Moa, and Grafren AB for helping me create the prototypes and visualisations of the concepts, as well as providing feedback on the portfolio. Lastly, I want to thank my partner Niklas who has been very helpful by discussing different matters, providing feedback, and by being the initial test-person for the various studies.
# Table of Contents

1 Introduction ................................................................. 1
   1.1 Background .......................................................... 1
      1.1.1 The material graphene ...................................... 1
      1.1.2 The main method of the thesis ............................. 2
   1.2 Objective and Research Questions .............................. 2
   1.3 A Case Study of Grafren AB ................................. 2
   1.4 Goals ............................................................... 3
      1.4.1 Product goals .................................................. 3
      1.4.2 Effect goals ................................................... 3
   1.5 Limitations and Delimitations ................................. 4
   1.6 Thesis Outline ..................................................... 4

2 Theoretical Framework .................................................. 6
   2.1 Material Driven Design ............................................ 6
      2.1.1 The process of MDD ......................................... 7
   2.2 Product Development Processes ............................... 9
      2.2.1 Fuzzy front end ............................................... 10
      2.2.2 The design paradox .......................................... 10
   2.3 User Studies ........................................................ 11
   2.4 Idea Generating Workshops ..................................... 12
   2.5 E-Textiles .......................................................... 14
      2.5.1 Manufacturing process of graphene textiles .......... 15

3 Understanding the Material ........................................... 16
   3.1 Methods - Understanding the Material ....................... 16
      3.1.1 Method - Technical properties of the material ....... 17
      3.1.2 Method - Perceived characteristics of the material ... 17
      3.1.3 Method - Material benchmarking ......................... 19
3.2 Results - Understanding the Material

3.2.1 Results - Technical properties of the material

3.2.2 Results - Perceived characteristics of the material

3.2.3 Results - Material benchmarking

3.3 Discussion - Understanding the Material

3.3.1 Discussion of the user study results

3.3.2 Discussion of the user study methods

3.3.3 Discussion of the material benchmarking

3.4 Conclusions - Understanding the Material

3.4.1 What are the main technical properties of the material?

3.4.2 What are the limits and opportunities of the material?

3.4.3 What are the unique sensorial qualities of the material?

3.4.4 What do people think are the most and least pleasing sensorial qualities of the material?

3.4.5 Does the material remind people of another material?

3.4.6 How would people describe the material, and what meanings does it evoke?

3.4.7 Does the material bring out any emotions, e.g., surprise, fear, love, relaxation?

3.4.8 How do people behave and interact with the material?

4 Creating the Material Experience Vision

4.1 Methods - Creating the Material Experience Vision

4.2 Reflections of the Previous Results

4.2.1 Reflections of the user study results

4.2.2 Reflections of the material benchmarking results

4.3 Creating the Material Experience Vision

4.3.1 The vision - Reflecting upon the eight questions

4.3.2 The vision - The material experience

5 Manifesting the Material Experience Patterns
### 8.2 Concept Development

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2.5</td>
<td>Concept 5. Anti-mosquito jacket</td>
<td>77</td>
</tr>
<tr>
<td>8.2.6</td>
<td>Concept 6. Smart carpet</td>
<td>78</td>
</tr>
<tr>
<td>8.2.7</td>
<td>Concept 7. Sign language interpreter</td>
<td>79</td>
</tr>
</tbody>
</table>

### 8.3 Discussion - Concept Development

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3.1</td>
<td>Discussion of concept 1. Textile camping cooker</td>
<td>80</td>
</tr>
<tr>
<td>8.3.2</td>
<td>Discussion of concept 2. Damage detection fabric</td>
<td>81</td>
</tr>
<tr>
<td>8.3.3</td>
<td>Discussion of concept 3. Textile keyboard</td>
<td>82</td>
</tr>
<tr>
<td>8.3.4</td>
<td>Discussion of concept 4. Smart Stroller</td>
<td>82</td>
</tr>
<tr>
<td>8.3.5</td>
<td>Discussion of concept 5. Anti-mosquito jacket</td>
<td>83</td>
</tr>
<tr>
<td>8.3.6</td>
<td>Discussion of concept 6. Smart carpet</td>
<td>83</td>
</tr>
<tr>
<td>8.3.7</td>
<td>Discussion of concept 7. Sign language interpreter</td>
<td>83</td>
</tr>
<tr>
<td>8.3.8</td>
<td>Discussion of the discarded concepts</td>
<td>84</td>
</tr>
</tbody>
</table>

### 9 Discussion

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>Discussion of the Results</td>
<td>85</td>
</tr>
<tr>
<td>9.2</td>
<td>Discussion of the Method MDD</td>
<td>85</td>
</tr>
<tr>
<td>9.3</td>
<td>Source Reflection</td>
<td>87</td>
</tr>
<tr>
<td>9.4</td>
<td>Ethical and Societal Considerations</td>
<td>87</td>
</tr>
</tbody>
</table>

### 10 Conclusions

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>RQ1: What are some novel and/or advanced products based on graphene textiles, that visualise the possibilities of the material?</td>
<td>89</td>
</tr>
<tr>
<td>10.1.1</td>
<td>RQ1.1: What are the unique properties of graphene textiles?</td>
<td>89</td>
</tr>
<tr>
<td>10.1.2</td>
<td>RQ1.2: How are graphene textiles perceived by people?</td>
<td>89</td>
</tr>
<tr>
<td>10.1.3</td>
<td>RQ1.3: How can products be designed so that the unique qualities of graphene textiles are highlighted?</td>
<td>90</td>
</tr>
<tr>
<td>10.2</td>
<td>RQ2: What are the effects of applying the method Material Driven Design to a material with qualities that are not noticeable by sight or touch?</td>
<td>90</td>
</tr>
<tr>
<td>10.3</td>
<td>Future Studies</td>
<td>91</td>
</tr>
</tbody>
</table>

### References

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
</tr>
</tbody>
</table>
List of Tables

1. The products with graphene textiles that Grafren AB are currently working on. ........................................ 3

2. Summary of the products from the benchmarking study. In this table, the organisations, materials, and areas of use are listed. The number corresponds with the number in the textual descriptions in chapter 3.2.3 except for (0), which is the case study company. ........................................ 42

3. Summary of the products from the benchmarking study. In this table, some often occurring qualities are compared for an overview. If the material or product is described as having the listed feature, there is an x in the box. If not, the box is left empty. If it is not mentioned or unclear, there is a question mark. The number corresponds with the descriptions in the textual descriptions in chapter 3.2.3 except for (0), which is the case study company. 43
## List of Figures

1. An illustration of graphene being separated from a block of graphite. Inspired by an image at the Grafren AB website. .......................... 1

2. An illustration of the thesis process and roughly where the research questions (RQ) are answered. ................................................. 4

3. An illustration of the four steps in the Material Driven Design (MDD) method. Inspired by an image in the article by Karana, Barati, et al. (2015) .... 6

4. An illustration of the six steps in a design process, according to the description of Ulrich and Eppinger (2016), and inspired by a similar figure in the book. 9

5. An illustration of the design paradox based on the descriptions of Ullman (2002) ................................................................. 11

6. An illustration of the dip-coating process, based on the textual descriptions from Khair et al. (2019) and verbal descriptions from Grafren AB. 15

7. The different prototype material samples provided by Grafren for the user study. (1A) A conductive textile with low stretch and an additional water repellent coating. (1B) A soft conductive textile with high stretch. (1C) A textile that is partly coated, and therefore partly conductive. (2A) A glove with pressure sensors and conductive threads on two fingers. (2B) A glove with a strain sensor and conductive threads on one finger. (2C) A small strip of graphene fabric that can act as a sensor. (3) A heatable textile with two parallel conductive threads ........................................... 18

8. An illustration of the heatable function of the graphene textile. Energy is sent into one of the conductive threads, travels across the fabric, and then exits through the other conductive thread. This way, the fabric between the threads is heated. .................................................. 21

9. How the participants interacted with the material samples. Based on the observations of the moderator during the user study. The dark circles represent the amount of participants who performed the listed actions from the Ma2E4 toolkit. .................................................. 22

10. The figure shows how many participants displayed each emotion during the user study. These results are based on the perceptions of the moderator. The dark circles represent the amount of participants who exhibited the emotions listed from the Ma2E4 toolkit. ........................................ 23

11. The meanings for the three textile types, collected through the questionnaire. 23

12. The perceived sensorial qualities of the rough conductive textile sample from the users, as well as an average value.Submitted through the questionnaire. 24

13. The perceived sensorial qualities of the soft conductive textile sample from the users, as well as an average value. Submitted through the questionnaire. 24
14 The perceived sensorial qualities of the textile sensor samples from all users, as well as an average value. Submitted through the questionnaire. .............. 24

15 The perceived sensorial qualities of the heatable textile sample from all users, as well as an average value. Submitted through the questionnaire. .............. 24

16 An example of the smart textile from Purdue University (Martinez 2021). Photo by Rebecca McElhoe (June 9, 2021). Copyright and Courtesy of Purdue University and Rebecca McElhoe. Image used with permission. .............. 25

17 One of the textiles with LED-lights at the exhibit of Barbara Jansen (Jurén 2015). Photo by Henrik Bengtsson (n.d.). Copyright by Textilmuseet. Image used with permission. .................................................. 26

18 An illustration of how the body heat emitted from the skin of the wearer is trapped by the heat insulating fabric. Inspired by an image on the Nanostitch (2016) website. ................................................................. 27

19 An image of the Fabricoc textile from the website (EXO2 2021a). Copyright by EXO2 The Heat Inside. Image used with permission. ....................... 27


21 Illustration of Nextiles’ tread based sensor. Image from the website (Nextiles 2021). Copyright 2021 by Nextiles, Inc. Image used with permission. ........... 28

22 A prototype of the wearable microgrid where it can power a wristwatch. Image from the article by Labios (2021). Photo by Lu Yin (2021). Copyright by the Regents of the University of California. Image used with permission. 30

23 An illustration of the stretchable display from Samsung. The figure is inspired by an image at the Samsung Newsroom web page (Samsung 2021). ........... 30

24 Illustration of the three factors; materials, people, and practices. And the relationships between them; encounters, performances, and collaborations. ... 39

25 The comments from the user study regarding what the participants think the most pleasant quality of the material is. If multiple people gave the same answer, they are overlapping. .................................................. 40

26 The comments from the user study regarding what the participants think the most unique quality of the material is. If multiple people gave the same answer, they are overlapping. .................................................. 40

27 The comments from the user study regarding what the participants think the most disturbing quality of the material is. To the left are all comments, with a summary of their content in the boxes with arrows going into them. To the right, the comments are divided into the two main categories of answers, though not all comments belong in either of the two categories. ............. 41

28 Figure containing the most common keywords used to describe the materials and products found in the benchmarking study and reflections below. ........... 43
29  Mind map of the thoughts about the first question for the material experience vision: *What unique qualities of the material should be emphasised in the final product?*  

30  Mind map of the thoughts about the second question for the material experience vision: *In which contexts could the material make a positive impact?*  

31  Mind map of the thoughts about the third question for the material experience vision: *How would people interact with the material within different contexts?*  

32  Mind map of the thoughts about the fourth question for the material experience vision: *What would the unique contribution of the material be?*  

33  Mind map visualising the thoughts regarding the fifth question for the material experience vision: *How would the material be perceived on a sensorial and interpretive level?*  

34  Mind map visualising the thoughts regarding the sixth question for the material experience vision: *What kind of emotions would the material evoke from people?*  

35  Mind map of the thoughts about the eighth question for the material experience vision: *What would the material’s role be in a wider context?*  

36  A more descriptive figure of the material experience vision for graphene coated textiles. Illustration is based on the textual descriptions from Giaccardi and Karana (2015) and inspired by an image in the same article.  

37  The mood board attempting to convey the word *futuristic.*  

38  The mood board attempting to convey the word *manufactured.*  

39  The mood board attempting to convey the word *safe.*  

40  The results from the questionnaire regarding the mood board for the meaning *futuristic,* along with how many votes the options received.  

41  The results from the questionnaire regarding the mood board for the meaning *manufactured,* along with how many votes the options received.  

42  The results from the questionnaire regarding the mood board for the meaning *safe,* along with how many votes the options received.  

43  To the left: a photo of a prototype of the heatable graphene textile in nature, cooking a cup of pasta. The textile is powered by batteries (see the black box) and sits on top of an insulating layer to protect the ground from the heat. To the right: the textile is wrapped around the battery box and held to demonstrate the small size. Photos by Louise Joelsion (2021).  

44  Thermal images of a heatable textile prototype, where the power is deactivated (left) and activated (right). Image credit to Gafren AB (2021).
45 A visualisation of how a seemingly unnoticeable injury could be detected by the fabric. The left image shows a firefighter in action with a small cut on his leg (photos are edited and originally from Unsplash). The upper right image is an enlargement of the cut (photos are edited and originally from Unsplash). In the bottom right image is an example of a damaged graphene fabric, where two parallel conductive threads keep track of any change in resistance between them (graphene fabric sample provided by Grafren AB, photo by Louise Josefsson (2021)).

46 Illustrations of how the application could look. To the left, a view of where the uniform is damaged. To the right, an overview of the team and the notification that something is wrong with the team member Charlie.

47 A visual prototype of a textile keyboard, where the frames of the keys are marked with white thread. Photo by Louise Josefsson (2021).

48 Graphene pressure sensitive fabric, provided by Grafren AB. The conductive threads visible in the image are what makes the pressure sensors possible. Each pair corresponds to one key. Photo by Louise Josefsson (2021).

49 Illustration of how the anti-mosquito jacket could look when deactivated.

50 Illustration of how the anti-mosquito jacket could look when activated.

51 Illustration of when a mosquito sits down on the anti-mosquito jacket.

52 Illustration of when the mosquito gets zapped by the anti-mosquito jacket.

53 Illustration of how the carpet keeps track of the people (pink dots) inside the building.

54 Illustration of an emergency and the carpet lights up the closest way out for everyone.

55 Illustration of an emergency and the carpet lights up the closest way out for everyone.

56 A prototype of the glove, with the decorative threads illustrating approximately where the strain sensors are located. The far-right photo shows where the pressure sensor is located for the activation feature. Photos by Louise Josefsson (2021).

57 Illustration of how the application can look. To the left, languages are selected. To the right is the layout before the translation begins.

58 The scale which the emotions are perceived to be, and if they are pleasant or unpleasant.

59 The three meanings are reflected upon further. The meaning are listed at the top as themes, and the words on post-it notes below are meant to help describe what the themes should convey.

60 The overall view of the workshop setup in MIRO for workshop2.
86 The leisure-grouping in the affinity diagram of ideas ............................................ 131
87 The c-box diagram of the selected 55 ideas .............................................................. 132
88 15 ideas within the fashion category that are presented to the company for voting .......................................................... 133
89 15 ideas within the games category that are presented to the company for voting .......................................................... 134
90 15 ideas within the sport category that are presented to the company for voting .......................................................... 134
91 15 ideas within the home category that are presented to the company for voting .......................................................... 135
92 15 ideas within the health category that are presented to the company for voting .......................................................... 135
93 15 ideas within the transport category that are presented to the company for voting .......................................................... 136
94 The sketch process of the textile keyboard concept ..................................................... 137
95 The sketch and prototype process of the textile camping cooker concept ..................... 138
96 The sketch process of the smart stroller concept ....................................................... 139
97 The sketch process of the discarded rehabilitation gloves concept ............................... 139
98 The sketch process of the anti-mosquito jacket concept ............................................. 140
99 The sketch process of the sign language interpreter concept ....................................... 141
100 The sketch process of the smart carpet concept ...................................................... 142
101 The sketch process of the discarded smart bike concept ............................................ 142
102 The sketch process of the discarded smart couch concept ......................................... 143
103 The sketch process of the discarded luminous workout clothes concept ....................... 144
104 The sketch process of the discarded message clothes concept .................................... 144
## Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDD</td>
<td>Material Driven Design. A product development methodology where the material is the starting point, as opposed to a product or a problem (Karana, Barati, et al. 2015).</td>
</tr>
<tr>
<td>Iterative</td>
<td>Repeating the same process several times.</td>
</tr>
<tr>
<td>Material benchmarking</td>
<td>A study to compare one material with others, as well as any applications.</td>
</tr>
<tr>
<td>MDMS</td>
<td>Meaning Driven Materials Selection. A method that helps the designer understand how certain key characteristics of a material can influence the user’s perceived opinion of it (Karana, Hekkert, et al. 2009).</td>
</tr>
<tr>
<td>FFE</td>
<td>Fuzzy Front End. A chaotic and unstructured initial phase in the product development process (Koen et al. 2001).</td>
</tr>
<tr>
<td>E-textile</td>
<td>A textile with electronic and/or conducive properties (Hu et al. 2010).</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence.</td>
</tr>
</tbody>
</table>
1 Introduction

In this chapter, the thesis is introduced. The background of the material is presented along with the goals, research questions, limitations, and thesis structure.

1.1 Background

In the background, the material is presented, as well as the main method used for this thesis.

1.1.1 The material graphene

Graphene is a two-dimensional carbon based material. It is defined as a single layer of carbon atoms in a hexagonal (honeycomb) structure, where each atom is attached to three others (ISO [2017]). In simple terms, graphene is one atom layer of graphite, as illustrated in Figure 1. The ISO standard allows material with up to ten atom layers to be called graphene, anything thicker than that is considered graphite (GrafrenAB [2021]). The particular structure of graphene gives the material certain unique characteristics and properties, including electrical conduction and extremely high thermal conductivity (Takai et al. [2020]).

![Figure 1: An illustration of graphene being separated from a block of graphite. Inspired by an image at the Grafren AB website.](image)

Graphene is an attractive component to use in textile coatings in order to make electrically conductive textiles, due to its electrical and thermal conductive properties GrafrenAB [2021]. Such textiles are commonly made by attaching conductive particles to a fabric. According to Khair et al. [2019], it is beneficial to use carbon based particles as they have excellent electrical properties, as well as mechanical and environmental stability. Other particles commonly used are of metal or polymer (Khair et al. [2019]). As graphene is a two-dimensional material, it is considered undetectable when applied on the textile.

Since graphene is the building block of graphite, it can be obtained by exfoliating graphite, either chemically or mechanically (GrafrenAB [2021]). One problem with this process, though, is that it is very difficult to successfully remove impurities and non-graphene fractions. If these impurities are not removed, the quality of the graphene is reduced (GrafrenAB [2021]).
1.1.2 The main method of the thesis

When conducting a design project, Wikberg Nilsson et al. (2015) consider it important to reflect upon which strategy is most suitable for each project. The writers mean that since every situation is unique, the process and methods used should always be reviewed and reflected upon to ensure that the intended goal is reached. Since this thesis has a material as a starting point, the main structure follows the method Material Driven Design (MDD) by Karana, Barati, et al. (2015), which includes the following steps:

1. Understanding the material from a technical and experiential perspective.
2. Creating a material experience vision.
3. Manifesting the material experience patterns.
4. Designing material/product concepts.

However, as the description of the method is quite general, complimentary methods are added when needed. For example, in the final step of MDD, product development methods by Ulrich and Eppinger (2016) and Koen et al. (2001) are used to specify the development process.

1.2 Objective and Research Questions

The objective is to use the method MDD to explore a wide variety of suitable applications for graphene textiles. This is to raise awareness of the potential of the material, as well as exploring how the method MDD can be applied to a material whose physical qualities are undetectable. The objectives are reached by answering the following research questions:

RQ1 What are some novel and/or advanced products based on graphene textiles, that visualise the possibilities of the material?

RQ2 What are the effects of applying the method Material Driven Design to a material with qualities that are not noticeable by sight or touch?

In order to properly answer RQ1, it is divided into the three following sub-questions:

RQ1.1 What are the unique properties of graphene textiles?
RQ1.2 How are graphene textiles perceived by people?
RQ1.3 How can products be designed so that the unique qualities of graphene textiles are highlighted?

1.3 A Case Study of Grafren AB

In order to reach the objective and answer the research questions, the company Grafren AB is used for a case study. Grafren AB is a startup company located in Linköping that specialises in graphene flakes separation and coatings. The work includes integrating graphene with textiles, and thus creating electrically conductive textiles.
Grafren AB have three main types of graphene textiles; conductive textiles, heatable textiles, and two types of textile sensors; pressure and strain sensors. These textiles have qualities such as electrical conductivity, joule heating, and pressure sensing while remaining soft, flexible, breathable, and lightweight. With an additional coating, the textiles can also be made water resistant. The company provide this material as a technical component for clients and do currently have three ongoing product orders with the textiles, as can be seen in Table 1.

Table 1: The products with graphene textiles that Grafren AB are currently working on.

<table>
<thead>
<tr>
<th>Product</th>
<th>Type of Textile</th>
<th>Description</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heatable water cover for skiing</td>
<td>Heatable textile</td>
<td>During long distance training in cold climates, skiers carry a container of water with them to stay hydrated, and drink from it with a long straw. During the cold weather, the water freezes while inside the straw. The heatable cover keeps the water warm enough to keep it in liquid form.</td>
<td>Outdoor sports</td>
</tr>
<tr>
<td>Car seat pressure sensor</td>
<td>Textile pressure sensor</td>
<td>A pressure sensor in car seats, so the seatbelt indicator is able to sense when to activate.</td>
<td>Automobile</td>
</tr>
<tr>
<td>Hospital mattress sensor</td>
<td>Pressure sensing textile mat</td>
<td>With pressure sensors in mattresses at hospitals, it is possible to see how a patient move and if their position need to be adjusted to avoid bedsores.</td>
<td>Healthcare</td>
</tr>
</tbody>
</table>

1.4 Goals

The different goals of the thesis are presented below.

1.4.1 Product goals

The product goal is to visualise the potential of graphene textiles through a portfolio containing 5-8 conceptual products, meaning products that are not fully developed. All three textile types from Grafren AB should be included. The concepts should also demonstrate a wide range of the possibilities of the material and be presented in a suitable way to demonstrate the various features.

1.4.2 Effect goals

The effect goals of RQ1 are to raise awareness of graphene textiles, and increase knowledge of the different functions. The portfolio is meant to provide inspirational ideas on how to apply the material in products. It is intended that Grafren AB will benefit from this by receiving attention and business when displaying the portfolio. The effect goal for RQ2 is to contribute with more knowledge about the method MDD, to allow others to learn from
this work and continue improving the method.

1.5 Limitations and Delimitations

The limitations that the thesis must consider are discussed below.

- The medium(s) in which the concepts and portfolio are presented are limited to the current skills of the author.

- The manufacturing process of the graphene textiles are not disclosed by the company due to secrecy requirements. Therefore, the manufacturing aspects are disregarded in this thesis. A general description of the process is, however, provided for examining possible limitations relevant to product design.

- The technical specifications of graphene are not investigated in detail due to the limited time frame and existing knowledge of the author. However, enough information about the material is collected in order to determine approximate limitations and possibilities relevant to product design.

- Any activities requiring participants need to be adapted to those who are geographically available or be conducted online.

- Since the final product designs are conceptual, any following steps of the chosen product development methods are excluded from this study.

1.6 Thesis Outline

As every step in the work process is highly dependent on the results from the previous step, the report is written in a chronological order to be easier to follow. The process follows the different phases of MDD by Karana, Barati, et al. (2015), which is explained further in chapter 2.1. As can be seen in Figure 2, information is first collected through literature and relevant knowledgeable people to create the theoretical frame of reference. After a sufficient amount is gathered, the MDD process begins with the steps understanding the material, creating the material experience vision, and manifesting the material experience patterns. From these steps, a vision is formed about how the material should be used to create a beneficial user experience in a product.

![Figure 2: An illustration of the thesis process and roughly where the research questions (RQ) are answered.](image-url)
The next step is to develop concepts, which starts with organising workshops for an extensive idea generation. In the following step evaluation and selection of ideas, these ideas are evaluated in order to select 12-15 concepts for further development. The development process is then conducted in iterations to achieve the best results. Throughout that process, the final concepts are selected and then developed further to reach the final designs, which are presented in the portfolio.
2 Theoretical Framework

The theory that the project is based upon is presented in this chapter, including MDD, product development processes, user studies, workshops, and E-textiles.

2.1 Material Driven Design

MDD is a suitable method for when the starting point of a design process is a material, as opposed to the more common ones; a product or a problem (Karana, Barati, et al. 2015). Despite being relatively new, MDD has been applied successfully in several projects, for example by Jafferson et al. (2021), Majumdar et al. (2017), and Olcay (2017). The method is visualised in Figure 3 and based on the four following steps (Karana, Barati, et al. 2015).

1. Understanding the material from a technical and experiential perspective.
2. Creating a material experience vision.
3. Manifesting the material experience patterns.
4. Designing material/product concepts.

![Figure 3: An illustration of the four steps in the Material Driven Design (MDD) method. Inspired by an image in the article by Karana, Barati, et al. 2015.](image)

With MDD, Karana, Barati, et al. (2015) mean for the designer to not only look at the technical specifications of the material, but to distinguish the other, more subjective, characteristics, e.g. how it is perceived. Asbjörn Sörensen et al. (2017) state that a material has a great influence on the physical appearance and perception of a product. Therefore, Asbjörn Sörensen et al. (2017) mean that it is important to consider both the technical properties as well as the sensorial characteristics in the design, as both affect the user experience.
of the product. Karana, Barati, et al. (2015) agree that the material as well as the situation greatly impact how a product is perceived. Therefore, Karana, Barati, et al. (2015) mean that the designer should aim towards understanding not only what the material is, but what impressions people get from it, what it can do, and what it makes people do. This includes understanding the material experience and its four experiential levels:

- The aesthetic experience of the material - how people perceive the sensorial aspects, e.g. if it is cold or shiny.
- The interpretation of the material - if the material is perceived as modern or cosy, etc.
- The emotional experience of the material - for example, if the material makes people feel amazed, bored, or surprised.
- The performative level - e.g. if the material feels inviting to touch.

According to Karana, Barati, et al. (2015), all four levels are highly dependent on the current time, context, object, and subject. Since the overall situation will affect how the material is perceived, the writers mean that it is important to explore the material in different contexts and environments. Veelaert et al. (2020) mean that the four levels also affect each other, e.g. something that is perceived as glossy can be interpreted to belong in an office.

2.1.1 The process of MDD

Step 1: Understanding the material

The first step includes researching the technical specifications of the material, learning the experiential characteristics, and conducting a material benchmarking. The technical properties should be investigated to gain an understanding of the possibilities and limitations in regard to product design, e.g. the mechanical properties and how it can be shaped (Karana, Barati, et al. 2015). It is encouraged to perform experiments and have a hands-on approach to get familiar with the material at this stage, but also to collect technical information. After this investigation is completed, the designer should have sufficient knowledge about the material to know of its qualities, limitations, and manufacturing process (Karana, Barati, et al. 2015).

The experiential characteristics of the material are subjective, meaning that it is important to reflect and draw conclusions based on the findings (Karana, Barati, et al. 2015). To help with that, the four experiential levels, as already mentioned, should be considered; sensorial, interpretive, affective, and performative. For this part, Karana, Barati, et al. (2015) encourage the designer to introduce the material to other people in order to collect any reactions and see how they interact with it. These user studies are meant to help the designer realise how future products made with the material could be interpreted and handled. After completing the user studies, the designer should also understand the sensorial qualities of the material, the strengths and weaknesses, and if it is associated with other materials (Karana, Barati, et al. 2015).

One way to put the material in different situations and contexts, Karana, Barati, et al. (2015) recommend conducting a material benchmarking study, as it puts the material next to similar materials and their applications. The writers mean that this activity can help
clarify how the material might be used in future products, and how similar materials are perceived in their respective markets. Karana, Barati, et al. (2015) states that the above described activities could be conducted in a linear form. The writers argue, though, that the activities should preferably be conducted simultaneously, as that would further increase the understanding of the different perspectives.

Step 2: Creating the material experience vision
The goal of step 2 is to reflect upon the results of the previous step, and to create a vision of how the material should be used in products to achieve a superior user experience and performance (Karana, Barati, et al. 2015). The role of the material in a bigger context, such as in society or in different markets, should also be considered, as well as its relation to other products. Karana, Barati, et al. (2015) recommend the designer to investigate how relevant values in society have changed over time to construct a vision for future applications. In order to accomplish this, Karana, Barati, et al. (2015) urge the designer to reflect on the technical and experiential characteristics of the material. As this part is very subjective, Karana, Barati, et al. (2015) mean that it is intended for the designer to consider the previous results, but to also be creative when constructing the vision.

Step 3: Manifesting the material experience patterns
When there is a vision for the material, it is time to investigate which formal qualities are required to have the material fit into the intended contexts (Karana, Barati, et al. 2015). In other words, the designer should investigate why current products and materials are perceived the way they are in order to develop design guidelines. These guidelines should then be used later in the concept development phase to ensure that the product and material are perceived as intended by the newly created vision. For this step, Karana, Barati, et al. (2015) recommend using the method Meaning Driven Material Selection (MDMS), which aims towards increasing the understanding of how key aspects of a material, e.g. shape and colour, affect the perceived meanings of it. Karana, Barati, et al. (2015) give the example that a material might be considered cheap if it is transparent, thin, or have sharp edges.

In MDMS, a user study is conducted where participants are asked to perform the following three tasks (Karana, Hekkert, et al. 2009):

1. Select a material that embodies a certain meaning, such as high-quality, modern, or feminine.
2. Provide a picture of the material, as well as a picture of a product containing the material, that fulfils task 1.
3. Motivate the choice of product, and evaluate the material against a set of provided criteria.

The results of the study are to be collected, summarised, and interpreted in order to reach a set of formal qualities of what the product needs in order to be perceived in the intended way (Karana, Hekkert, et al. 2009). These qualities and explored meanings are then to be discussed and brought over to step 4 of MDD to provide guidance in the concept development (Karana, Barati, et al. 2015).

Step 4: Creating material/product concepts
This final step is all about developing products with the previously acquired knowledge
It is, however, not specified by Karana, Barati, et al. (2015) how this should be accomplished.

2.2 Product Development Processes

According to Ulrich and Eppinger (2016), a product development process generally consists of six steps. Each one receives input from the former and delivering an output to the next. The steps can be seen in Figure 4 below, and are:

1. Planning
2. Concept development
3. System-level design
4. Detail design
5. Testing and refinement
6. Production ramp-up

Figure 4: An illustration of the six steps in a design process, according to the description of Ulrich and Eppinger (2016), and inspired by a similar figure in the book.

According to Ulrich and Eppinger (2016), the goals are decided in the planning stage based on information regarding the market, business strategy, identified opportunities, etc. In the following step, the concept development, the needs of the target group are investigated in order to develop multiple concepts simultaneously. The writers argue that a concept is more developed than an idea, and should include a description of the form, function, and features of the product. In the system-level design step, Ulrich and Eppinger (2016) suggest that one or more concepts should be selected to develop the systems and components of the product, as well as how the product should be produced and assembled. In the following step, the detailed design and technical specifications are decided, as well as the plan for production. Next, in the testing and refinement step, the product is manufactured and tested to determine if the previously made plan satisfies the requirements. According to Ulrich and Eppinger (2016), in the final step, the production ramp-up, the product is produced in the planned production system with the intention of reviewing the manufacturing process in case anything needs to be changed. Afterwards, the products are quality checked.
The concept development step, also referred to as the front-end process by Ulrich and Eppinger (2016), usually includes multiple activities conducted simultaneously through iterations. Some of these activities include identifying customer needs, establishing product specifications, conducting benchmarking of competitive products, prototyping, as well as generating, selecting, and testing concepts. Ulrich and Eppinger (2016) consider it important to understand the customer needs, and to translate them into product specifications to ensure that the development team knows how to apply the needs in the product design. It is also recommended to search for similar products on the market to understand how potential competitors look, and thus how the new product can receive an advantage on the market. The writers mean that this phase is very uncertain as new information could be found at any time that could affect a concept to the extent that a redesign would be necessary. Therefore, Ulrich and Eppinger (2016) recommend working on several concepts in parallel, while conducting these activities in iterations. This is in line with how Wikberg Nilsson et al. (2015) describe the creative process as being non-linear.

### 2.2.1 Fuzzy front end

The Fuzzy Front End (FFE) process is described as the chaotic initial phase of a development process, where concept development and collection of information occur in parallel (Koen et al. 2001). It is similar to the front-end process by Ulrich and Eppinger (2016), with multiple activities conducted in parallel to develop several concepts simultaneously (Koen et al. 2001).

During the FFE, Koen et al. (2001) suggest that the development team should identify the opportunities they want to explore further, as well as analysing these opportunities to decide which ones to pursue. Such analysis could be of users, markets, business goals, strategies, or scientific experiments. Koen et al. (2001) also recommend generating ideas, for example through various brainstorming exercises, and iterate the ideas in order to find new solutions. After this, the writers mean that ideas should be selected, depending on the previously gathered information, to be developed into concepts. However, because ideas often need room to grow to show their potential, several ideas should be developed simultaneously. During this development phase, more information should be gathered about customer needs, competing products, etc. Koen et al. (2001) stress that FFE is not a linear process, and that, for example, new ideas may lead to the discovery of new opportunities instead of the other way around. By conducting these activities simultaneously, Koen et al. (2001) argue that the risk of new information emerging late in the project is reduced. With that, the risk of needing to make last minute changes is also reduced.

### 2.2.2 The design paradox

In support of developing multiple concepts at a time is the design paradox by Ullman (2002) and Poudel et al. (2012), which is visualised in Figure 5. According to Ullman (2002), Poudel et al. (2012), and Toniolo et al. (2014), not enough information can be collected early in a development project. The writers argue that the designer’s knowledge increases throughout the project, which is why decisions should be made successively as more information is gathered. It is an argument for collecting information continuously along the design phase, and thus reduce the risk of new information arising at the end that leads to last minute design changes (Ullman 2002, Poudel et al. 2012, Toniolo et al. 2014).
2.3 User Studies

Carter (2007) and McDonald et al. (2021) think that usability testing is a highly suitable method for learning how a person is experiencing the use of an artefact. According to Barnum (2020), the goals of a user study should be established early in the planning process because then the activities can be adapted to ensure that the desired information is collected, to fulfil the goals in the appointed time. Other decisions that should be considered during the planning stage are *What to test?, Where to test it?, and How to test it?* (Barnum 2020).

During a usability study, it is important that the user continuously convey their experience (Carter 2007). This can be done verbally (i.e. explaining what they are thinking/experiencing) and non-verbally (e.g. body language and facial expressions) (Carter 2007). The moderator of the test can often interpret some of the non-verbal communication, but cannot rely on it fully as it is next to impossible to understand the reasons behind every expression without further explanation (Carter 2007). If questions need to be asked during the study, Barnum (2020) recommends formulating them to begin with *what* or *how* instead of *why*, as the latter might give the impression that the user did something wrong, which is to be avoided.

The reason for having the participants reflect upon their actions during the interaction, as opposed to afterwards, is according to Carter (2007) because there is a risk of them misremembering or forgetting something. McDonald et al. (2021) add that it is also more time-consuming to collect this information afterwards instead of during the test. Since usability studies usually are time-sensitive, McDonald et al. (2021) argue that it is a huge benefit to have a method that makes it easier to process the information continuously. However, the writers mean that it can also be beneficial to ask some complementary questions afterwards, depending on the goal of the study.

One approach to continuously collect information about the user’s experience during the test is the use of the technique *think aloud*, where the user is encouraged to verbally express each thought as they come (Carter 2007; McDonald et al. 2021). For this to work, however, it is crucial that the user is comfortable in the test environment and with the moderator.
Carter (2007) means that this can be achieved by having the moderator acting friendly and encouraging, and never express any negativity, as that might give the user the impression that they are doing something wrong. Carter (2007) suggests that the moderator should take on an open-minded role and act as though they are exploring the artefact together with the user, as that would imply there is no wrong way to perform. McDonald et al. (2021) add that the think aloud technique could help the session seem less formal and have the participant forget that they are observed, something that might help them relax. It is, however, important to not go overboard with the act (McDonald et al. 2021). Carter (2007) means that the moderator should appear genuine, because it would make the participant feel more inclined to ask questions.

Something to consider with think aloud, according to McDonald et al. (2021), is that all interventions of the moderator will affect the user. Barnum (2020) argues that to receive reliable results, it is important that all participants have received the same tasks and the same artefacts. Otherwise, the results need to be revised to consider how those changes could have affected the results (Barnum 2020). Therefore, the moderator should be careful with how they act to not affect the results of the study. For this reason, Barnum (2020) recommends that the moderator have a neutral approach to ensure that all tests are conducted in the same way. However, as usability studies are also affected by the context, location, mood of the participant, etc., McDonald et al. (2021) mean that it is impossible for all tests to be conducted with exactly the same prerequisites.

Before the test starts, the moderator should give a brief explanation of the test to the user, as well as the goal of the study. It should be made clear to the user that it is the artefact that is to be examined, not the user, and that there is no “wrong” answer. If the think aloud method is used, McDonald et al. (2021) recommend to only provide general instructions of how the user is meant to act, but avoid more specific instructions to limit the influence on the user. The moderator should also be aware of their own bias when interacting with the participant and evaluating the results, to limit the risk of their own opinions affecting the results (McDonald et al. 2021).

It is recommended to have a pilot test of the user study to evaluate the test itself (Barnum 2020; Nielsen 2011). Barnum (2020) means that it is useful for someone to observe the moderator in this pilot study, in particular the verbal and non-verbal language to see if they may affect the user in an unintended way. If that is the case, changes can be made before the actual study begins. After the user study is completed, Barnum (2020) recommends organising the results, for example into categories, for an easier evaluation and processing.

2.4 Idea Generating Workshops

To generate new and innovative ideas is no easy task, according to Wikberg Nilsson et al. (2015), and it is often connected to one’s creative ability. However, like all abilities, it can be improved with practice. To facilitate the process of coming up with something new, Wikberg Nilsson et al. (2015), Boeijen et al. (2020), and Ritter and Mostert (2018) recommend conducting idea generating workshops. Such workshops can be conducted in different ways with the help of various methods, and are often done in groups.

Wikberg Nilsson et al. (2015) and Shestopalov (2019) state that the goal of the idea generating session should be to come up with as many ideas as possible, instead of as innovative
ideas as possible. Quantity over quality. Wikberg Nilsson et al. (2015) mean that this is because it is often easier to think of something new when every existing idea has been said. Therefore, the writers mean that when there is a large quantity of ideas to choose from, innovative ones are often found. Ritter and Mostert (2018) agree, and warn that it is common for people to start evaluating the ideas before a sufficient amount is generated. Wikberg Nilsson et al. (2015) also argue that it is important to find new perspectives in order to come up with new ideas. Shestopalov (2019) means that this is why various creative methods are used, to trick the brain to be more creative by seeing the problem from different angles.

Amabile (1988) and Wikberg Nilsson et al. (2015) describe three items needed for creative work; knowledge about the situation, an ability to dare think outside the box, and to have the motivation to conduct the creative work. Amabile (1988) and Wikberg Nilsson et al. (2015) mean that it is next to impossible to solve a problem without any knowledge of the situation, which is why information should be collected before any solutions are suggested. Wikberg Nilsson et al. (2015) state that, even if the goal is quantity over quality, the participants should still be informed to the degree that useful suggestions can be considered. To improve the ability to think outside the box, Wikberg Nilsson et al. (2015) suggest using creative methods. The final item, the ability to find motivation, is considered the most important by Amabile (1988 and Wikberg Nilsson et al. (2015). To improve the chances of success regarding this, the writers argue that it is important to be motivated from within, i.e., to find joy and be enthusiastic about the task as well as having support from the group. To only be motivated by outside sources, e.g. money, will not be as effective, according to Amabile (1988).

A person’s ability to be creative when generating ideas is also dependent on the social environment. It is crucial that everyone feels comfortable and safe enough to share their ideas without fear of criticism or judgement (Amabile 1988; Wikberg Nilsson et al. 2015; Boeijen et al. 2020; Shestopalov 2019; Wilson 2020). What constitutes as a good or bad idea can be evaluated at a later time, not during the idea generating session. Amabile (1988) means that idea generation should never be framed as a competition between participants, but as a collective effort, in order to create a more inclusive environment. Boeijen et al. (2020) and Paulus et al. (2015) support this and state that a large benefit of generating ideas as a group is the opportunity to get inspired by others and develop their ideas further.

During a workshop, Wikberg Nilsson et al. (2015), Lucid (2021), and Wilson (2020) highly recommend having a facilitator to lead the group through all exercises. The facilitator’s job is to prepare everything to the extent that it can be explained to the participants, go over the rules (in particular the no criticism rule), as well as making sure that the rules are followed throughout the workshop. Wikberg Nilsson et al. (2015) and Lucid (2021) mean that it is the facilitator’s job to make sure that everyone gets the opportunity to speak, to steer the group in the desired direction, encourage them, and change the activity or take a break if the energy dips. This kind of workshop should not feel like a formal meeting, but something fun where the group can enjoy themselves (Wikberg Nilsson et al. 2015).

When choosing how many participants should be included in an idea generating workshop, it highly depends on which exercises are used. In general, Boeijen et al. (2020) recommend having 4-15 people per group, Lucid (2021) suggests no more than ten people, and Wikberg Nilsson et al. (2015) recommend approximately five per group for their methods. Keeney
Wilson (2020) and Lucid (2021) warn that the waiting time can increase if there are too many participants. If everyone is to present their ideas one at a time, it may lead to someone forgetting their idea due to them waiting too long listening to the others (Keeney 2012; Wilson 2020; Lucid 2021). It could also lead to the energy dipping, and thus the motivation decreasing.

Paulus et al. (2015) recommend having a high tempo during the workshop, as their research suggest that if the pace slows down, the participants may be led to believe that there are no more ideas and thus stop trying. Wikberg Nilsson et al. (2015) agree, and argue that a high tempo could help the participants let their initial thoughts and reactions flow freely, without second guessing themselves too much. To maintain the energy and motivation, Paulus et al. (2015) strongly recommend the use of strategically placed quick breaks to recharge. Lucid (2021) on the other hand, recommends having shorter sessions, approximately 15-30 minutes, to make it easier for the participants to maintain focus. Lucid (2021) also suggests that creative sessions should be scheduled in the beginning of the day to avoid mental fatigue.

Regarding the creative methods used during the workshop, Wikberg Nilsson et al. (2015) recommend conducting multiple exercises in order to change the perspective. Amabile (1988) mean that the selection should vary depending on the situation. If the group have a high internal motivation, i.e., if they are enthusiastic and driven by their own passion for the task, she suggests having a relatively unstructured workshop, to allow the group a more free brainstorming. On the other hand, if the group is mostly motivated by external factors, e.g., the goals of an organisation, she recommends preparing a clear strategy with well known methods. Shestopalov (2019) recommends using an organised setup with clear goals and time frames, as do Lucid (2021) and Keeney (2012). Keeney (2012) also recommends establishing a clear goal and objective for the participants before starting, as he means that it will be easier for the group to work towards the goal if they understand what is asked of them.

2.5 E-Textiles

E-textiles are, as mentioned previously, textiles which are electrically conductive (Hu et al. 2010). Often, this is done by coating the fabric with conductive particles (Hu et al. 2010). The market for E-textiles is growing rapidly as more functions are thought of, such as incorporating sensors, heaters, and energy harvesters into clothing (Acar et al. 2019), as well as electromagnetic interference (EMI) shields (Uzun et al. 2021). Combining technology with clothes opens up possibilities to, for example, facilitate health monitoring, having technical devices integrated in everyday wear, or simply make life easier for people in different ways. Uzun et al. (2021) also mention the use of special cases for phones, wallets, and laptops that protects the digital information via EMI shields.

Some important qualities of E-textiles compared to the more traditional electrical devices are that the material remains flexible, soft, lightweight, and allows air and moisture to pass through (Acar et al. 2019; Hu et al. 2010). These characteristics are highly relevant when designing products that need to be close to the skin, both from a functional perspective, and when considering comfort (Acar et al. 2019).
2.5.1 Manufacturing process of graphene textiles

Extracting graphene from graphite can be done in several ways, but the most established method is to reduce graphite into a powder, mixing it with a liquid and applying mechanical shear forces (Khair et al. 2019). This separates the graphite particles into tiny graphene flakes. It is, however, very difficult to then remove the excess material from the graphene flakes, and if these impurities are not removed, the quality of the graphene is reduced significantly (Khair et al. 2019).

The manufacturing process of graphene textiles does in general involve reducing the thin graphene layers to a powder called graphene oxide, adding a liquid, and then dipping the textile into said liquid (Khair et al. 2019). This process is called dip-coating, and an illustration of the process can be seen in Figure 6. It is one of the most common methods for E-textiles made with graphene (Khair et al. 2019; Hu et al. 2010). It is also one of the most simple methods to adapt to large scale production at a relatively low cost (Acar et al. 2019; Uzun et al. 2021). If other conductive particles are used, another coating process may be preferred.

When dipping the textile in the graphene-liquid, the fabric is usually pulled through different rolls to keep it steady. First it goes through the liquid, then it is pressed through two rolls to make sure that the textile is thoroughly soaked with graphene, and to remove any excess liquid, before heat is applied to both sides of the fabric to make sure that the graphene oxide is attached to the fibres (Khair et al. 2019; Acar et al. 2019). It is important to adapt the heat to the textile to avoid any damages. According to Khair et al. (2019), the properties of the E-textiles depend on how long the fabric is immersed in the liquid, what kind of solvent is used in combination with the graphene oxide, and how much pressure is applied to the fabric after the immersion.

![Figure 6: An illustration of the dip-coating process, based on the textual descriptions from Khair et al. (2019) and verbal descriptions from Grafren AB.](image-url)
In this section of the report, the implementation of the first three steps of MDD are described.

3 Understanding the Material

This chapter consists of the implementation of the first step in MDD. First, the specific methods are described, followed by the results and discussion. Finally, questions from Karana, Barati, et al. (2015) are answered as the conclusions.

3.1 Methods - Understanding the Material

The methods used in this chapter are; a literature study and dialogue with the company to learn of the technical properties of the material, a user study to gather experiential impressions of the material, and a benchmarking study to investigate similar materials on the market. These activities are conducted with an overlap, as suggested by Karana, Barati, et al. (2015). The literature study and dialogue with the company start first, followed by the user studies and benchmarking. These methods aim toward answering the following questions from Karana, Barati, et al. (2015).

1. What are the main technical properties of the material?
2. What are the limits and opportunities of the material?
3. What are the unique sensorial qualities of the material?
4. What do people think are the most and least pleasing sensorial qualities of the material?
5. Does the material remind people of another material?
6. How would people describe the material, and what meanings does it evoke?
7. Does the material bring out any emotions, e.g. surprise, fear, love, or relaxation?
8. How do people behave and interact with the material?
9. What are the most convenient manufacturing processes to form the material?
10. How does the material behave in other manufacturing processes?

These questions correlate strongly with questions that Ashby and Johnson (2014) write are useful when gathering knowledge from different fields, which the writers claim is helpful when brainstorming applications for new materials. However, as the specific manufacturing process that Grafren AB use are not disclosed to the public, the final two questions are disregarded in this thesis.
3.1.1 Method - Technical properties of the material

In order to understand how the graphene textiles work and what functions they possess, the technical properties are examined. Overall information about graphene and E-textiles is also collected through a literature study, as can be found in chapter 1.1 and 2.5.

In order to understand more about the specific textiles that Grafren AB offer, employees at the company explain and demonstrate the different functions and characteristics of the material. The technical information presented below, in section 3.2.1, is solely retrieved from Grafren AB. The goal with this method is to get an understanding of the mechanical opportunities and limitations of using the material in a product.

3.1.2 Method - Perceived characteristics of the material

In order to understand how the textiles from Grafren AB are perceived, Karana, Barati, et al. (2015) recommend conducting a user study to collect impressions and potential interacting patterns. To help plan and prepare for the user study, the questions recommended by Barnum (2020) are considered.

- **The goal** is to understand the experiential characteristics on a sensorial, interpretive, affective, and performative level.
- **What to test?** The three types of graphene textiles; conductive, heatable, and sensors.
- **Where to test it?** In person, at a location where each participant is comfortable and have easy access to.
- **How to test it?** By using the Ma2E4 toolkit developed by Camere and Karana (2018) for investigating experiential characteristics of materials, as well as the *think aloud* technique.

There are three types of textiles to be tested, and they are to be evaluated separately to see if their experiential qualities differ. The samples included in this study are prototypes provided by Grafren AB and can be seen in Figure 7. The different samples are:

- (1A) A conductive textile with low stretch and an additional water repellent coating.
- (1B) A soft conductive textile with high stretch.
- (1C) A textile that is partly coated, and therefore partly conductive.
- (2A) A glove with pressure sensors and conductive threads on two fingers.
- (2B) A glove with a strain sensor and conductive treads on one finger.
- (2C) A small strip of graphene fabric that can act as a sensor.
- (3) A heatable textile with two parallel conductive threads.

To help demonstrate the conductivity, a battery connected to a light with cables is also provided (as seen to the right in the figure).
Figure 7: The different prototype material samples provided by Grafren for the user study. (1A) A conductive textile with low stretch and an additional water repellent coating. (1B) A soft conductive textile with high stretch. (1C) A textile that is partly coated, and therefore partly conductive. (2A) A glove with pressure sensors and conductive threads on two fingers. (2B) A glove with a strain sensor and conductive threads on one finger. (2C) A small strip of graphene fabric that can act as a sensor. (3) A heatable textile with two parallel conductive threads.

The Ma2E4 toolkit includes different lists of descriptive words of emotions, actions, meanings, and sensorial qualities (Camere and Karana 2018). It is meant to be used for user studies to understand the experience of the material, i.e. how it makes people feel, think, and act. The described use by Camere and Karana (2018) is that the user interacts with the material and fills out a form. In this thesis, the toolkit is used to collect information about the experiential characteristics of the material samples, and be time efficient. A few adaptations are made; the images from the toolkit are not included, and most of the content is filled out by the moderator (which in this case is the thesis author). These changes are made to be time efficient, and to facilitate for the users.

The strategy is to present one textile type at a time while explaining and demonstrating the functions. The user is encouraged to interact with the samples, ask questions, and express their thoughts as they go, according to the think aloud technique, as explained earlier by Carter (2007) and McDonald et al. (2021). During this interaction, the moderator is to fill out which emotions the participant expresses, the intensity of each emotion, and how the participant is interacting with the material. When the participant feels satisfied with the interaction, they are to fill out the sensorial part of the toolkit in a questionnaire, as well as choosing three meanings they think represent their impressions of the textile type. The toolkit provides meanings to choose from, but to not limit the options, the users are able
to write other words if they want to. After this, the next textile type is presented, and the process repeated. To fill out the questionnaire after each type, the risk of the participants mixing up the impressions or forgetting something is reduced. See the lists of words and the questionnaire in Appendix 1. Since the conductive aspect is necessary for understanding how the sensors and heaters work, the conductive material samples (1A-C) are presented first, followed by the sensors (2A-C) and lastly the heatable textile (3). At the end of the entire session, four questions are asked, three from the toolkit (Camere and Karana 2018), and one added to benefit the project:

- What is the most pleasant quality of the material?
- What is the most disturbing quality of the material?
- What is the most unique quality of the material?
- Can you think of any product that should be made with this material?

The final question is added to gather as many ideas as possible for potential products. As the initial part of the concept development phase is to generate new ideas, it is considered beneficial to start collecting ideas right away. All ideas are documented and saved to be reviewed later. The reason for asking these questions verbally instead of including them in the questionnaire is to receive more elaborate answers. Since the questions are open and could lead to long answers, it might be easier for the users to formulate themselves verbally instead of in writing.

The location of the user study is a place familiar and neutral to the participants, to ensure that they feel comfortable and do not get distracted by the surroundings. Because physical interactions with the material are necessary for this study, it needs to take place in person, as opposed to online. Each user is to perform the test individually. The length of each session is aimed towards not exceeding 30 minutes, like Veelaert et al. (2020) suggest, in order to prevent the participants from losing focus. There are six users in this study, which is one more than the recommended amount of five by Nielsen (2012). Everyone is between the age of 20 and 25, have a friendly connection to the author, and are largely chosen due to their availability. Given that all are familiar with both the location and the moderator, it is deemed easier for them to be comfortable enough to use the think aloud technique.

As recommended by Barnum (2020) and Nielsen (2011), a pilot test is conducted before the actual study, in an attempt to evaluate and improve the test itself as well as the questionnaire, as recommended by Boeijen et al. (2020). During this pilot study, a pilot user (not counted among the six participants) conducts the test and then provides feedback to the moderator.

### 3.1.3 Method - Material benchmarking

As Karana, Barati, et al. (2015) state, a material benchmarking is conducted as a part of this step, in order to compare the material to similar materials on the market, as well as products. The goal is to see where graphene textiles could fit in on the market and to investigate possibilities of future application areas. It is also useful to compare the characteristics of the products on the existing markets, to see if there are any shared features.
The benchmarking could also shed light upon how different values have changed over time, and if any characteristics are emphasised (Karana, Barati, et al. 2015).

The products and materials investigated at this stage are foremost E-textiles, wearable technology, and products that share one or more of the functions of the three textile types in focus. As E-textiles are not yet very common on the market, any potential future competitor is also deemed appropriate to look into. Therefore, the products investigated in the benchmarking can either be on the market or in development.

The materials and applications are investigated in multiple ways, e.g. by searching online and in literature using key-words such as E-textile, smart textile, and wearable technology. Grafren AB are also listing some of their competitors. In addition to this, news sources that have a technical and innovative focus are looked into.

3.2 Results - Understanding the Material

The results of the technical investigation, the user study, and the benchmarking are presented below.

3.2.1 Results - Technical properties of the material

Grafren AB currently have three types of E-textiles; conductive textiles, heatable textiles, and textile sensors. For the last two types, conductive threads are needed to make the textile fully functional. These conductive threads can be made of a variety of materials, for example metal or polyester. Though, if non-conductive materials are used, like polyester, the threads need to be coated with conductive paint. This conductive paint is often made of a mix of an adhesive and conductive particles, e.g. carbon, silver, or other metals. After it is made conductive, the thread can become dyed in any colour and used like any other thread in sewing machines or embroidery, etc.

For one square meter of fabric, approximately 2-3 grams of graphene is needed for a sufficient coating. However, this varies greatly, mostly due to the thickness of the fabric. Any textile could theoretically become conductive with a graphene coating, but it has not been properly tested at this point to state with certainty. It is also possible to coat only part of a textile with graphene, so that only specific parts become conductive, as can be seen in sample 1C in Figure 7. As the graphene coating is naturally black, the textile also becomes black after the coating. It should, theoretically, be possible to dye the fabric afterwards in any other colour, though it has not been tested yet.

Since graphene has a higher conductivity than water, the material should remain functional when wet. No graphene textile or thread is fully water resistant, but that can be changed with an additional coating. Then, it is also possible to wash the textile in a regular washing machine, as the protective coating prevents the graphene coating from coming off like regular dye may in clothing.

The durability and expected life span of the material is difficult to state with any certainty. It depends greatly on the application, the choice of fabric, the kind of environment the product would be in, if any additional coatings are added, etc. The life span would therefore have to be estimated for each product.
While these textiles are electrically conductive, they are still harmless to touch or wear while a current is lead through. However, the textile should be insulated to protect it from everyday wear. If two pieces of fabrics overlap, the current can travel between them. Thanks to the conductive properties, the graphene textile is able to sense when the resistance in the material changes. Since these textiles use electricity, a power source is needed, such as a battery.

Technical properties of the conductive textile
The conductive textile can block an electromagnetic field to approximately 90%.

Technical properties of the textile sensors
The pressure sensor is able to tell the difference in weight of approximately 0.3 grams. For any data to be collected, conductive threads need to be attached to the pressure surface. For the strain sensor, a conductive thread needs to be placed at either end of the sensor. The fabric then senses any change in the resistance between these two points, and sends the information through the threads. For example, if the sensor is placed over the elbow or a finger so that the bendable joint is between the end-points of the sensor, it is able to sense when that joint is moved as the fabric either stretches or relaxes.

Technical properties of the heatable textile
It is possible to momentarily transfer heat through this graphene textile. By incorporating two conductive threads parallel to each other, energy can be sent across the fabric between the threads, as seen illustrated in Figure 8, which raises the temperature of the fabric. The temperature can be reached in seconds, and as soon as the power is turned off, the textile loses the heat, i.e. it does not store the thermal energy. The heat limit depends on the limitation of the textile and can therefore vary. The textile should not be stretched during the heating, as the even spread of the energy is dependent on the even resistance in the textile. This means that if the fabric is stretched, the resistance changes and varies across the surface, and therefore is the surface not evenly heated.

Figure 8: An illustration of the heatable function of the graphene textile. Energy is sent into one of the conductive threads, travels across the fabric, and then exits through the other conductive thread. This way, the fabric between the threads is heated.

To set the temperature, calculations are needed to determine how much energy is required to reach the desired temperature in the specified environment. It is also possible to add controllers to adjust the temperature during use by adjusting the power supply. Regarding the distance between the threads, it is preferable to keep them only a few centimetres apart, as the effect may decrease when the distance increases. If a larger surface is to be heated, it is better to use several heatable segments.
3.2.2 Results - Perceived characteristics of the material

Seven users are included in the results, counting all participants plus the pilot-user. In general, the material samples were received well during the user study. See in Figure 9 how the participants interacted with the three textile types. In the figure, the circles represent the number of participants, thus showing how many interacted with the textile types in the listed ways. As can be seen, many lifted and held the samples, as well as touching and stretching them.

<table>
<thead>
<tr>
<th>Conductive textiles</th>
<th>Textile sensors</th>
<th>Heatable textile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td>Bending</td>
<td>Bending</td>
</tr>
<tr>
<td>Caressing</td>
<td>Caressing</td>
<td>Caressing</td>
</tr>
<tr>
<td>Compressing</td>
<td>Compressing</td>
<td>Compressing</td>
</tr>
<tr>
<td>Fiddling</td>
<td>Fiddling</td>
<td>Fiddling</td>
</tr>
<tr>
<td>Flexing</td>
<td>Flexing</td>
<td>Flexing</td>
</tr>
<tr>
<td>Folding</td>
<td>Folding</td>
<td>Folding</td>
</tr>
<tr>
<td>Grasping</td>
<td>Grasping</td>
<td>Grasping</td>
</tr>
<tr>
<td>Grazing</td>
<td>Grazing</td>
<td>Grazing</td>
</tr>
<tr>
<td>Holding</td>
<td>Holding</td>
<td>Holding</td>
</tr>
<tr>
<td>Lifting</td>
<td>Lifting</td>
<td>Lifting</td>
</tr>
<tr>
<td>Picking</td>
<td>Picking</td>
<td>Picking</td>
</tr>
<tr>
<td>Pinching</td>
<td>Pinching</td>
<td>Pinching</td>
</tr>
<tr>
<td>Poking</td>
<td>Poking</td>
<td>Poking</td>
</tr>
<tr>
<td>Pressing</td>
<td>Pressing</td>
<td>Pressing</td>
</tr>
<tr>
<td>Pushing</td>
<td>Pushing</td>
<td>Pushing</td>
</tr>
<tr>
<td>Rubbing</td>
<td>Rubbing</td>
<td>Rubbing</td>
</tr>
<tr>
<td>Smelling</td>
<td>Smelling</td>
<td>Smelling</td>
</tr>
<tr>
<td>Squeezing</td>
<td>Squeezing</td>
<td>Squeezing</td>
</tr>
<tr>
<td>Weighing</td>
<td>Weighing</td>
<td>Weighing</td>
</tr>
</tbody>
</table>

Figure 9: How the participants interacted with the material samples. Based on the observations of the moderator during the user study. The dark circles represent the amount of participants who performed the listed actions from the Ma2E4 toolkit.

The emotions displayed by the participants during the study are presented in Figure 10, where the circles represent the number of participants. A vast majority of the displayed emotions are positive. Many seemed surprised of the various functions of the textiles, and everyone appeared curious and asked questions to learn more of the functions and possible applications. The few who felt distrust were concerned of having a conductive material in direct contact with the skin, as well as exhibiting a scepticism of the durability of the heatable textile.
Figure 10: The figure shows how many participants displayed each emotion during the user study. These results are based on the perceptions of the moderator. The dark circles represent the amount of participants who exhibited the emotions listed from the Ma2E4 toolkit.

The perceived meanings of each textile type are collected through the questionnaire that the participants filled out. The results can be seen in Figure [11]. The three most common meanings for the conductive textiles are; manufactured, futuristic, and professional. For the textile sensors: futuristic, professional, and then a tie between masculine and manufactured. For the heatable textile: manufactured, elegant, and a tie between strange and innatural. The three most common overall are: futuristic, manufactured, and professional.

Figure 11: The meanings for the three textile types, collected through the questionnaire.

The sensorial qualities are estimated by the participants in the questionnaire. See these results for the rough conductive textile (1A), the soft conductive textile (1B-C), the textile sensors (2A-B), and the heatable textile (3) in Figure [12, 13, 14, and 15] respectively, along with the average value for each one.
Regarding the four final questions, a majority of the participants thought that the most pleasant quality was that the material is a combination of textile and electricity, while appearing and feeling like a regular textile. Several also mentioned that they liked that the textile itself can be heated. Regarding the most disturbing quality, several mentioned
factors regarding how the different textiles felt. Some said that it felt unnatural to have a conductive material in direct contact with the skin and wondered if it would be safe in different weathers. For the most unique quality, the participants said the main function, that it is a fabric that can be conductive and used for sensors.

The participants thought of several potential products each, many had to do with heatable clothes, blankets, pillows, etc. For the sensors, they mentioned gloves that could help in physical rehabilitation to see how much mobility and strength people get back, as well as a way for controlling games in e.g. VR or motion capture. To see all answers to the four final questions, please read Appendix 1.

3.2.3 Results - Material benchmarking

Below are the materials and products found in the benchmarking study presented. They are divided in the same textile types as the ones from the case study company; conductive, heatable, and sensors. Some wearable technology is also included at the end.

Conductive textiles
(1) At Purdue University, researchers have developed a conductive coil that can be integrated in textiles, as well as a spray which can make the textile (and the coil) repellent to water, mud and oil (Sala de Medeiros et al. 2021). This opens up the opportunity to integrate electronic components in clothes that can be washed in regular washing machines. The coil is made of a silk and nanocarbon composite, making it conductive while being flexible, stretchable and breathable (Sala de Medeiros et al. 2021). The coil does not need a separate power source, but is said to be able to operate by harvesting the energy from nearby radio or WiFi waves (Martinez 2021). The initial application areas in mind are for the healthcare industry, security, and communication (Martinez 2021). See an example of such a textile in Figure 16.

Figure 16: An example of the smart textile from Purdue University (Martinez 2021). Photo by Rebecca McElhoe [June 9, 2021]. Copyright and Courtesy of Purdue University and Rebecca McElhoe. Image used with permission.

(2) From Chalmers University is a conductive thread made of cellulose developed in an effort to make more sustainable products for the healthcare industry (Borg 2021). The thread is capable of generating electricity when heat is applied on one end. For example, Borg (2021)
writes that it can generate approximately 0.2 microwatts from the 37 degrees of a person’s body heat. The thread is made conductive by coating it with a conductive polymeric dye, and it is also possible to incorporate silver nanowires to increase the conductivity (Borg 2021). The purpose of this thread, he writes, is to present a renewable material that can offer a more sustainable option for electronics used in healthcare.

(3) As an artistic exhibition, Barbara Jansen integrated almost translucent optic fibres and LED-lights with textiles as part of her dissertation at the School of Textiles at Borås (Jurén 2015). The textile can be connected to a computer and therefore light up in different combinations and patterns. For parts of the exhibit, Barbara programmed the fabric to have the light move to the beat of music. Jurén (2015) writes how she claims that it can even be possible for the light to respond to physical activity or the weather. See one art piece from the exhibition in Figure 17.

![Figure 17: One of the textiles with LED-lights at the exhibit of Barbara Jansen (Jurén 2015). Photo by Henrik Bengsson (n.d.). Copyright by Textilmuseet. Image used with permission.](image)

(4) Researchers at Fudan University have developed a textile made of conductive fibres, luminescent fibres, and cotton fibres, all woven together (IDTechEx 2021b). At the intersections of the fibres, where the luminescent and conductive fibres connect, it is possible for the fabric to light up. The light patterns can be controlled, making it possible to create displays that are flexible, stretchable, breathable, and washable (IDTechEx 2021b; Fudan University 2021). The luminescent fibres come in a variety of colours and the main intended use is to improve ways of communicate (Fudan University 2021).

Heatable textiles

(5) Nanostitch is a company that have developed a textile that can capture the body heat of the wearer in order to use it as insulation to keep them warm in cold weathers (Nanostitch 2016). See an illustration in Figure 18. This product is currently on the market, but is not an E-textile. Regular fabric is combined with a coffee charcoal additive mixed with oxide to
create the desired effect of increasing the temperature closest to the body by approximately 10 degrees (Nanostitch 2016).

Figure 18: An illustration of how the body heat omitted from the skin of the wearer is trapped by the heat insulating fabric. Inspired by an image on the Nanostitch (2016) website.

(6) FabRoc, a textile developed by EXO2 (2021a), can be heated with a power source of, e.g. batteries. The textile has a base of polymer and appears to be coated in conductive particles to allow an even distribution of heat. The textile is claimed to not overheat, be waterproof, stretchable, and durable (EXO2 2021a). See an example of the textile in Figure 19. It is also said to remain functional despite wear and tear, and minor rips. The textile is currently on the market and is included in products such as gloves, outdoor clothing, back supports, and insoles (EXO2 2021b).

Figure 19: An image of the FabRoc textile from the website (EXO2 2021a). Copyright by EXO2 The Heat Inside. Image used with permission.

(7) Heatable socks from INF are made for outdoor activity in cold weather (INF 2021). The socks are made of cotton and spandex and the heat is distributed through a heatable coil. It is not specified if they can be washed, but they are advertised as moist adsorbent, breathable, elastic, soft, and quick to dry (INF 2021). They are powered by rechargeable lithium batteries placed at the top of the hilt of the sock (INF 2021).

(8) Heatable gloves with a fabric that contains conductive silver nanowires are developed for the American military (ACS 2017). These gloves are meant to be washable and allow the wearer to keep warm without sweating. Batteries are needed to provide heating, and hydrogel particles are added in an outer layer to absorb any moisture, as can be seen illustrated in Figure 20 (ACS 2017).
Textile sensors

Nextiles is an American startup company that has developed a semi-conductive thread that can be used to collect data on multiple points on the thread (IDTechEx 2021a). This is because each point can sense mechanical changes. Their main market is the sports industry, where athletes have the threads sewn into clothing to collect data to measure the performance. Examples of such parameters are: force, stretching, bending, pressure, and velocity (IDTechEx 2021a). The technology can be incorporated into any fabric, all that is needed is the thread based sensor and a small place for the battery and Bluetooth technology (Nextiles 2021). This can be seen in Figure 21. Clothes with these sensors can also be washed in a regular washing machine, and the semi-conductive threads are made of a combination of regular threads, like nylon or cotton, and printed circuit boards (Nextiles 2021). The company is currently focused on the professional sports industry, but they see potential in the military, fitness, and automotive industry as well (IDTechEx 2021a).
At MIT, there is a fabric made of special fibres that are able to collect, process, and store information locally (Ham 2021). By combining hundreds of microscale silicon chips, a polymer fibre can be constructed with electrical connections between each chip (Ham 2021). The fibre is as thin and flexible as regular sewing thread, and can be washed without losing its function. The fibres can also act as sensors and collect data such as body temperature (Ham 2021). Data can be collected through all the connection points in the fibre, and the data can be stored for approximately two months without any power source needed (Ham 2021). With this information, programs can be connected to interpret the information. One example that is mentioned is an AI that is able to deduce the physical activity of the wearer based on only their body temperature (Ham 2021).

A team from MIT are developing touch sensors made of certain fibres that can be integrated into regular clothing (Conner-Simons 2021). These touch sensors are then able to measure a person's movement and posture, and with that data there are several possible applications (Conner-Simons 2021). Examples include predicting what the current activity the person is engaged in (like sitting or walking), give suggestions on how to improve one's posture, be used as a touch sensitive skin for robots, or various uses in the healthcare sector. The team claim that one benefit, compared to other sensors, is that it is suitable for a large scale production as well as being flexible, breathable, and washable (Conner-Simons 2021).

Google is working on a music control string with a technology called Helical Sensing Matrix (HSM). It gives the user the ability to control their music by e.g. twisting, sliding, pinching, or patting the string of their hoodie (Kataria 2020). By including optic fibres in the hoodie strings, it is also possible to provide visual feedback, in addition to hearing the change in the music. According to Kataria (2020), Google also seem to be working on similar products to incorporate touch sensors in various textile items for either collecting data or creating controllers.

### Wearable technology

Aside from the previously mentioned E-textiles, below are some examples of other types of wearable technology:

At the University of California San Diego, a system of a wearable microgrid is in development. This system can, in several ways, transform the wearer's movement into electrical energy and power wearable electronic devices (Labios 2021). The system consists of sweat-powered biofuel cells and motion-powered generators which can transform the wearer's movements into electrical energy (Labios 2021), see a prototype in Figure 22. The power is then stored in energy-storing supercapacitors. To connect everything is a system of printed silver interconnections, which is covered with a waterproof coating to make it durable and washable (Labios 2021).
(14) Samsung is working on a stretchable display that can be attached and worn directly on the skin. The prototype, illustrated in Figure 23, uses a sensor to measure the wearer’s pulse while the value is visible on the display (Samsung 2021). It is made of an elastomer, organic LED-display, and a photoplethysmography sensor, which makes the product flexible enough to allow wrist movements without disturbing the function (Samsung 2021). The main focus is to apply this in healthcare products.

Other examples of more common wearable technologies are fitbits, smartwatches, and tags. These items are mostly worn to make daily interactions easier or to help keep track of one’s
health. The first two mentioned are located on the wrist, the last one can come in several shapes and forms, e.g. a card worn around the neck or in the belt, or more discrete versions like rings.

### 3.3 Discussion - Understanding the Material

When looking at the overall technical properties of the graphene textiles, there seem to be countless possible applications. As many experiential properties depend on the textile, as opposed to the coating, the properties vary greatly depending on which fabric is used. There are not many similar materials on the market, but quite a few in development, meaning that there is an interest for E-textiles.

For the heatable textile, the movement of the fabric during use should be considered when designing a product. This is because the even distribution of heat is dependent on the resistance of the textile. If it stretches during use, the resistance changes and the temperature will therefore vary across the surface. Even if it is not dangerous, it would most likely affect the usability of the product and the user experience. Considering this, it is beneficial that the heatable segments should be fairly narrow. Then the segments could be strategically placed on the product to reduce the risk of stretching them.

The durability of a graphene textile is uncertain, as the wear and tear depend on the application and the environment. It is also unclear how resistant the graphene particles are to mechanical friction or washing. It is beneficial to have the option of coating only parts of a fabric. Though, from a manufacturing point of view, it would probably be more efficient to attach a graphene coated piece afterwards if only a small part of a textile needs to be conductive. One visual downside with the coating, is that the fabric becomes black. It should be possible to dye the fabric afterwards, but according to Grafren AB, it has not been tested to say with certainty.

During this step in MDD, the material was unfortunately not tested on or experimented with in any larger extent. Due to the tight time plan and the complexity of the material, it was not possible to conduct any extensive tests. Therefore, information that could have been collected through experiments was instead collected from the company. The author did interact with the material samples (same as in the user study, see Figure 7) to get an idea of how the material feels in the different forms. Like Karana, Barati, et al. (2015) write, it did improve the knowledge of the material’s qualities and limitations to interact with it physically. More experiments would definitely have been helpful from a design perspective, for example how the function is affected by washing it or dying it after the graphene coating is applied.

Like Karana, Barati, et al. (2015) write, it is beneficial to conduct the three methods of this step (technical investigation, user study, and benchmarking) simultaneously. New questions appeared along the work which could be answered by the other methods. Although, it was good to start with the technical investigation to learn the basics of the material before starting with the other two. Without that basic knowledge, it would have been next to impossible to plan and conduct a suitable user study, as it would not have been possible to know what to test. The same goes for the benchmarking study, it would have been difficult to know what similar materials to look for.
3.3.1 Discussion of the user study results

During the user study, people appeared to get a very positive impression of the material and did not seem hesitant to touch and interact with the samples. Only a few felt a bit uncertain about how safe it was to touch the material while a current went through, but after a demonstration they seemed to believe it was safe. Though, some still seemed a bit uncomfortable with the idea to have a conductive textile in direct contact with the skin for a longer period of time. Many users seemed very impressed and fascinated that it is possible to make the fabric water resistant, in particular as it is possible to see through the fibres of the textile at the same time.

The results shown in Figure 12 and 13 support the previously made assumptions that the sensorial qualities only depend on the textile, not the coating. The observations on how the participants interacted with the material, as shown in Figure 9, do not seem particularly telling or special in terms of drawing conclusions regarding the user interactions. The results do suggest that the participants were more curious of the first sample, and interacted with it in more ways. Though, as these results are based on the observations of the moderator, there is a margin of error to consider.

Apart from the initial doubt by a few users, the participants interacted with the samples without any apparent hesitancy. One interesting observation is that the users interacted more roughly with the material while they filled out the sensorial qualities of the questionnaire, than they did initially. A possible reason for that could be that the questions included estimations of very specific sensorial qualities, which the participants probably did not consider during the initial interaction, and therefore felt the material more thoroughly.

It was rather difficult to get extensive answers to the questions What is the most pleasant quality of the material? and What is the most unique quality of the material?. The participants gave very similar answers to both; that it feels like regular fabric but has many additional, and unexpected, qualities and functions. Beforehand, the expectation had been to receive a wider range of answers to those questions that did not only regard the main function of the material. One guess could be that the toolkit is aimed towards, and therefore more suited for, a product where the sensorial qualities do not differ as much as in this case. As of now, it is possible that since the physical qualities varied between the samples, that when asked of one aspect, thoughts went to what they all had in common.

When asking about potential products for the material, many seemed to have a hard time gathering their thoughts enough to wrap their head around what it could actually be used for. The products that the users mentioned were very similar. This brings the question as to how much the workshop participants, in the concept development phase of the thesis, should be informed about the material. Those who had been told a little of what the material could do before the test said afterwards that they had not really understood the benefits and variety of the qualities until they actually saw and felt the samples. It could therefore possibly be a good idea to have a small demonstration before the workshop to make sure that everyone understands the functions and uniqueness of the material. When asked, all participants said that they would like to take part in the workshop as well, provided that the time and day works with their schedule. This is positive and possibly shows that graphene textiles are interesting to the public, not just to scientists.
3.3.2 Discussion of the user study methods

The pilot study of both the user test and the questionnaire, as suggested by Barnum (2020), Nielsen (2011), and Boeijen et al. (2020), was very useful. Both to see how everything worked and if the questions were formulated in a clear way, but also as a way for the moderator to practice and get a sense of how to act in the different situations. It was not ideal that the pilot study took place only an hour before the first session, but fortunately, only a small change needed to be made. In an attempt to appear interested and active, the moderator remained standing during the extent of the session. However, to remain standing and not doing anything when the participant filled out the questionnaire was perceived as stressful for both the participant and moderator. Therefore, during the user study, the moderator remained seated and pretended to be occupied while the user filled out the form to not make them feel stressed. Another downside with the pilot study was that only a pilot-user was present, when Barnum (2020) suggest that another person should be there to observe the moderator. Though, as the session did not include any complicated tests, it was deemed acceptable.

During the pilot study, the moderator also attempted to take notes while observing and conversing with the user. This was stressful, and it felt difficult to do everything while appearing interested to the user. Therefore, during the actual study, the moderator waited to take notes until the users worked on the form. One risk with this however, according to McDonald et al. (2021), is that the moderator forgot something that was said or observed. Though, as the interacting parts of the study were often only a few minutes, it seemed acceptable to wait with the note-taking. For future studies, it would be beneficial to have two people leading the user studies, one who observes and take notes, and one who leads the test and can put their entire focus on the participant.

The goals of the study were formulated in the beginning to ensure that the right thing was tested, as recommended by Barnum (2020). Each user also received the same samples and information in mostly the same order. The information order and timing varied slightly depending on what questions the participants asked. In the beginning of each test, the moderator explained that the purpose was to explore the samples and that there was no wrong answer or action, but nothing more specific, as suggested by Barnum (2020) and McDonald et al. (2021). This approach appeared to set the participants in a good state of mind where they could explore the samples and ask questions without fear of judgement.

The think aloud technique was very useful. Most participants seemed to be comfortable enough to share their thoughts, and clarified what they meant when asked by the moderator. Like Carter (2007) and McDonald et al. (2021) suggest, the moderator attempted to appear friendly and somewhat enthusiastic about the material in order to make the participants feel more comfortable. Everything was explored together (Carter 2007), but the user was the one leading and asking questions, while the moderator more attempted to be there as a support (Barnum 2020). It is possible that this success is partly due to that most participants have taken part in, or organised, user studies before. It was also helpful that a friendly relationship already existed, because then the initial trust was there from the beginning.

One downside regarding the participants, though, is that it was not a diverse group. All were friends of the author, around the same age, from the same university, where most were
studying the same program. But as the thesis is very front-heavy and time sensitive, it was considered acceptable and efficient to not spend more time searching for participants. As both positive and negative aspects were brought up, and the users brought different perspectives in their thought and reflections, the study still felt very useful.

Only one test was significantly different from the others, in the sense that it had two participants at the same time instead of one. The two people were available at the same time, and if they were to have conducted the test individually one would have had to wait outside. As this session took place late in the afternoon, due to the availability of the participants and moderator, everyone was fairly tired. Because of that, both were allowed to participate at the same time. Given that both had experience in user studies, were comfortable with each other, and because the questionnaire is filled out individually, the risk of them influencing each other was deemed low. A benefit of having two participants instead of one was that they discussed their thoughts with each other regarding their impressions and possible applications, which appeared to both raise the energy, and make the discussion more genuine than the participants who were only able to voice their thoughts alone. It was much easier to follow the discussion between the two, and it was very interesting and useful to follow their thought processes, in particular when they discussed possible applications for the material at the end.

Of the seven participants in the recently presented results, six are from test sessions and one from the pilot study. As only a few things were altered after the pilot study, that participant’s impressions of the material are still included in the results, as the risk of them being affected by any differences in the study is considered minimal. Because the two different fabrics used for the conductive samples (1A and 1B) are very different, it was decided for them to be judged separately in the sensorial part of the questionnaire. In order to still collect information of both, the user group was divided between the two, and each user was asked to fill in the sensorial part of the questionnaire with one of the two samples in mind.

There was a risk that the impressions of the former textiles affected the following ones, but there simply was not enough users or time available to conduct entirely separate tests for all the different textile types. To counter this problem, the order that the material samples were presented in was carefully considered so that the initial impressions were not too influential of the following.

The toolkit was very helpful during the user study, in particular by providing different emotions, actions, sensorial qualities, and meanings ready to fill out. The scale to note the intensity of the emotions was, however, not very useful in this case. As people express themselves differently, it felt very difficult to estimate and compare the intensity of their reactions. However, all participants expressed positive emotions, with a few expressing slightly negative emotions as noted in Figure 10. In most cases, the intensity appeared to be highest for the first type (the conductive fabrics), then it went down a little for the sensors, only to go up again for the final sample, which was the heatable textile. Given that the first textile type was the participants’ first interaction with a conductive textile, it is not surprising that it received the most intense reactions. The following types were only variants of the first, therefore not as exciting. To introduce heat, however, appeared special enough to increase the intensity a bit more at the end. Perhaps the results would have been considered more reliable if the emotions also had been included in the questionnaire, for the
participants to fill out themselves. However, it is then possible that the questionnaire had been too time consuming.

Like McDonald et al. (2021) write, questions were asked at the end, where three were recommended by the toolkit (Camere and Karana 2018) and one brought up by the thesis author. It felt beneficial to conclude the test with some final reflections, both to get the users to reflect on the material, and to get answers to the questions from the toolkit. These questions seemed good, because they summarised a lot of information and thoughts. Despite hearing the reasoning during the session, these answers were surprising.

3.3.3 Discussion of the material benchmarking

From the material benchmarking, it became apparent that there are very few E-textiles on the current market. Most that are, have focused on very specific markets with a professional interest, instead of making products aimed toward the general public. Since Grafren AB do not have any current products on the market, it feels reasonable to also check the E-textiles that are in development, as they may be competitors in the near future.

Quite a few companies did not publish what material they use to make the textile conductive, which makes it difficult to compare them. Though, as it appears to be common to use metal particles, it could be assumed that those are used in some cases.

3.4 Conclusions - Understanding the Material

When looking at the overall results from the first step of MDD, the material appears to have a place on the market, have technical properties that provide an advantage compared to others, as well as raising an interest of consumers. The material could also provide a more sustainable option to some of the existing materials. As a vast majority of the users mentioned that they could not have guessed that the material samples were anything special by only looking or touching them, it also fits the profile of undetectable wearable technology in fabric.

In the remaining conclusions, the previous results and reflections are summarised in order to answer the eight questions from Karana, Barati, et al. (2015), which are listed in the beginning of this chapter.

3.4.1 What are the main technical properties of the material?

The material is light, flexible, and lets through air and moisture, meaning that it also is breathable. By using graphene as the conductive particles, the textile gets a superior conductivity, is biodegradable, and versatile since the coating can be applied to multiple textiles. The textile also gets a high sensitivity to change in resistance and can be made waterproof with an additional coating, without interfering with the conductive properties.

Conductive textiles
It is able to block the electromagnetic field to approximately 90%.
Heatable textiles
The actual fabric is heated and the temperature can be altered during use.

Textile sensors
The pressure sensors can be as specific as approximately 0.3 grams.

3.4.2 What are the limits and opportunities of the material?
Opportunities
It is a unique material. There is nothing with the same qualities on the market today. There are other E-textiles in development, but it is not apparent that they share the same superior conductivity and comfort qualities, while being biodegradable. With the graphene coating, the actual textile becomes conductive. Many different fabrics can be coated, and only parts of a textile can be coated if needed. With an additional coating, graphene textiles could also become water repellent and washable.

Limitations
The material is not waterproof from the start, therefore an additional coating is needed to ensure that the graphene coating is not worn off during use. There should also be an additional layer separating the textile from the skin to avoid direct contact, even though direct contact is not dangerous for the wearer. A power source is also needed, the size depending on the application, as well as conductive threads for the heaters and sensors.

3.4.3 What are the unique sensorial qualities of the material?
Since graphene is a two-dimensional material, it is not detectable on the textile, either visually or by touch. This means that the sensorial qualities are determined by the fabric instead of the graphene coating.

3.4.4 What do people think are the most and least pleasing sensorial qualities of the material?
The sensorial qualities only depend on the chosen fabric, and will therefore vary.

3.4.5 Does the material remind people of another material?
Graphene textiles can be compared to regular textiles, or other E-textiles. The heatable one reminded some people of clothing with heatable wires incorporated.

3.4.6 How would people describe the material, and what meanings does it evoke?
In general, people described the graphene textiles as; manufactured, futuristic, and professional. Though, this is also dependent on the graphene textile type.

Conductive textiles
Manufactured, futuristic, and professional.
3.4.7 Does the material bring out any emotions, e.g. surprise, fear, love, relaxation?

When first seeing the material, there was no particular reaction. When being introduced to the conductive properties of each textile type, the most common reactions were; fascination, curiosity, and surprise. Some also expressed distrust and concern, due to having a conductive material in direct contact with the skin.

3.4.8 How do people behave and interact with the material?

People become curious when they learn of the technical functions of the material. They touch it, hold it, and play around with it, almost as if they are trying to feel how it differs from a regular textile. When first hearing that it is conductive, some act a bit hesitant, but after a demonstration showing that it is safe, most people seem okay to interact with it like they would with any other textile.
4 Creating the Material Experience Vision

In this chapter, the implementation of step 2 of MDD is described. The purpose of this step is to create the material experience vision, i.e., to reflect and decide on what the material’s future role should be in relation to products, users, and a larger context (Karana, Barati, et al. 2015) based on the results of step 1.

4.1 Methods - Creating the Material Experience Vision

Given that this step is fairly subjective, Karana, Barati, et al. (2015) suggest organising the previous findings in different ways, in search for correlations and to draw conclusions. To help create the vision, the writers provide the following questions to reflect upon:

1. What unique qualities of the material should be emphasised in the final product?
2. In which contexts could the material make a positive impact?
3. How would people interact with the material within different contexts?
4. What would the unique contribution of the material be?
5. How would the material be perceived on a sensorial and interpretive level?
6. What kind of emotions would the material evoke from people?
7. What would people do with a product containing the material?
8. What would the material’s role be in a wider context?

When developing the material experience vision, Giaccardi and Karana (2015) mean it is important to consider the four experiential levels: sensorial, interpretive, affective, and performative, as previously mentioned by Karana, Barati, et al. (2015). Giaccardi and Karana (2015) write that how a product is perceived varies depending on multiple factors, including the person interacting with it, the material it is made of, as well as the surroundings and current context. The writers therefore recommend analysing all four experiential levels with the purpose of learning how they work together in the intended contexts. Giaccardi and Karana (2015) mean that the first three (sensorial, interpretive, and affective) should influence the fourth one (performative) in the sense that how the user interacts with the product depends on how they think it looks and feels etc.

Along with the four experiential levels, Giaccardi and Karana (2015) write about three additional factors to consider for the material experience vision; material, people, and practices. The writers mean that the different relationships between these three factors affect the interaction and user experience. The relationship between material and people is called encounters, and symbolises the very first time the user interacts with the material, and is therefore when the initial impressions are formed (Giaccardi and Karana 2015). The relationship between people and practices is called performances, which is when the user and material have re-occurring interactions. During these interactions, Giaccardi and Karana (2015) argue that the user’s impressions of the product and material, as well as the interaction, are developed further. As the user gets more comfortable and used to the material
(and product), they may use it differently than they did in the beginning. The final relationship, which is between practices and materials, is called collaborations. In this relationship, the user makes changes to the material which may affect the properties of the product and influence the interaction further on (Giaccardi and Karana 2015). See an illustration of the three factors and their relationships in Figure 24 below.

Figure 24: Illustration of the three factors; materials, people, and practices. And the relationships between them; encounters, performances, and collaborations.

To clarify how these relationships may look, Giaccardi and Karana (2015) bring up the example of a user receiving a porcelain bowl. During the encounter, the user is very careful with the bowl as they perceive it as fragile. As time goes on, the user gets more used to the bowl and is not as careful with it (performances). After a while, the bowl may break. Then the user might attempt to fix it with glue and paint, and thus affect how the bowl looks and how it will be handled in the future (collaborations). By bringing up the three factors and their relationships, Giaccardi and Karana (2015) argue that it is not enough to reflect on how the material may be used at one point in one context, but to consider how the material may be used for the duration of its time with a user, and how the interaction develops.

4.2 Reflections of the Previous Results

In this section, the work process leading up to the vision is described, where the previous results are reflected upon in search of potential conclusions.

4.2.1 Reflections of the user study results

From the user study, the results of the final questions are reflected upon further. Each answer is written as a post-it note in the program Miro to simplify the work process.

The replies considering the most pleasant qualities can be found in Figure 28 and the replies considering the most unique qualities can be seen in Figure 26. The answers to both questions are quite similar and focus on the main functions of the material; a fabric that does not appear to be anything special, but that possesses conductive properties. The
material is considered something new and different, which implies that it is also interesting
and positive with a high innovation level. The fact that a conductive textile can be both
discrete and comfortable led to some users thinking that there are many possibilities for
future applications. These results also suggest that the pleasant qualities have little to
do with the specific textiles, but the main function, i.e. the conductive properties of the
graphene coating.

Pleasant qualities

<table>
<thead>
<tr>
<th>Cool material.</th>
<th>Ability to be both waterproof and heatable.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric is soft and conductive.</td>
<td>Textiles work together.</td>
</tr>
<tr>
<td>There seem to be many possibilities.</td>
<td>Possibilities of electrical applications.</td>
</tr>
<tr>
<td>It is not apparent anything special is going on.</td>
<td>The textile itself is heatable.</td>
</tr>
</tbody>
</table>

Figure 25: The comments from the user study regarding what the participants think the most pleasant quality of the material is. If multiple people gave the same answer, they are overlapping.

Unique qualities

<table>
<thead>
<tr>
<th>It is a new technology with high innovation.</th>
<th>Such a sensitive touch sensor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>The actual fabric is heated.</td>
<td>Movement detection with strain sensors.</td>
</tr>
<tr>
<td>Electricity in clothing.</td>
<td>Something as thin as a fabric can be made conductive.</td>
</tr>
<tr>
<td>Fabric can be used for sensors.</td>
<td>The fabric is conductive.</td>
</tr>
</tbody>
</table>

Figure 26: The comments from the user study regarding what the participants think the most unique quality of the material is. If multiple people gave the same answer, they are overlapping.

The replies regarding the most disturbing quality, as can be seen in Figure 27, can be divided into two categories. The first one considers the comfort of some of the textile samples, where the rougher conductive sample (1A in Figure 7) as well as the heatable textile sample (3 in Figure 7) were not considered attractive choices for clothes. This is both due to a lack of comfort and due to their appearance. Given that this has nothing to do with the graphene coating, but the choice of fabric, the results suggest that the fabric should be carefully selected for each product. The other category considers that several participants thought it was unnatural to combine electricity and fabric, as well as concerning to have something conductive so close to the skin. Therefore, this worry should be considered during the product development to ensure that the user understands how the product works and feels safe.
4.2.2 Refections of the material benchmarking results

The descriptions of the products and materials found in the benchmarking study are investigated to see if any trends appear about how wearable technologies and E-textiles are marketed. If all go in one direction it should be reflected upon why. See a summary of the benchmarking organisations and their materials and products in Table 2 and 3 for an easy comparison.

In Table 2 it becomes apparent that there are multiple markets with similar products or materials in development or on sale. However, it is not clear which materials are included in the products, in particular which materials that are used to create the conductive properties. Some write about conductive particles, but do not specify which ones. This makes it more difficult to compare the different materials.

In Table 3, keywords are used to create an overview of the different properties of the various products and materials. These keywords are based on the most common descriptions found in the benchmarking study. When examining the keywords further, see Figure 28, it becomes apparent that much of the wearable technology, in particular the sensors and heaters, are described as invisible technologies. Meaning that the technology providing the product with additional functions should not be noticed by the user. That could be a reason why words like flexible, breathable, stretchable, lightweight, and water-resistant are used to describe most products. As seen in Figure 28, this leads to the conclusion that all companies want the wearer to be able to treat their wearable technology like regular clothes. The technology is meant to collect information or provide various additional features not found in regular clothes, but not be noticeable. When reflecting further upon this message, it could perhaps be to make life as easy as possible for the user, and prevent any need to change behaviours to use the product. The organisations want to make it as effortless as possible for people to use their products.
Table 2: Summary of the products from the benchmarking study. In this table, the organisations, materials, and areas of use are listed. The number corresponds with the number in the textual descriptions in chapter 3.2.3 except for (0), which is the case study company.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Organisation</th>
<th>Material</th>
<th>Current area of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Grafren AB</td>
<td>Fabric and graphene particles.</td>
<td>- Outdoor activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Automobile</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Healthcare</td>
</tr>
<tr>
<td>1</td>
<td>Purdue University</td>
<td>Silk- and nanocarbon composite and unknown spray.</td>
<td>- Healthcare</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Safety</td>
</tr>
<tr>
<td>2</td>
<td>Chalmers University</td>
<td>Cellulose thread and polymer based dye.</td>
<td>- Healthcare</td>
</tr>
<tr>
<td>3</td>
<td>The school of textiles in Borås</td>
<td>Fabric, translucent optic fibers, and LED-lights.</td>
<td>- Art</td>
</tr>
<tr>
<td>4</td>
<td>Fudan University</td>
<td>Conductive fibers, luminescent fibers, and cotton fibers.</td>
<td>- Communication</td>
</tr>
<tr>
<td>5</td>
<td>Nanostitch</td>
<td>Fabric, coffee charcoal additive and oxide.</td>
<td>- Outdoor activity</td>
</tr>
<tr>
<td>6</td>
<td>ThermoKnitt</td>
<td>Polymer based textile and conductive particles.</td>
<td>- Outdoor activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Physical rehabilitation</td>
</tr>
<tr>
<td>7</td>
<td>INF</td>
<td>Cotton, spandex, and heatable coil.</td>
<td>- Outdoor activity</td>
</tr>
<tr>
<td>8</td>
<td>US Army</td>
<td>Silver nanowires, fabric, and hydrogel.</td>
<td>- Military</td>
</tr>
<tr>
<td>9</td>
<td>Nextiles</td>
<td>Nylon or cotton and printed circuit boards.</td>
<td>- Military</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Automotive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Fitness</td>
</tr>
<tr>
<td>10</td>
<td>MIT</td>
<td>Polymer fiber.</td>
<td>- Outdoor activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Sport</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Leisure</td>
</tr>
<tr>
<td>11</td>
<td>MIT</td>
<td>Textile fibers and &quot;custom-made functional fibers&quot;.</td>
<td>- Fitness</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Healthcare</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Physical rehabilitation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Robotics</td>
</tr>
<tr>
<td>12</td>
<td>Google</td>
<td>Not stated.</td>
<td>- Controllers</td>
</tr>
<tr>
<td>13</td>
<td>University of California San Diego</td>
<td>Biofuel cells, generators, supercapacitors, silver, and waterproof coating.</td>
<td>- Leisure</td>
</tr>
<tr>
<td>14</td>
<td>Samsung</td>
<td>Elastomer, organic LED-display, and photoplethysmography sensor.</td>
<td>- Healthcare</td>
</tr>
</tbody>
</table>
Table 3: Summary of the products from the benchmarking study. In this table, some often occurring qualities are compared for an overview. If the material or product is described as having the listed feature, there is an x in the box. If not, the box is left empty. If it is not mentioned or unclear, there is a question mark. The number corresponds with the descriptions in the textual descriptions in chapter 3.2.3, except for [0], which is the case study company.

<table>
<thead>
<tr>
<th>Conductive</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heatable</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Sensors</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Stretchable</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Breathable</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Washable</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Powersource needed</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Renewable material</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Currently on the market</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Figure 28: Figure containing the most common keywords used to describe the materials and products found in the benchmarking study and reflections below.

Washable/Waterproof
Flexible

Breathable
 Stretchable
Durable
No power source needed.
Powered by batteries.

Comfortable to wear as it can be combined with different fabrics.
No need to be extra careful, a minor rip will not damage the technology.
Light to wear, no battery to consider.
Only a small power source needed, still comfortable to wear.

The wearer can treat the item as a regular piece of fabric.
4.3 Creating the Material Experience Vision

The material experience vision is created by reflecting on the eight questions listed above from Karana, Barati, et al. (2015), and the material experience, i.e. three factors and their relationships as described by Giaccardi and Karana (2015).

4.3.1 The vision - Reflecting upon the eight questions

The eight questions are reflected upon using mind maps. This is to collect and visualise the thoughts and reflections of the thesis author. It is also beneficial for discovering if the answers go well together or if any are contradicting.

See the mind map for question one, *What unique qualities of the material should be emphasised in the final product?*, in Figure 29 below. It is quite difficult to think of how this material should be emphasised in a product when the previous research indicate that it should be an invisible background technology. The main unique quality of a graphene textile is that it is indistinguishable from regular fabric, something that gives it an advantage compared to other wearable technologies. Therefore, the focus should not be to highlight these unique qualities, but to make full use of them to have the material be indistinguishable from regular textiles. The goal should be that the only people who know which components are graphene textiles, are people who have been purposefully made aware of it.

![Mind map of question one](image)

*Figure 29: Mind map of the thoughts about the first question for the material experience vision: What unique qualities of the material should be emphasised in the final product?*

The next question is *In which contexts could the material make a positive impact?* and the mind map can be seen in Figure 30. The overall impact the material could make is
to help make much of the current technology more sustainable, due to graphene being carbon based. As graphene can be combined with practically any textile, it could also make the technology lighter and more comfortable to wear, which could lead to developments in wearable technology. As many areas in today’s society use some form of technology, this material could be applied to a vast majority of businesses and industries, either to add additional features in current textiles, or to replace other materials entirely.

Regarding the specific industries considered in this thesis so far, lots of focus have been placed on the sports industry, healthcare sector, and the collection of information. According to Ashby and Johnson (2014), it is common for a new material to be applied in a professional industry first, as opposed to the general consumer market. An industry that Ashby and Johnson (2014) mention that is quite popular for new products is the sports industry. The writers mean that some benefits with that industry is that it is very visible and quick to adapt to new findings. One guess as to why it could be more common for a new product to be aimed towards a visible and niched market could be that it is easier to make something tailored to a selected few as opposed to the general consumer. And if a major sport star is seen wearing or using a product, the publicity could lead to more people getting interested in the product and therefore open up the market for the company. Therefore, it could be a good idea to start with the sports industry to gain traction. And the use of conductive textiles, as well as heaters and sensors, could facilitate for professional athletes in several ways.

For the healthcare sector, this new material could improve the equipment used by the personnel, but also for people in need of extra assistance at home. Graphene textiles could also possibly make the healthcare sector more sustainable by replacing existing materials in disposable products. To introduce a more sustainable option might not in itself improve the equipment, but make the overall system more sustainable.

This material could also be used to improve communication, as seen in (4) in the benchmarking study, both between different people, and between people and technology. This could open up more options for people with various disabilities to be heard and seen, and thus make society a bit more accessible and equal.

To collect more information about people through sensors could be both good and bad. Increasing the knowledge about how people move in different activities could be useful in e.g. rehabilitation or improving an athlete’s form. In (10) from the benchmarking, it is mentioned that an AI could tell which activity the user is doing based on body temperature. With this kind of information, patterns could be discovered and perhaps used for preventing injuries by making people aware of their harmful activities before any actual damage is done. It could, in short, help people live a more healthy lifestyle. However, today, lots of information is collected about people, and then sold for various marketing schemes. If sensors are used to collect even more information about peoples’ habits, the handling of that data should be carefully considered to ensure that information is not leaked or misused.

Other contexts that could benefit from the implementation of graphene textiles are possibly transportation of various kinds, due to the low weight of textiles. The game industry is another possible industry, in particular augmented or virtual reality. Sensors could be used in such environments to make the games more interactive, lifelike, and physically active. There are also countless applications for this material to simply make life a bit more comfortable for people, or facilitate various professions.
2. In which contexts could the material make a positive impact?

- More sustainable technology
  - More comfortable to wear
  - Easier to wear and carry
- Improved wearable technology
  - Professional
  - Hobby
- Improved sports equipment
  - More sustainable healthcare equipment
  - Disability aid
  - A more equal and accessible society
- Improved healthcare equipment and appliances
  - More ways to communicate
  - Low weight
- More ways to communicate
  - VR for more physically active gaming
  - VR for more professional applications
  - Connect to mobile games
- Transportation
  - Easier to collect information with sensors
  - Learn more
  - Offer assistance
- Games
- Research

See the mind map for question three in Figure 31 regarding how people are meant to interact with the material in different contexts. This is highly dependent on the product and how the material is used. If the material works as a hidden technology, it is not meant to be interacted with, but rather treated the same as the rest of the product.
If the material, on the other hand, is meant to be interacted with, for example if it is being used as a controller like in (12) from the benchmarking study, then it should be with simple touches. Since the touch sensor is very sensitive, if that is used then the interactions should only require simple movements in various sequences for different commands. Of course, this is highly dependable on the product. One important aspect to remember, though, is to make sure to clarify how the interaction is meant to work, and to include suitable feedback to ensure that the user understands immediately if the interaction is successful. As the material blends in with regular fabric, one way could be to make that part distinguishable from the rest.

Figure 31: Mind map of the thoughts about the third question for the material experience vision: How would people interact with the material within different contexts?

The unique contribution of the material, as seen in Figure 32, is simply improved technology. At the moment, there is no other material that is both biodegradable and an E-textile with superb conductivity.
Figure 32: Mind map of the thoughts about the fourth question for the material experience vision: What would the unique contribution of the material be?

See the mind map in Figure 33 regarding how the material should be perceived on a sensorial and interpretive level. Because the sensorial qualities depend on the textile instead of the graphene coating, the sensorial qualities should be considered at a later stage when the product is decided and a suitable textile can be selected.

When considering the interpretive level and how the material is meant to be perceived, it seems appropriate to have the basis be the current positive characteristics of the material, and highlight them further. Therefore, the most popular meanings from the user study are considered: futuristic, manufactured, and professional. Since the material is very new, it is suitable for it to be considered futuristic. The products that can be made with this material could be similar to existing ones, but E-textiles do not seem to be very established yet on the market, meaning that such products will probably be considered new, innovative, high tech, and therefore futuristic. Because it is not common to combine fabric and electricity, it is expected that most people will feel like the participants from the user study, i.e. that it is not natural, but something man-made. That makes it suitable to strive towards the word manufactured. The word also fits quite well with being futuristic, as such products are often perceived in media as something newly created and previously unheard of. The word professional, however, feels more limiting than the other two when considering the wide range of possible products. It might fit for some products, but not all. It is therefore not included in the vision, but could be good to consider at a later stage when the product is decided.

Therefore, the meanings are futuristic and manufactured. Though, since some users were concerned of interacting so closely with a conductive material, this worry should be combated in the design in order to make the user feel safe. The word safe is therefore added as another meaning. It is meant to not only ensure that the product is safe to use, but that it is also...
perceived as safe to use. The participants who expressed concern seemed less worried after learning how the material worked. Therefore, a way to make the product be perceived as safe could be to make it appear simple. If the product is easy to understand, any worry of unknown functions would be reduced. To further explain the meanings futuristic and manufactured, the words aloof, innatural, masculine, calm, ordinary, and elegant from the user study are used as "sub-meanings", as can be seen in Figure 33.

![Mind map visualising the thoughts regarding the fifth question for the material experience vision: How would the material be perceived on a sensorial and interpretive level?](image)

Figure 33: Mind map visualising the thoughts regarding the fifth question for the material experience vision: How would the material be perceived on a sensorial and interpretive level?

Regarding which emotions the material should evoke from people, see the mind map in Figure 34. In general, the emotional response towards the material should be neutral or positive, depending on how the material is used in the product. If the material is hidden, it should not evoke any particular emotions as it should not be noticed. If it is noticed, the emotion should foremost be surprise that this textile is different from the rest, as well as curiosity and fascination regarding how it works. These emotions are based on the reactions from the user study. If the material is clearly displayed, the emotions would be roughly the same, as well as perhaps disbelief that it can do what is advertised, and initial caution as the fabric is conductive.
Question seven *What would people do with a product containing the material?* is not considered at this stage as it is deemed too abstract to answer. It should be considered at a later stage, when the product is more determined.

The final question, regarding the material’s role in a future context, is connected to question four. Thanks to the unique characteristics of graphene textiles, the material can be used to improve technology in different ways, including comfort and sustainability. As seen in Figure 35, this should be used to further the material’s purpose of improving the lives of people in different ways.

Figure 34: Mind map visualising the thoughts regarding the sixth question for the material experience vision: *What kind of emotions would the material evoke from people?*

Figure 35: Mind map of the thoughts about the eighth question for the material experience vision: *What would the material’s role be in a wider context?*
4.3.2 The vision - The material experience

To summarise the material experience, as explained above by Giaccardi and Karana (2015) and shown in Figure 24, the information and discussion above are used to formulate how the usage of a material is to be developed over time. In Figure 36, the relations between material, people, and practices are reflected upon. The figure is used to tell a story of how these relationships changes over time. This depends, of course, on the product, but in this general scenario the product is considered an item used every day, or often, by a regular person.

![Diagram](Image)

**Figure 36: A more descriptive figure of the material experience vision for graphene coated textiles. Illustration is based on the textual descriptions from Giaccardi and Karana (2015) and inspired by an image in the same article.**

For the initial interaction (encounter), the user might feel a bit uncertain of how the product works, but is overall happy with it and does not notice that any part of the fabric feels or looks different unless it is purposefully highlighted. After a few interactions (performance),
the user feels very comfortable using the product, and if any actions had to be carefully
considered before, they now go automatically as the user has become accustomed to them.
If there was any worry before, it is now gone and the product is being used regularly and
without any additional care compared to similar products.

In the *collaboration* phase, the product has been used to the extent that it is starting to
show. Perhaps the fabric is starting to look worn down, perhaps the colour is fading, or
some holes are appearing. At this stage, there is not enough knowledge about the graphene
coating to make assumptions of how the function is affected after extensive use. If it can
be assumed that the functionality is still intact, then one possibility could be that the user
simply patches the holes up to avoid any further damage and uses the product differently.
Some examples for that could be to use it more carefully to keep the product functional for
a longer time, to continue as before, or even to use it less carefully as it is close to breaking
anyway. It would depend on the user and product.
5 Manifesting the Material Experience Patterns

After step 2 of MDD, which is described in the previous chapter, there is now a vision for how graphene textiles should be used and perceived in future products. While the specific contexts for the products are not yet determined, the vision is very general and should be applicable in most situations. When moving on towards step 3 of MDD, it is time to create the design guidelines. These guidelines are based on the vision and meant to be used in the development phase to help the designer ensure that the products follow the vision. The goal of this chapter is therefore to investigate how the established meanings are embodied in current materials and products. Through that, guidelines can be established to facilitate the design process in the concept development phase.

5.1 Methods - Manifesting the Material Experience Patterns

The main method is an adapted version of MDMS (Meaning Driven Materials Selection), as previously described in chapter 2.1.1. This method consists of a user study where the participants are meant to receive a word (a meaning) and then find a material, as well as a product containing said material, which they think embodies that meaning (Karana, Hekkert, et al. 2009). From that, the designer is meant to gain an understanding of how the various aspects of a material and product affect the user’s perception of them.

Unfortunately, due to time limitations, this is not possible to accomplish. Instead, a modified version of MDMS is used to confirm the perceptions of the thesis author, as opposed to collect perceptions from scratch. For this, the author is to find images to embody the meanings chosen in the vision, and organise them in mood boards. Then, the mood boards are sent out to participants along with a list of possible meanings, and the participants are to match the mood board with the word they think best represents it as a whole. If the study is deemed successful, i.e. if the participants agree with the author’s interpretations, the mood boards are meant to be used in the concept development phase to guide the design toward the vision.

To prepare for this second user study, the questions from Barnum (2020) are used once more:

- **The goal** is to develop design guidelines to use in the development phase, so that the products are perceived in the intended way.

- **What to test?** How well the author's interpretations of the meanings from the vision agree with the interpretations of other people.

- **Where to test it?** Online.

- **How to test it?** Through a questionnaire.

First, the meanings established in the vision for future products (futuristic, manufactured, and safe) need to be developed further as they are very abstract and general at this point. This is done by a reversed *affinity diagram*, a method suggested by a senior lecturer at Linköping University. The method consists of grouping lots of ideas or information together, usually from a brainstorming session, and then finding themes that represent each group.
(Friis Dam and Yu Siang 2020). Because the three meanings from the vision are very abstract in themselves, they are deemed fitting to be the general themes. This is why the affinity diagram is done in reverse, i.e. by starting with the themes and then brainstorming the more detailed descriptions. To make full use of the previously collected results, other meanings from the first user study are included as sub-meanings, as seen in the previous chapter in Figure [33]

The mood boards are made by searching the internet for suitable images. For copyright reasons, only sites that have a creative common licence are used, so that all images can be used freely in this thesis. The search words used to find suitable images are mostly the themes or the sub-meanings.

As this user study is based on quantitative answers rather than qualitative, a questionnaire is deemed an appropriate method to collect the opinions of the participants. This is supported by Boeijen et al. (2020) and Osv alder et al. (2015), who mean that it is a suitable method for validating existing results. Depending on the topic and goal of the survey, Boeijen et al. (2020) suggest selecting respondents with some previous knowledge about the area. The supervisors of this thesis agree and suggest that the participants should be familiar with what a mood board is and how it is used, to ensure that the users understand what is asked of them. The participants of this study are therefore people known to the author, where most have either personal experience in creating and using mood boards, or have been made familiar with it through the author.

According to Osv alder et al. (2015), it is crucial that the questions are well made in a questionnaire. The questions should be formulated in a way that removes any doubt of what is asked, without leading the users towards a particular answer (Osv alder et al. 2015). The amount of questions should also be considered, as too many may make the participants tired and unmotivated (Boeijen et al. 2020; Osv alder et al. 2015). The writers argue that the less the participants need to write, i.e. the less effort is needed, the more inclined they will be to help.

Osv alder et al. (2015) write that, when constructing a questionnaire, it is important to consider the validity and the reliability of the results. The validity is investigating whether the questionnaire is in fact measuring what it is intended to measure, i.e. the formulation and placement of the questions (Osv alder et al. 2015). Boeijen et al. (2020) and Osv alder et al. (2015) mean that it is unfortunately quite common that some questions are misunderstood, and therefore not contributing to the results. The reliability, on the other hand, is whether the results can be replicated, i.e. if the same respondent would give the same answers when filling out the questionnaire on multiple occasions (Osv alder et al. 2015). The participant’s mood, for example, should not have a great influence on the answers. One way to increase the chance of having well formulated questions to ensure that the validity and reliability are high, is to test the questionnaire through pilot studies before it is sent out (Osv alder et al. 2015; Boeijen et al. 2020). Because of this, there is one pilot study to collect feedback on the mood boards and the questionnaire.

5.2 Results - Manifesting the Material Experience Patterns

In this section, the mood boards and the results of the questionnaire are presented. To see the developments of the three meanings in the affinity diagram, the image sources of the
mood boards, and the questionnaire, please read Appendix 2.

See the mood board representing the meaning *futuristic* in Figure 37. Words like *high tech*, *innovative*, *innatural*, and *smart* are used to further define this meaning.

![Image of mood board](image)

**Figure 37:** The mood board attempting to convey the word *futuristic*.

See the mood board representing the meaning *manufactured* in Figure 38. Words like *man made*, *elegant*, *hard*, and *calm* are used to further define the meaning.

![Image of mood board](image)

**Figure 38:** The mood board attempting to convey the word *manufactured*.
See the mood board representing the meaning safe in Figure 39. Words like familiar, calm, simple, cozy, and joy are used to further define the meaning.

The results of the questionnaire, i.e. what word the participants chose for each mood board, can be seen in Figure 40, 41, and 42 for the futuristic, manufactured, and safe mood board respectively. There are 15 respondents in total to the questionnaire.
5.3 Discussion - Manifesting the Material Experience Patterns

The use of the reversed affinity diagram was helpful. Before, the meanings only represented abstract concepts, but after brainstorming sub-meanings, they became useful to more properly define what the main meanings should convey. It was also helpful to draw inspiration from other meanings collected in the first user study. As this method did not get as much influence from participants as preferred, it seemed beneficial to make full use of the previously collected results. However, all sub-meanings from the user study were reflected upon before use, given that those meanings were words the participant felt that the material samples expressed at that moment. In this step, the meanings are meant to convey what the material should convey in the future. Though, in order to make these guidelines somewhat realistic, it seems suitable to stay fairly close to the current impressions of the material.

The mood board for futuristic is meant to convey a feeling of excitement, innovation, and technical advancements. Something new. When media is depicting a technically advanced future, lights are often used in different forms for various effects, possibly to include technology in more places. From the results of the questionnaire, see Figure 40, it is deemed that the vision of the author, as it is displayed in the mood board in Figure 37, is able to convey the intended message as a vast majority of the participants chose the intended word, or a sub-meaning.

Safe is quite difficult to find embodied in products or materials. Therefore, the attempt for that mood board, see Figure 39, was to provide a feeling of comfort and positivity. Something that makes the user feel at ease, without appearing complicated or difficult. As seen in Figure 42, a majority of the responses chose the word comfortable, meaning that this mood board is not as clear as the futuristic one. But as comfortable, simple, and elegant are all used as sub-meanings to safe, the results are still considered positive and the mood board successful.

The mood board for manufactured, see Figure 38, was the one most difficult to construct, as that meaning felt the most difficult to define. But the idea is that it should feel man-made
and well made while elegant, as opposed to rough or industrial. Products can be man-made and beautiful, for example the lipstick, watch, and violin. The intended products should be able to be replicated, and in some instances mass-produced, while being attractive to own. Based on the results from the questionnaire, see Figure 41, this mood board was the one with the largest variety of answers, and thus probably the one most difficult to interpret. Manufactured was still one of the most popular choices along with elegant, one of the sub-meanings used for several images. Therefore, this mood board is also considered successful, though slightly less so than the other ones.

It should be noted that the results from the questionnaire would probably be different with another setup. As of now, the meanings and some sub-meanings were the only choices for each mood board. Therefore, it might have been easier to guess which the intended meaning is, than if the participants were to write a meaning of their own. However, due to the short time frame, this particular strategy was chosen, but it is something to consider for future work.

5.4 Conclusions - Manifesting the Material Experience Patterns

In conclusion, the mood boards displayed in Figure 37, 38, and 39 can be used as guidelines when developing the concepts to help the products follow the vision. But to ensure that each product embodies the intended meanings and will be perceived in the intended way, each individual design should be investigated closely.
In the following chapters, the implementation of step 4 of MDD is described. The previous work from the material research phase is used to develop conceptual products for the portfolio. Considering the information that has already been collected, and according to the concept development methods described by Ulrich and Eppinger (2016) and Koen et al. (2001), this phase includes generating ideas, selecting ideas, and developing them into concepts.

First, workshops are conducted to generate a large amount of ideas for possible applications for the three kinds of graphene textiles; conductive, heatable, and sensors. Then, the suitability of the ideas are evaluated together with the case study company, in order to select 12-15 concepts for further development. Along the following iterative concept development process, 5-8 concepts are selected to be part of the portfolio. These activities are included in the FFE and front end processes by Koen et al. (2001) and Ulrich and Eppinger (2016), but follow a more structured plan than FFE.

6 Idea Generation

In order to achieve RQ1 and come up with novel and/or advanced products with graphene textiles, ideas need to be generated. Wikberg Nilsson et al. (2015), Boeijen et al. (2020), Shestopalov (2019), and Ritter and Mostert (2018) recommend conducting various idea generating activities in a group to accomplish this. It is therefore considered beneficial to gather participants to conduct workshops instead of having the author attempt to generate ideas individually.

6.1 Methods - Idea Generation

The goal of the workshop is to generate as many ideas as possible, since Wikberg Nilsson et al. (2015), Shestopalov (2019), and Ritter and Mostert (2018) mean that when there is a large quantity of ideas, innovative ones are often found. Given that one goal of the thesis is to show the wide range of possibilities for the material, the generated ideas should also aim for a variety of products.

In order to generate ideas from several perspectives, Wikberg Nilsson et al. (2015), Lucid (2021), and Shestopalov (2019) recommend including people with different backgrounds and experiences. Wikberg Nilsson et al. (2015) mean that by having a diverse group, the probability increases for the ideas to become more innovative and original. Since the properties of graphene textiles are fairly unique and not well heard of, it seems interesting and beneficial to include participants with various knowledge of the material.

Due to logistic reasons and for simplicity, the participants are separated into two different workshops based on their knowledge of graphene textiles. The participants with extensive knowledge about the material are employees of the case study company. The other participants are people known to the author, many of them students from Linköping University with little to no knowledge of graphene textiles. Most of them do, however, have extended
knowledge and experience of conducting and participating in creative idea generating activities.

The search for participants without any knowledge of graphene textiles started during the first user study. At the end of each session, the participants were asked if they would be interested to participate in an idea generating workshop, provided that they are available when the day and time is decided. More people than needed were asked to participate, to ensure that there is a sufficient amount. Apart from the first user study, people are asked to participate if they show interest in the project or if they are known to the author as someone with idea generating experience. A few weeks before the workshop is meant to take place, a day and time is decided.

The workshop with Grafren AB (henceforth referred to as workshop1) is conducted first and takes place in person at the company. The other workshop (henceforth referred to as workshop2) is conducted online after workshop1, with the help of the programs Zoom and MIRO, since the participants do not live in the same city. In workshop1 there are three participants; two men and one woman. In workshop2 there are seven participants; six women and one man, who are divided into two groups to prevent the discussions from becoming too time-consuming. If there are too many participants, Lucid (2021) explains that it is common that some people end up dominating the conversation, sometimes accidentally, while others might find it difficult to speak up and share their thoughts. In a large group, it is also more time-consuming to let everyone have a turn, which might slow the pace down and reduce the energy of the group, something that Paulus et al. (2015) warn could reduce the productivity. Lucid (2021) also brings up how longer discussions may lead to someone forgetting a thought, which could mean a loss of ideas.

The thesis author is taking on the role of the facilitator for both workshops. It is highly recommended by Wikberg Nilsson et al. (2015) and Lucid (2021) to have a facilitator to lead the workshop, as explained previously in chapter 2.4. As the facilitator is the one who must be knowledgeable about all activities, rules, and the itinerary, it is appropriate to have the person preparing everything to take on that role. In this case, that is the thesis author. This could, however, mean a loss of the author's ideas, but since those have been collected throughout the project, the focus should be on collecting the ideas of others. The role of the facilitator is also more demanding than that of a participant, which makes it suitable for the author to shoulder that responsibility.

As mentioned previously, it is beneficial to generate ideas in groups as opposed to individually, since the participants could then get inspired by each other (Boeijen et al. 2021; Ritter and Mostert 2018; Paulus et al. 2015). Paulus et al. (2015) suggest alternating between generating ideas individually and in groups. Then, the writers mean that the participants can write down ideas individually without disruptions, and then get inspired by the group discussions. Ritter and Mostert (2018) even argue that it is more beneficial to generate ideas in groups after conducting individual brainstorming, as their research suggest that the ideas tend to get more original when the activities are conducted in that order. Ritter and Mostert (2018) mean that a higher originality means a higher quality of the ideas. The writers also state that it is important to adapt the brainstorming activities to the group and goal, as these results may vary for different activities.
6.1.1 Method - Workshop itinerary

To give the participants an idea of what to expect during the workshop, some information is sent out beforehand, as recommended by Lucid (2021) and Wilson (2020). The groups for workshop1 and 2 receive different information as they have different knowledge and experiences. Both groups are informed of the general agenda of the workshop and what equipment they will need. Since the workshop1 group already possesses the most information about the material, they do not need to prepare anything else. The group for workshop2 also receives a short description of the functions of the material. Wikberg Nilsson et al. (2015) argue that it is important for the groups to receive basic information of the situation to be able to consider somewhat realistic solutions.

Both workshops start with an introduction where the goal, rules, and agenda are presented. For workshop2, the functions and qualities of the material are described, to refresh their memories and in case someone did not have time to read the previously sent information. During the introduction, it is also stated how long the workshop is meant to last and everyone is thanked for participating. The activities are then conducted in a set time schedule. However, it is important to keep the energy of the group high and to have the participants engaged and having fun (Pauleus et al. 2015). Therefore, if an exercise appears to be confusing for the group or takes longer than expected, the facilitator may adjust the schedule. Learnings gathered from the first workshop are also used to improve the second one. In the end of each workshop, the group is gathered for a final discussion where the participants are encouraged to share any ideas they liked or found interesting. See the specified schedule for each workshop in Appendix 3.

The workshops are planned to take no more than two hours, including introduction, activities, breaks, and the final discussion. The activities alone are planned to take approximately one hour. Though, as these sessions often take longer than expected, based on the experience of the author, some extra time is added to the final discussion to prevent the risk of running out of time. Workshop1 is conducted at 13:00-15:00 and workshop2 at 18:00-20:00 on the same day, with the times considering the availability of the participants.

For workshop1, the equipment used are post-it notes in different colours, pens, a timer, and a whiteboard. Because workshop2 takes place online, the program MIRO is used to facilitate the workshop. A board is prepared beforehand by the facilitator to make it easy for the participants to follow and navigate through the different exercises, as well as being fun to promote creativity. To see this MIRO setup, please read Appendix 3.

6.1.2 Method - Workshop activities

Since the goal of the workshops is to get a wide selection of ideas, the strategy is to use several activities to include multiple perspectives (Shestopalov 2019). The activities are the same for both workshops. Since there are both positive and negative aspects to brainstorming individually and in groups, the strategy is to mix the two in the hopes of getting the best results, as well as making it more fun and varied for the participants. The activities are:

1. Value words.
2. Idea drainage.
3. Swap material.

4. Figure storming - version 1.

5. Random connections.

6. Figure storming - version 2.

1. Value words
In the initial exercise, the purpose is to get everyone started and reflecting about the material. This is done by having the participants share associations about graphene textiles. The following example is given to help everyone understand what is asked of them: *Associations about wood could be words like warm, nature, cozy, or sustainable.* During this exercise, the participants are to speak up when they think of an association. If everyone does not speak, the facilitator should assign the word to ensure everyone gets the opportunity. All value words are written down for everyone to see.

It is recommended by Wikberg Nilsson et al. (2015) to use a warm-up activity to get the participants to loosen up a little and get into the creative mindset. When brainstorming with strangers, it may take some time before everyone feels comfortable enough to share their ideas. Therefore, this activity is considered good to start with as it has the participants reflecting about the material as well as breaking the ice.

2. Idea drainage
It is likely that the participants are entering the workshop with some ideas, or have got inspired from the first exercise. In order to keep the group open-minded and focusing on exploring new possibilities, this activity consists of everyone getting all existing ideas out of their heads. According to Wikberg Nilsson et al. (2015), it is easier to think of something new when the existing possibilities have been stated. The strategy for this activity is for all participants to write down ideas individually before presenting their ideas to the group to gather inspiration. This setup is called rapid ideation (Wilson 2020).

3. Swap material
In this activity, the group is meant to choose a product and think of how it can be improved when a material in it is exchanged for a graphene textile. The activity also follows the structure of rapid ideation, where the participants write down ideas individually and then discuss together. The entire group ideate based on the same product. The following list of products are provided as possible options, but the group is free to choose another if they want. The options are: ambulance, curtains, robot, couch, bed, bottle, jacket, flowerpot, car, shoe, stroller, and pants. By providing a list, the choice may be easier and quicker for the group. It is not the product that is important, but the ideas that come from it.

4./6. Figure storming
This is a high tempo exercise, where the group looks at a problem from the perspectives of different people (Wilson 2020). Two versions of this activity are used. In the first version, the group is to answer the question *What would [GROUP] use graphene coated textiles for?* from the perspectives of IKEA, NASA, kids, and hospital. In the second version, the question is *How could we improve the lives of [GROUP] with graphene coated textiles?* and the groups are athletes, seniors, and evil overlord.
By quickly switching between different groups, the participants are likely to come up with some crazy ideas while having fun. It is recommended by IDEO-ORG (n.d.) to use an open formulation such as "How might we..." to frame the question in an innovative and friendly way. The strategy is the same for both versions; the participants are brainstorming together as a group while taking turns writing down all ideas. This method has been done by the thesis author several times. Wilson (2020) writes how this method can help the more shy participants share ideas as they are posing as someone else.

5. Random connections
This activity is based on the description of Ritter and Mostert (2018), where the participants are given a random word. First, they are meant to write down associations to that word together in the group, and then use the associations as inspirations to individually brainstorm new product ideas. After that, there is a group discussion. This activity is conducted for three rounds, with three random words that are decided beforehand by the facilitator; apple, walk, and circus. According to Ritter and Mostert (2018), this method is good for generating lots of original ideas.

6.2 Results - Idea Generation
From workshop1, approximately 150 ideas are generated. From workshop2, the number of ideas are 240. When adding the ideas previously collected by the author and the first user study, there are in total 461 ideas for products with graphene textiles. Note that no ideas are sorted so far, meaning that there probably are duplicates. All ideas can be found in Appendix 4.

The value words generated in the initial exercise are presented below:

<table>
<thead>
<tr>
<th>Workshop1</th>
<th>Workshop2</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-tech</td>
<td>Futuristic</td>
</tr>
<tr>
<td>Black</td>
<td>Hard</td>
</tr>
<tr>
<td>Science</td>
<td>Limitless</td>
</tr>
<tr>
<td>Sustainable</td>
<td>Hi-tech</td>
</tr>
<tr>
<td>Futuristic</td>
<td>Cool</td>
</tr>
<tr>
<td>Expensive</td>
<td>New</td>
</tr>
<tr>
<td>Reliable</td>
<td>Updating</td>
</tr>
<tr>
<td>Magic</td>
<td>Upcycling</td>
</tr>
<tr>
<td>Light</td>
<td>Cold</td>
</tr>
<tr>
<td>Toxic</td>
<td>Innovative</td>
</tr>
<tr>
<td>Thin</td>
<td>Science fiction</td>
</tr>
<tr>
<td>Strong</td>
<td>Flexible</td>
</tr>
<tr>
<td>High performance</td>
<td>Environmentally friendly</td>
</tr>
<tr>
<td></td>
<td>Diverse</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
</tr>
</tbody>
</table>
6.3 Discussion - Idea Generating Workshops

The idea generating phase of the thesis is considered a great success. The ideas from the workshop are many and (before looking into them more closely) seem to have a wide range of products, which will be useful in the next step. When adding the ideas generated or collected by the author throughout the previous steps, it is a satisfying amount.

By having two workshops, two different perspectives are included. When looking back at both workshop discussions and the ideas generated, there is a noticeable difference between the groups. For example, the workshop1 group, containing Grafren AB, had a more business related perspective. When they discussed which product to choose in the swap material exercise, for example, they reflected upon the different markets and which one would be more beneficial to choose. They also considered the limitations and opportunities of the material more, something the other group were unable to do as they did not possess that knowledge. The workshop2 group, on the other hand, seemed to explore possibilities more freely and think from the perspective of what could be interesting or useful to do, as opposed to the business approach, and generated more general ideas.

It was very useful to have a facilitator to lead the exercises, keeping track of the time, and adjusting the schedule when needed. Everyone understood the "no criticism" rule immediately, and there was only a need to assign the word to people in workshop2 during the initial value words exercise, when no one had spoken yet, as well as during the final discussion. This could be because the full group of seven people is quite big for a discussion, and no one felt confident enough to start sharing. By assigning the word it provided everyone with a space where they could talk without the concern of taking up space from someone else or being interrupted. If people also do not know each other, they might not feel that what they have to say is important enough to speak up. That this workshop took place over Zoom could also have a negative effect on the discussions.

6.3.1 Discussion of the participants and groups

It would have been interesting to see which ideas would have come up if the groups had been mixed, as that would have mixed the perspectives of the participants further. Then, they could have inspired each other and the workshop2 group would perhaps understand a bit better what is possible with the material. The workshop1 group, on the other hand, would perhaps have left the business perspective. There are, however, some benefits to keeping the groups divided. The participants in workshop1 all knew each other and had a common goal. In workshop2, most people knew someone in the group and were of a similar age. A majority also had experience with brainstorming. This setup hopefully made everyone comfortable enough to dare to explore new possibilities without fear of judgement, which Wikberg Nilsson et al. (2015) and Amabile (1988) mean is crucial for a successful brainstorming. There is a risk, though, that the company hierarchy in workshop1 would affect the participants, meaning that the employees might not be comfortable to share all ideas with their boss. This risk is, however, considered minimal as the company culture is very friendly and open. The company is also small, as a startup is, with only four employees in total. After working on the thesis at the company for a few months, the culture appeared open and accepting enough that a workshop should be successful.
It was a successful strategy to scout for more workshop participants than needed, since two people cancelled shortly before the workshops due to a collision of other engagements. Originally, the amount of participants was four for workshop1, and eight for workshop2. When asked during the first user study, everyone expressed interest in participating. This raised the belief that graphene textiles is an interesting material, which could mean that the internal motivation of the participants would be increased. As mentioned previously in chapter 2.4 by Amabile (1988) and Wikberg Nilsson et al. (2015), a higher internal motivation often leads to better results in creative work. Of course, as the efforts of the participants are mostly done for the benefit of the thesis author, it is reasonable to assume a fair level of external motivation as well. When comparing the two groups, it is plausible that the company has a higher internal motivation compared to the workshop2 group, since they expect to benefit from the results.

6.3.2 Discussion of the workshop itinerary

Due to the fact that the participants probably have more external motivation for participating than internal, the workshops followed a fairly structured schedule, as recommended by Amabile (1988), Shestopalov (2019), and Lucid (2021). This way, it was easy for the facilitator to prepare and see if something should be altered along the way. For example, if the group needs more time than planned for one activity, another activity needs to be removed or shortened to ensure that the workshop is not longer than planned. A schedule also ensures that breaks are added at appropriate times. As Paulus et al. (2015) suggest, breaks are added to allow the participants to recharge and ensure they do not get too tired. The total time planned for both workshops were two hours, which is longer than the 15-30 minutes that Lucid (2021) recommends. However, from the experience of the thesis author, 30 minutes is not enough time to gather the amount of ideas needed. The recommended length by Lucid (2021) was instead noted and used as the approximate interval for the breaks.

The strategy to include several activities, some with multiple rounds, was partly to maintain a high tempo and keep it fun and interesting for the groups. But also to prevent anyone from getting stuck. Paulus et al. (2015) mean that when people can not think of more ideas, they believe there are no more to be thought of, and therefore stop trying. By quite quickly moving from one exercise to the next, the intention was to force the group to regularly change perspective, which is good to keep them interested, but also to include many perspectives as Wikberg Nilsson et al. (2015) and Shestopalov (2019) recommend. This strategy also means that if one exercise was uninspiring for some participants, they did not have to wait long for the next to start.

The itinerary was constructed in a way to mix the different approaches and keep the energy level high. The first two exercises (value words and idea drainage) were included as warm-ups and icebreakers. Since swap material and random connections, require more time, and perhaps effort, than figure storming, it felt suitable to alternate them. Hopefully, the participants would be excited to get going after idea drainage, which made it appropriate to begin with a more demanding exercise. Swap material was chosen since it followed the pattern of the first two; first the participants reflected upon the material, considered any ideas that popped up, and then got to apply the material in various products. It also seemed beneficial to conclude the idea generating activities with a figure storming, to end
with something quick and fun. At least that was the intention.

As Lucid (2021) mentions, it is important to consider the time when the workshop is conducted, as people might be more alert in the morning than in the evening. However, because people are working or studying, it was not possible to conduct workshop2 in another time than in the evening. To prevent the group from becoming tired and unfocused, the activities were conducted in a fairly high tempo, which Wikberg Nilsson et al. (2015) and Paulus et al. (2015) mean increases the energy. Fortunately, workshop1 could be conducted during the day at the company during work hours, and their energy level was noticeably higher compared with workshop2. This could have to do with the time, or that workshop2 was conducted over Zoom, where it is more difficult to sense the energy of the group.

6.3.3 Discussion of workshop1

Despite having a carefully constructed time schedule, it was altered almost immediately after observing how many ideas the participants produced in the allocated time for the idea drainage exercise. They needed more time to write down ideas individually. However, part of the time plan was to make approximate divisions between the activities, and to adapt it to the situation. Therefore, the change was easy to decide as it was more important to keep the participants engaged than it was to manically follow the plan.

The group seemed to appreciate the exercise swap material, and asked to repeat it for a second product, when the plan had been to only run it once. As their energy was high and the previous one had led to some interesting ideas and discussions, it was an accepted change. The other activities were adapted similarly based on the mood of the group and the time plan. A positive impact this could have lead to is an increasing feeling that this was something the entire group did together, as opposed something they did to help the author, which therefore increased their internal motivation. And, as Amabile (1988) states, it is more suitable for a group with internal motivation to have a less strict workshop structure.

The activity random connections, on the other hand, was not a hit. It was therefore decided not to repeat it for a second round as planned. From the article by Ritter and Mostert (2018), it was said to be very inspiring, but that was not the case for this group. That could, however, be due to the choice of word they had received: apple. Unfortunately, during the preparations, only the fruit associations were considered while the Apple company associations were forgotten. As most of the associations the group made were of the tech and company kind, the words may not have been the easiest to base a brainstorming session on for the group. It was, however, quite beneficial for the time plan. Despite skipping the second round for random connections, there was only enough time for one round of the final activity since a second round of swap material was added.

During the exercises, the facilitator participated partly in the individual idea generation and discussion, while keeping track of the schedule. During the idea drainage exercise, the facilitator simply sat at the table with the participants, keeping an eye on the timer. However, as that felt as if it could be construed as being bored or impatient, the strategy became to participate in the idea generation while keeping track of the time. From the pilot test of the first user study, it was perceived as stressful to have the facilitator constantly standing and watching the participant. Therefore, it was considered more natural and inspiring to have the facilitator participate in the workshop.
The ideas from the facilitator could possibly have affected the participants. A positive aspect is that this group got a little more mixed, as someone with a different perspective joined. A negative possibility of having the facilitator joining, could be that the participants got the idea that "correct" answers existed, and thus did not brainstorm as freely. However, this was considered during the session, and did not seem to be the case. The participants came up with a large variety of ideas and seemed focused on their goal.

Afterwards, the company gave great feedback and said that they had a good time and thought that the workshop had been useful. They also made certain to receive all ideas generated (which they got after everything was documented digitally). This is excellent feedback, both regarding the quality of ideas, but also considering the planning and execution of the workshop itself.

6.3.4 Discussion of workshop2

For workshop2, it worked very well to use the program MIRO. It was easy to prepare and since a majority of the participants had used the program before, it appeared to be easy for them to navigate and conduct the exercises. There were, however, some problems for the facilitator to use the breakout-room feature in Zoom. It did not work as expected to send messages to both groups simultaneously, as one group remained in the main room. It was also a bit difficult to keep the two groups to the same schedule. As one group contained four people and the other three people, the discussions naturally took longer for the first one, meaning that the group with three people started with the next exercise before the others had finished their group discussion. This led to some longer individual brainstorming for the smaller group, and one missed discussion for the larger group. The facilitator jumped between the two groups and tried to take time to listen to both, but it was difficult to divide the time evenly. It was easier to let the groups know to go from brainstorming to discussion in person than by message. Before each new activity, however, all participants were called back to the main room to hear the instructions to make sure they were the same for both groups.

One change made after workshop1 was that, for workshop2, the groups got to brainstorm twice for the same subject when having individual brainstorming. For workshop1, the group moved on to another activity or word/product/group after only one individual session and discussion. Though, when reflecting after workshop1, it might be more useful to have two rounds for the same subject, as then the chance of being inspired by the discussion increases. If the activity or subject changes, then the inspiration may be lost. Since swap material was very popular in workshop1, a second round was added in workshop2 as well. Preparations were also made for a third round, but it was dependent on the time and was therefore not conducted.

It may not have been the best strategy to schedule workshop2 in the evening as some participants appeared tired, like Lucid (2021) anticipated. Though, that choice was necessary as otherwise not everyone would have been able to participate.

For the exercise random connections, these groups appeared to get more inspired than those in workshop1. This was done for two rounds with the words walk and circus. However, even though the groups brainstormed associations before brainstorming products, some appeared to forget the associations when moving on to the products. Only a few seemed to generate
product ideas based on the associations. This was not pointed out during the exercise to prevent anyone feeling they did something wrong, but should be noted for future work to prevent misunderstandings. Either way, some interesting and fun ideas were generated.

6.4 Conclusions - Idea Generation

To generate a large amount of ideas, it is beneficial to include several groups of people with different perspectives. The activities and workshop setup used in this thesis were good starting points, though during a workshop, the schedule should be ready to be adapted to keep the participants engaged and interested. Of the 390 ideas generated during the workshops, making it 461 ideas in total, it is extremely likely that 5-8 are good enough to develop conceptual products deemed worthy for the portfolio and to achieve the goals of the thesis.
7 Evaluation of Ideas

When a substantial amount of ideas has been generated, Wikberg Nilsson et al. (2015), Ulrich and Eppinger (2016), and Koen et al. (2001) suggest selecting several ideas for parallel development, and successively remove some along the way, instead of choosing only one or a few from the start. Wikberg Nilsson et al. (2015), Ulrich and Eppinger (2016), Koen et al. (2001), and Ullman (2002) mean that by selecting the final idea too quickly, before sufficient information is collected, it is possible to miss out on the potential of others. By working simultaneously on several ideas, it is easier to compare them and make a more informed choice (Wikberg Nilsson et al. 2015; Koen et al. 2001; Ulrich and Eppinger 2016). Therefore, out of all the 461 ideas generated throughout the project, 12-15 are selected for further development. To achieve this, all ideas need to be evaluated.

7.1 Methods - Evaluation of Ideas

First, all ideas are gathered in the same place, the program MIRO. Each idea is written on one post-it note for simplicity and clarity. All ideas are then read through by the thesis author and organised in different groups according to the affinity diagram method (Friis Dam and Yu Siang 2020). As one thesis goal is to include products from different markets in the portfolio, that is the basis of the groupings here. Though, this is highly subjective as some ideas might fit into multiple markets.

Ideas that are not relevant for this thesis are discarded at this stage, but saved nonetheless to not lose anything. Such discarded ideas are, for example, non-textiles, ideas that are too general, or where neither of the three graphene textile types are able to accomplish the function. For the ideas in the final category, only those that with certainty cannot accomplish the intended function are discarded, the rest remain included until further notice.

After all ideas are grouped, any duplicates are removed. To still keep track of which ideas are mentioned several times, the remaining post-it note receives a different colour. Headlines are also made to further structure the diagram. All ideas then get tagged by which of the textiles would be included in the product; conductive, heatable, or sensors. This is to keep track of them and ensure that the selected ideas for the portfolio include at least one of each textile type.

In the next step, there is a need to narrow the selection. To do this, the author reads through all ideas and mark those of personal interest, while attempting to include ideas from each category. Next, these ideas are placed in an innovative/easy to implement graph for the method c-box, as described by Boeijen et al. (2020). The placement for each idea is estimated compared to the rest, meaning that they are not compared with an outer parameter (Boeijen et al. 2020). This is done to get an idea of how the ideas compare and to see which ones would be most innovative and easy to implement.

After the ideas are evaluated in the c-box graph, the ideas are looked over again to see which can be combined into a single product, or if any are better standing alone. This is to create ideas for full products, as opposed to parts of a product. Then, the thesis author and the company are to vote on the ideas in order to pick out 12-15 for further development. As the portfolio is meant to benefit the case study company after the project, it is reasonable...
that they have a say in which ideas are included. Though, they are reminded of considering which ideas would benefit from a visual display, and which would be helpful to visualise the characteristics of the graphene textiles to demonstrate the possibilities of the material. Each idea is described by the author while written down on a whiteboard. The company can then ask questions or discuss their options before voting. At the end, five people with 15 votes each places their votes on the ideas they prefer. The votes are distributed as one vote per idea.

7.2 Results - The Ideas Chosen for Further Development

The 461 ideas are evaluated. After removing the duplicates and non-relevant ideas, there are 204 ideas left. These are divided into 14 categories which, along with all ideas, the c-box graph, and the 45 ideas can be found in Appendix 4. After the voting, the following 14 ideas are chosen for further development. According to Grafren AB, all ideas appear possible to create.

Idea 1. Textile keyboard
Fabric with pressure sensors that works as a keyboard.

Idea 2. Sign language translation gloves
Gloves with pressure and strain sensors along the fingers and wrists that can identify the movements of sign language. When connected to a program, sign language can then be translated in real time to facilitate communication.

Idea 3. Smart home couch
A couch with sensors to control smart home technology.

Idea 4. Portable camping kitchen
Heatable fabric used for cooking when camping.

Idea 5. Stroller
A stroller with a few additional features for extra safety and comfort. There are pressure sensors on the handles to take notice when someone touches them. Without a touch, an automatic brake is activated for increased safety. When the handles are touched in cold weather, they are heated. The mattress inside the stroller can also be heated, and sensors can track the baby’s activity and, for example, tell if the baby is asleep or have been forgotten somewhere.

Idea 6. Luminous workout clothes
Workout clothes that can light up dynamically in different ways and patterns. Perhaps for extra safety for outdoor runs after dark, or something that matches the beat of the music the wearer is listening to.

Idea 7. Rehabilitation gloves
Gloves with pressure and strain sensors along the fingers and wrists, used to measure the recovery of, e.g. stroke patients.

Idea 8. Damage detection fabric
Fabric with sensors in them that can notify when the fabric is about to break.
Idea 9. Mosquito shocking clothes
Outdoor clothes with a small current going through them when activated. With that, if a mosquito sits down on the garment, it is electrocuted.

Idea 10. Exoskeleton clothes
Sensors in clothes that feel when the wearer begins to move, which activates an exoskeleton to help complete the motion. Meant for people with reduced strength.

Idea 11. Sensors in shop carpets
In large stores, pressure sensors in the carpets can track how many customers are in the store and where they are. With this information it is easier for the management to dispatch staff to the right places for a satisfying customer service, and collecting data on customer behaviour. In emergencies, it is easy to check that everyone is out of harms way, and if optic fibres are incorporated, a path to the nearest exit can be lit up to help people quickly find their way out.

Idea 12. VR-gloves
Gloves with pressure and strain sensors along the fingers and wrists, used for easy control of applications for virtual reality.

Idea 13. Bike
A bike with pressure sensors in the handles and the seat. With this, data can be collected about the posture of the biker to help them prevent injuries. When it is cold outside, the seat and handles can also be heated when touched for increased comfort.

Idea 14. Luminous message clothes
Clothes that can display messages. Possible uses could be if someone is lost, e.g. a child or a confused elderly. If needed, the guardian could send a message to be displayed on the lost person’s shirt saying they are lost and if seen to call a certain number.

7.3 Discussion - Evaluation Process
The chosen selection all seem like good ideas, and together they cover a wide range of markets, situations, and products. Some are more applicable to businesses and proper professions, while some are just meant to be used for fun. It seems like a good mix so far, where everyone can find something of interest.

The use of the affinity diagram method was most helpful, as groupings of the many ideas were very necessary if any evaluation could be conducted. It was difficult at times to know where to place each idea, and some were moved later on. The naming of each category was decided after the grouping, as suggested by Friis Dam and Yu Siang (2020), and were meant to help the author get an overview of everything. To mark the ideas that had duplicates served as a reminder of what many people thought of. As the portfolio is meant to be inspiring and help people see new opportunities, it might be more beneficial to discard the ones that many considered, and focus on the unusual ones that will make people look twice in curiosity. It also felt very useful to mark which textile type would be needed for each idea. As all three are included in the investigations of the thesis, it is important that all three are included in the portfolio. It is also interesting to see which textile type has most suggestions among the participants, i.e. which ones did the participants think of most applications for.
For the first selection of ideas, it is a highly subjective method to have the thesis author alone go over all of them and choose solely based on personal interest. According to Ulrich and Eppinger (2016) and Koen et al. (2001), this selection should be made based on previous research about customer needs, business strategies, markets, etc. However, since the goal in this case is to make an inspirational portfolio containing conceptual products, this information is not possible to collect. It becomes relevant later, when a product is meant to be fully developed. Therefore, another selection process was needed. Grafren AB could not go over all 204 ideas, it was almost too much to have them vote on 45 ideas. Since the thesis author is the one to develop the ideas, this strategy seemed like a suitable choice for making the first selection. Great care was placed on selecting ideas of a good variety and in multiple categories.

The use of the graph was not very helpful. It might have been interesting to estimate how easily the different ideas could become a reality, but it was not used afterwards. As it was only an estimation, and because all ideas had some level of innovation, it was not considered helpful during the vote. The company themselves estimated what could be possible, and since they have more knowledge about the material, their word weighed more heavily than the estimation of the author. Something noteworthy though, is that the chosen ideas vary in their innovative degree as well as how easy they would be to create. It is considered beneficial to have such a mix, as the products in the portfolio are meant to vary in multiple ways in order to appeal to many different companies and people.

Before the vote, the participants (employees of Grafren AB) expressed their thoughts freely while discussing possible applications for the ideas, as well as what markets could be relevant to look into. It is possible that they may have affected each other, in particular as the vote was not anonymous. Though, this risk is considered minimal as, based on the perception of the author, the company climate appear to be open and, as everyone have different areas of expertise, everyone is encouraged to share their point of view with the rest. They also appeared to consider the visual presentation aspect, i.e. which ideas would be suitable to present in a visual portfolio to show the width of possibilities of the material. Not everyone used up all of their 15 votes, but stopped when they felt that the ones they liked were included.

When making the final selection for this step, 12-15 ideas seemed like a suitable number considering that the portfolio is meant to contain 5-8 conceptual products. As Wikberg Nilsson et al. (2015), Koen et al. (2001), Ulrich and Eppinger (2016), and Ullman (2002) suggest, it is better to reduce the amount along the development phase as it is not possible to make an informed choice at the earlier stages.

### 7.4 Conclusions - Evaluation of Ideas

In conclusion, these evaluation methods are highly subjective. But considering the goals of the portfolio and the enormous amount of ideas to choose from, it is acceptable for this thesis. The 14 ideas that are meant to be developed appear to be a solid mix considering products, markets, users, level of innovation, and how easy they would be to create.
8 Concept Development

During this iterative development process, the 14 concepts are simultaneously developed to the extent that products can be visualised and presented in the portfolio. Some concepts are discarded along the way, as the goal is for the portfolio to contain 5-8 conceptual products. In this chapter, the methods used for the concept development are explained, followed by the results, i.e. the final concepts included in the portfolio. After that, the visualisation process is discussed along with the concepts.

8.1 Methods for Concept Development

This step in the thesis follows the FFE process by Koen et al. (2001), combined with the front-end process by Ulrich and Eppinger (2016), which are described previously in chapter 2.2. For these methods, several activities are conducted in parallel and in iterations to develop concepts. First, research is conducted to understand more about similar products and the current situation on the market. This is recommended by Koen et al. (2001) and Ulrich and Eppinger (2016), and is helpful in order to understand the customer needs, something Wikberg Nilsson et al. (2015) recommend doing when developing products. To start the visualisation process, sketching is conducted, as suggested by Ulrich and Eppinger (2016) and Boeijen et al. (2020). It is also considered how each concept should be presented in the portfolio, and what functions should be displayed. This is all done while considering the existing skills of the author and case study company. Prototypes are then made, as recommended by Ulrich and Eppinger (2016) and Wikberg Nilsson et al. (2015), both physical and digital ones. Along this process, people of different skills are consulted for feedback.

The activities may vary for each concept. Because the products are very different, the suitability of each activity is estimated to not waste time. All activities are, however, conducted quite shallowly. Due to the limited time and large amount of concepts, it is not possible to conduct a thorough development process for each one. The goal is to only develop the concepts to the extent suggested by Ulrich and Eppinger (2016), i.e. to include a description of the form, function, and main features. The portfolio is meant to be inspiring and visualise the wide range of possibilities of the material, not to present fully functional products with detailed designs. The intended message is "Look how amazing this is!" instead of "This is how it works".

8.2 Results - The Final Concepts

This section presents the seven final concepts that are included in the portfolio. These concepts are meant to display the wide possibilities of the graphene textiles from Grafren AB; conductive textiles, heatable textiles, and textile sensors. To see the visual process of the concepts, please read Appendix 5.

After discussing with the company, as well as considering the selected mediums for the concepts, it is decided that the portfolio should be displayed as a website, which can be found [at this link] or as printed versions in Appendix 6.
8.2.1 Concept 1. Textile camping cooker

With this thin and light piece of heatable fabric, cooking when camping becomes a lot easier. Only a single layer of heatable graphene fabric is needed, along with a power source (in this case, batteries), and an insulating bottom layer to protect the ground. See a prototype in Figure 43 where, to the left, the textile is cooking a cup of pasta on top of an insulating layer. As seen to the right in the figure, the cooker is very compact when packed, as the textile can be tightly wrapped around the battery box. The textile is also ultra light (only 7 grams), meaning that the only noticeable weight comes from the batteries. This makes it optimal for camping trips when space and weight are critical factors.

Figure 43: To the left: a photo of a prototype of the heatable graphene textile in nature, cooking a cup of pasta. The textile is powered by batteries (see the black box) and sits on top of an insulating layer to protect the ground from the heat. To the right: the textile is wrapped around the battery box and held to demonstrate the small size. Photos by Louise Josefsson (2021).

Given the incredible technology of graphene textiles, the fabric can reach the desired temperature in approximately ten seconds, and maintain that temperature until switched off. Then, because the textile does not store thermal energy, it is immediately cooled down, meaning that it can quickly be packed away. See a prototype of the textile through a heat camera when the power is off (left) and on (right) in Figure 44.

Figure 44: Thermal images of a heatable textile prototype, where the power is deactivated (left) and activated (right). Image credit to Grafen AB (2021).
8.2.2 Concept 2. Damage detection fabric

For people working in dangerous conditions, their protective uniform can provide additional assistance by sensing if it is damaged. The graphene textile can notice any damaged due to an ability to detect a change in resistance. If the protective uniform is damaged, it is possible that the wearer has sustained injuries as well. Only one thin layer of fabric is needed, and could be a suitable middle layer of the uniform. Possible uses could be for firefighters, military, and deepwater divers.

In Figure 45 below, an example is visualised of a firefighter who has received a small cut in his leg without noticing. See an enlargement of the cut in the top right image in the figure, and an example of a damaged graphene fabric where two parallel conductive threads keep track of any change in resistance between them, in the bottom right image.

Despite the firefighter not noticing, the damage is fortunately detected by the fabric, and a notification is sent to the team leader. This person can then see where the uniform is damaged and therefore where the firefighter might be injured (see the application in Figure 46). Depending on the situation, the leader can then make a more informed decision of a
suitable course of action.

Figure 46: Illustrations of how the application could look. To the left, a view of where the uniform is damaged. To the right, an overview of the team and the notification that something is wrong with the team member Charlie.

8.2.3 Concept 3. Textile keyboard

This keyboard is made of pressure sensitive graphene fabric. The fabric is an array of pressure sensors, where each sensor corresponds to a key. Only a single layer of fabric is needed, along with conductive threads to create the sensors. This keyboard is soft, lightweight, comfortable to use, and easy to transport. See a visual and technical prototype in Figure 47 and 48 respectively.

Figure 47: A visual prototype of a textile keyboard, where the frames of the keys are marked with white thread. Photo by Louise Josefsson (2021).
Figure 48: Graphene pressure sensitive fabric, provided by Grafren AB. The conductive threads visible in the image are what makes the pressure sensors possible. Each pair corresponds to one key. Photo by Louise Josefsson (2021).

8.2.4 Concept 4. Smart stroller

A stroller that does not look any different from regular ones, but that contains a few additional features for extra safety and comfort. The handles can sense when someone is holding them, due to graphene textile pressure sensors. This technology entails for an automatic brake to be activated when the handles are released. With the addition of heatable graphene fabric, the handles can also get warm when held during cold weather.

Inside the stroller, the mattress contains heatable graphene fabric and graphene textile pressure sensors. The heatable fabric keeps the baby cosy and warm during cold days. The sensors measure the baby’s activity, so that the guardian can, e.g., be notified when the baby is sleeping or awakening, or simply check the baby’s motion patterns. This could for example be checked in a mobile application.

8.2.5 Concept 5. Anti-mosquito jacket

Clothes that can prevent mosquito bites through electric shocks. When an insect gets in contact with the jacket, it is electrocuted by a small current. The current does not need to be strong enough to kill the insect, it could be sufficient to make it uncomfortable enough to fly away. The jacket would also be harmless for people to touch (but not lick the active surface). The exterior layer can be electrically activated, while remaining lightweight, breathable, and flexible thanks to the unique qualities of graphene textiles. See an illustration of the deactivated jacket in Figure 49. For a clear visual feedback, a pattern lights up upon activation, as seen in Figure 50. Figure 51 and 52 contain illustrations of a mosquito getting in contact with the jacket.
8.2.6 Concept 6. Smart carpet

In buildings where lots of people stay or visit, graphene textile pressure sensors in carpets could offer great assistance. Examples include schools, nursing homes, shopping centres, and hotels. Firstly, the carpet could provide live information of how many people are inside, as well as where they are and how they are moving. See an illustration of this in Figure 53. This can be used for multiple purposes. E.g., in stores or shopping centres, the sensors can collect valuable information about customer activity and help management dispatch staff for improved customer service. Thanks to the properties of graphene textile pressure sensors, only one layer of fabric and a power source are needed.

In emergencies, these sensors can notify when everyone is out of harms way, or if someone needs help and where. With the addition of optical sensors in the carpet, dynamic pathways could light up to guide everyone to the nearest exit, no matter where they are. See two examples of this in Figure 54 and 55.
8.2.7 Concept 7. Sign language interpreter

These gloves contain graphene strain sensors along the fingers and wrists, and are therefore able to identify the movements of sign language. This could open up for new ways of communication. The gloves only need one layer of graphene fabric and conductive threads for the sensors, and do therefore not feel any different to use compared to conventional gloves, and could come in different designs. A small battery is also needed, which could be hidden in the cuffs of the gloves. See a prototype in Figure 56. The gloves are activated by pressing the ring fingers against each other for three seconds, which is possible with graphene pressure sensors on the fingertips. As seen on the prototype to the far-right in Figure 56, the tips of the ring fingers are visually marked to make the design user friendly.

When activated, any sign language could be translated in real time to facilitate communication across mediums. This could be done in different ways; one option is to have a speaker incorporated into the cuffs of the gloves, another is to have text translations on a connected application. See illustrations of such an application in Figure 57. The program should be able to translate various sign languages into various speaking languages.
Figure 56: A prototype of the glove, with the decorative threads illustrating approximately where the strain sensors are located. The far-right photo shows where the pressure sensor is located for the activation feature. Photos by Louise Josefsson (2021).

Figure 57: Illustration of how the application can look. To the left, languages are selected. To the right is the layout before the translation begins.

8.3 Discussion - Concept Development

The use of FFE by Koen et al. (2001) and the front-end process by Ulrich and Eppinger (2016) benefitted this step of the thesis. Since the concepts are quite different, it was
helpful to follow an unstructured method where each activity had to be carefully considered for each product. The definition of a concept by Ulrich and Eppinger (2016) was also helpful in knowing how much everything should be developed. Although, the visualisation process helped with that as well. When working on how to explain each product, questions about the design arose that had to be answered. Because of that, the concepts were developed to the extent that they could be explained and presented well, which corresponded with the concept definition by Ulrich and Eppinger (2016).

Despite the different natures of the concepts, the first two activities in the development process were the same; sketching and research. First, all current ideas were written down or drawn in order to get them out of mind, as Wikberg Nilsson et al. (2015) suggest to get room for new possibilities. A small internet search was also conducted, both to see if there are any current products on the market, and to learn more about the specific area. This provided the knowledge needed for the development.

It was challenging to decide which mediums would be most fitting to present the different concepts in. Physical prototypes have the benefit of being able to be touched and examined in person, which might make the product easier to understand. In the example of the smart carpet, on the other hand, a physical prototype (i.e. a carpet) would not explain the function at all. For that, additional information is required, such as text, film, or storyboards. This is part of the challenge of presenting conceptual products with an invisible material, since the results from the material research phase suggest that the graphene coating itself is not what should be emphasised, but the possibilities and opportunities that it enables.

Many details are left out of the designs. This is both due to the limited time and large amount of concepts, but also due to the intention of the portfolio. Since it is only meant to inspire, details like the shape of buttons, specific colours, etc., are irrelevant. It might even be a disadvantage to specify such details. If the products remain conceptual, potential clients can take the idea, fill in the blanks, and make the product their own. If the concept is too detailed, it might be more difficult to adapt.

Because the products were to remain conceptual, it was quite difficult to incorporate the previously established design guidelines. Since those guidelines are focusing on the physical appearance and aesthetics of the product, it is not very relevant at this stage. For the concepts where physical prototypes were made, the three lead words futuristic, manufactured, and safe were considered. However, in first hand, the communication of the functions are prioritised, to ensure that the receiver understands the concept. At a later stage, the specific designs can be developed. The safety and comfort aspects were considered more than the rest, though, in particular for concepts where it is apparent that electricity is in close contact with the wearer. For example, for the anti-mosquito jacket, the visual feedback was considered to ensure that everyone in the surroundings is aware when it is activated for an increased feeling of safety.

8.3.1 Discussion of concept 1. Textile camping cooker

As mentioned previously in chapter it is important that the heatable textile is not stretchy. If it stretches during use, the resistance would vary across the surface, and the textile would therefore not be heated evenly. However, as the product is only meant to be lying on the ground during use, this should not be a problem. The fabric does not have to be comfortable
either, since it is not a wearable technology.

Buttons, or perhaps graphene pressure sensors, could be used to regulate the power. There should also be a visual feedback for when the power is on to avoid any misunderstandings and improve the user experience. Otherwise, the user might think that the textile is cooling down when it is set to a low temperature, which would waste energy. Graphene pressure sensors would be nice to include, though it might not be optimal for the intended environment of this product. Proper buttons might be more useful in the case of rain, for example. However, it would also depend on if the product is able to be used during rain. It is not optimal to prepare food in rain either way. Then again, this product might have an advantage as it could possibly be used inside the tent, or at least underneath a rain cover.

Something else to consider is the power usage. In this thesis, it is not investigated how much power is needed to cook something. The textile should also be tested properly to ensure that it can handle the heat, as well as any weather conditions it might get in contact with on a camping trip.

8.3.2 Discussion of concept 2. Damage detection fabric

The added value for this concept is security for situations where it is crucial to know immediately if someone could be hurt, but where the wearer might not have the time to constantly check for small wounds. It is not certain that the wearer needs help every time the fabric is damaged, but it provides more information to the person responsible, meaning that they are in a better place to make informed decisions. This fabric would probably be most suited for being a middle layer of a protective uniform. That way, it is not the first one damaged, nor does it have to be comfortable to have in direct contact with the skin. Though, depending on the situation, the protective outer layer could possibly receive the graphene coating and become the detecting layer as well.

8.3.3 Discussion of concept 3. Textile keyboard

There are many opportunities for this keyboard, since the main material is a textile. For example, it could be divided into two pieces, one for each hand, or even be located on various garments, e.g. on the sleeve of a jacket. However, to explain the concept in the portfolio and to make it easy to understand and recognise, it was decided to make the layout and design of the prototype similar to the already established keyboard. Though, it is exciting to think of the many variants and designs that could come of this rather simple concept.

Several fabrics were tested when prototyping, and it became obvious that it can not be very stretchy, as that made it difficult to sew and draw straight lines. See attempts for this in Appendix 5. As an additional feature, optical fibres could be incorporated to have the keys or lines become visible only when the keyboard is activated. This could create a clear feedback for a user friendly experience.

8.3.4 Discussion of concept 4. Smart Stroller

Given as this concept only includes additional features without any additional physical components, no visualisation would be very beneficial. It is an example of how graphene
textiles act as a hidden technology to facilitate everyday life and make it more comfortable. For the portfolio, however, an image of a regular stroller is used for the aesthetics and visual communication, which can be seen in Appendix 6.

8.3.5 Discussion of concept 5. Anti-mosquito jacket

The most important aspect to consider with this kind of product is the perceived safety, assuming that it is safe to use. To have it appear safe, the feedback is crucial. As several participants from the first user study felt uncomfortable to the thought of having a harmless active current in their clothes, this product would probably cause some unease. Even if the current is harmless to people, it is a product that is made to actively harm creatures. Therefore, it should be abundantly clear to the wearer and people around them how the jacket works and when it is activated. Since an active current is part of the product, it seems suitable to have the feedback be with light, as light indicates the use of electricity. This feedback should remain visible for as long as the jacket is activated, to ensure that no one forgets that it is activated.

8.3.6 Discussion of concept 6. Smart carpet

With this product, an enormous amount of information could be collected. As discussed in the benchmarking study in chapter 3.2.3, there are AIs that can deduct a person’s activity from body temperature. To therefore have sensors in a carpet opens up the possibility of collecting information about where people are, their movement patterns, if someone has fallen down, or dropped something. It might even be able to keep track of specific individuals.

It is difficult to state the possibilities and limitations of such a system at this stage. One aspect, though, that should be considered for such a product is the storage and usage of this collected information. Should everyone visiting such a building be made aware of the information being collected? What if someone is uncomfortable with it? And what should the responsibilities be of the organisation? How much should they be able to interpret and calculate from this information, and for what usage?

Apart from these concerns, in emergencies, this product could be extremely useful. No more headcounts outside when everyone is distraught, simply check the program to see if anyone is inside and where. It would facilitate the job for the emergency staff as well to know where they are needed. For visitors, with the assumption that very few people take the time to keep track of the emergency exits at all times, it would be very helpful, and could possibly reduce panic, to receive a personalised path outside in case of an emergency. Depending on the emergency, this path might even be able to lead people out while avoiding any critical areas.

8.3.7 Discussion of concept 7. Sign language interpreter

This concept brings out the unique properties of the graphene textile sensors. No other material can be used for such thin and comfortable gloves while collecting the necessary information for the service to work. The fact that the graphene coating is invisible is also an advantage, as it allows for many designs to be made to suit different occasions.
The design in the prototypes is developed to highlight the functions of the gloves, and therefore improve the user experience. Had the gloves been all black (which they could be), it might be difficult for the user to remember, for example, how to activate them. Or even differentiate them from regular gloves.

8.3.8 Discussion of the discarded concepts

During the initial sketching and research in the visualisation process, it became apparent that some concepts should be discarded due to being too similar, or too complicated.

There were three concepts based on gloves with pressure and strain sensors; the rehabilitation glove, VR-glove, and (the chosen) sign language interpreter. Since the portfolio is meant to present a width of possibilities, it might be a disadvantage to have a few products being very similar. Then, they might be compared to each other and draw focus from the overall collection of the portfolio. Therefore, it was decided to only include one concept with sensors in gloves. In the beginning, the rehabilitation glove was the one selected, as a way to include the healthcare industry. However, after discussing the concept with a nurse, it was mentioned that it is not ideal to use fabric in the healthcare industry, due to the high cleanliness regulations. The glove could perhaps be used by individuals, but not as measuring equipment at a hospital as intended. Therefore, the sign language interpreter was chosen to include how graphene textiles could improve ways of communication. The VR-glove was not chosen as it does not seem as special as the other two.

The bike and smart stroller concepts include similar features of sensors and heaters in existing products. Therefore, it felt beneficial to include only one of the two in the portfolio. The stroller was chosen to include the market of baby products. Since a lot of the products from the previously made benchmarking study included sports products, it seemed suitable to include some less explored markets in this project.

To include garments with dynamic lights seemed very new and different, something that could attract the large consumer market. With the rising trend of sustainable fashion, it seemed beneficial to include clothes that can change and be adapted for multiple occasions. Unfortunately, the ways of creating luminous fabric, as seen in (3) and (4) in the benchmarking study, do not seem to be possible to make with the textiles from Grafren AB. Since this thesis is limited to only focus on these types of graphene textiles, the dynamic lights concepts are for someone else to explore at a later time.

When looking into current exoskeleton products, it became apparent that the current knowledge of the author is not sufficient for attempting to develop something similar. It would have been interesting to see how such products could, perhaps, have become lighter and smaller if conductive fabric is incorporated. However, no further research was conducted in that area, as it would have taken too much time away from the other concepts.
9 Discussion

In this chapter, the results, main methods, sources, and ethical considerations are discussed.

9.1 Discussion of the Results

The seven concepts in the portfolio include the following markets; outdoor activity, safety, leisure, child care, and communication. The concepts highlight different opportunities of graphene textiles, and how the unique properties can be utilised and visualised. For example, the textile sensors are shown to be thin enough to function inside gloves while remaining invisible and comfortable. The conductive textile is shown to have diverse applications in the anti-mosquito jacket concept. It is also presented that this material do not only have to be used in completely new products, like the textile camping cooker, but could facilitate the incorporation of additional features in existing products, like the smart stroller and smart carpet. With this, the portfolio seems to contain a variety of application areas. All graphene textile types are included, and according to Grafren AB, all products should be possible to create. Therefore, the product goal of the thesis, to visualise the potential of the material through a portfolio containing 5-8 conceptual products, is achieved.

9.2 Discussion of the Method MDD

Since graphene is a two-dimensional material, and therefore has no distinguishable sensorial qualities, it becomes quite a challenge to use MDD, a method where the physical qualities are in focus. As the graphene coating can be applied to many textiles, these characteristics will vary solely depending on the textile. This was confirmed in the first user study, where the results seen in Figure 12, 13, 14, and 15 show that the sensorial qualities differ for all samples.

In this thesis, the activities of MDD have not been used precisely as described by Karana, Barati, et al. (2015), for several reasons. In step 1, minimal testing and experimentation was conducted, due to the thesis author’s limited previous knowledge about the material. In step 3, the activity to establish design guidelines was completely revised, as it would have been very time-consuming to gather enough results for them to become useful. Since the portfolio only contains conceptual products, and this step focuses on the physical appearance of products, the effort did not seem worth the gain. In addition to these two major alterations, some minor adaptations were made for various activities.

Karana, Barati, et al. (2015) state that it is possible to go directly from step 1 to step 4 in MDD, but that it is more beneficial to also conduct step 2 and 3, as those would allow the designer to reflect more deeply about the material. This statement goes in line with the results of this project. In step 2 and 3, little information was new, as practically all reflections and conclusions were based on the results of step 1. The questions provided in step 2 were very helpful when formulating a vision for the material. Even if some questions appeared to focus on the physical properties, they could be answered in a way to suit this project as well. Like Karana, Barati, et al. (2015) explain, this step is highly subjective and require a certain level of creativity from the designer. There is no right or wrong way to perform this activity, it is only a tool to help the designer create the vision. Therefore, the
questions can be used for a two-dimensional material if the designer decides it is possible.

In hindsight, it would probably have been beneficial to spend more time on step 1 to experiment with the material and thus learn more about it. Less time could have been spent on step 3, since that step had minimal influence on this particular project. Because the physical characteristics of graphene textiles will vary depending on the fabric, it is very difficult to create guidelines for every possible product. Also, since the material is meant to be used in different products for different companies, it is more probable that each company will have their own design guidelines to support their own vision. Therefore, in the future, it would probably be more useful to conduct this step later on in the project when the goals are more specific, for example if the product is decided. With a more clearly defined goal, it is easier to define guidelines for how to get there.

An argument against MDD as an academic method, is that there are several steps relying on subjective judgements. Step 2 for example, is entirely based on reflections, which will be different for each designer. On the other hand, design is highly subjective in itself, which make the results more difficult to replicate. Since MDD is also very influenced by the opinions and impressions of the users, i.e. other people, those results might vary as well in different studies. Given that different people have various experiences and backgrounds, they will most likely have different opinions and interpretations.

As mentioned previously, Karana, Barati, et al. (2015) do not explain each activity of MDD thoroughly, meaning that complementary methods are needed. For some activities, the writers refer to specific methods, most of which have writers including at least one author of MDD. It therefore seemed appropriate to follow these recommendations. Most of the activities have been very helpful in complementing the main method. Though, like MDD, it is clear that these methods and tools are directed toward materials with more distinguishable sensorial qualities.

The step in MDD containing the least amount of instructions is step 4. Basically, all Karana, Barati, et al. (2015) write for this step is to develop concepts based on the previously gathered information. On one hand, some guidelines on how to apply the previous learnings could have been helpful. On the other hand, a lot of research on how to conduct product development projects have already been made. Therefore, it could be assumed that Karana, Barati, et al. (2015) direct their article to designers who already possess that knowledge and know how to apply it. What is special about MDD are the first three steps, as those exclusively focus on the material. Therefore, it is not surprising that Karana, Barati, et al. (2015) put their focus on the steps which make their method unique, instead of repeating existing research. Though, it would have been interesting to know if the writers had a particular concept development method in mind when developing MDD.

According to Ulrich and Eppinger (2016), the main steps of a product development process are the same for most methods, even if the details may differ depending on the goal and starting point. Therefore, it might not make a big difference which development method is chosen for step 4 of MDD. In this project, it was helpful to follow the steps and strategies by Ulrich and Eppinger (2016) and Koen et al. (2001) to develop concepts simultaneously. It then became quite natural that some concepts were discarded as the process went on, and it successively became clear that some were not suited for this portfolio. This is also in accordance with the theory of Ullman (2002), that one often does not possess enough knowledge to make big decisions in the beginning of a development project.
9.3 Source Reflection

MDD is an appropriate method to choose when developing products with a new material. The steps seem logical, and are motivated quite well by Karana, Barati, et al. (2015). However, it is a fairly new method that has not been widely tested for various materials and situations by different people. Therefore, there are very few sources to base the work on, thus indicating that each step should be reflected upon closely before implementing it to ensure that it is a suitable step for the current project. This is not optimal, but deemed acceptable. Also, since RQ2 is about investigating MDD, it would not be possible to use a different method.

The information about the graphene textiles is also largely from the same source. Some general information about graphene was collected from published articles, but the information regarding the three textile types are solely from the case study company. Given that Grafren AB are the ones who developed the material, it is practically impossible to find such detailed information about the textile types elsewhere, without performing separate tests. Given the time limitations and the author's previous knowledge, this was not possible to do. Because the company will benefit from the results of the thesis, it is assumed that the information is reliable. Some risks, though, are that misunderstandings occurred, or that the thesis author did not ask the right questions or reflect properly on the information. Another risk is that the company is withholding information, though this is deemed highly unlikely. A discussion concerning secrecy was held in the beginning of the project, where it was specified that any information regarding the manufacturing process would be confidential, but information concerning the functions of the graphene textiles would be shared. Because of this, the manufacturing aspect was excluded from the thesis while the rest is considered reliable.

9.4 Ethical and Societal Considerations

When reflecting on the effects that graphene textiles might have in society, one possibility is that the material could provide the means of making it more inclusive. One example is the *sign language interpreter* concept, which could make it easier to communicate for different people. Another example is textile sensors in clothing that could warn the wearer of harmful behaviour (e.g. bad postures, inactivity) before an injury has occurred, which would improve the proactive care as opposed to letting it remain reactive.

Since graphene is carbon based, it is biodegradable. Therefore do graphene textiles appear to be a more sustainable option compared to other E-textiles. However, this should be investigated further to state with certainty, especially if any additional coatings are used, e.g. to increase the durability or to make the fabric water resistant. It is not clear, at this stage, what such coatings contain. Though, if graphene textiles are deemed a sustainable option to most current technology, the material could then help reduce the effects of climate change, both by replacing materials in existing products, and by introducing more functions in current products to reduce waste.

The possibility of using graphene textile sensors open up many new possibilities. One aspect that could be both good and bad is the opportunity to incorporate invisible sensors in clothes and other types of wearable technology. This would make it very easy to collect a
huge amount of information about how people move on a day-to-day basis. As brought up in the benchmarking study in chapter 3.2.3, an AI could be used to interpret this information with high accuracy. This could, on one hand, be of great help. For example, it would be easier to learn more about peoples’ habits in order to improve health or facilitate care. On the other hand, it could be possible that the information is not handled properly and used for, e.g. marketing purposes or that monitoring increases without being properly regulated. As seen in society several times, if a technical advancement grows quickly, the laws have trouble catching up. And if, for example, the smart carpet is made, information about people could be collected without anyone’s knowledge or consent. Those are risks that should be carefully considered before use.
10 Conclusions

In this chapter, the research questions are answered, and future studies recommended.

10.1 RQ1: What are some novel and/or advanced products based on graphene textiles, that visualise the possibilities of the material?

RQ1 is answered through the portfolio at this website (or in Appendix 6), and through RQ1.1 - RQ1.3 below.

10.1.1 RQ1.1: What are the unique properties of graphene textiles?

The main unique function of graphene textiles is that the material is conductive, while remaining low weight, soft, breathable, flexible, and stretchable. The material can also let through air and moisture, and is harmless to have in close contact to the skin. With graphene as the conductive particles for the coating, the conductive fabric is biodegradable and have superior conductive properties. The material also has an ability to sense a change in resistance, and can become water resistant with an additional coating. The graphene coating can be applied to many different textiles, thus making it a very versatile material. Given that graphene is a two-dimensional material, it is not possible to distinguish by sight or touch, which makes it practically invisible on the textile.

The three graphene textile types that are in focus in this thesis are; conductive textiles, heatable textiles, and textile sensors from Grafren AB. The conductive textile is able to block the electromagnetic field to approximately 90%. For the heatable textile, the fabric is heated by applying energy through conductive threads. The textile sensors function by registering a difference in resistance in the fabric through conductive threads. The sensor can either measure strain or pressure, where the latter can register a difference in weight of approximately 0.3 grams. All three types need only one thin piece of fabric coated with graphene to function.

10.1.2 RQ1.2: How are graphene textiles perceived by people?

When interacting with material samples on a prototype level, the reactions are mostly positive. People are surprised, curious, and fascinated when told about the different functions and seeing the various properties demonstrated. A few appear concerned about having a conductive material so close to the skin, though the worry seem to be reduced after receiving a demonstration that the textile is safe to touch while active. Several people also mention that it feels unnatural to combine electricity with fabric. The graphene textiles look and feel no different from regular fabric, which indicates that the graphene coating is undetectable. This confirms the invisible properties of the two-dimensional graphene coating.
10.1.3 RQ1.3: How can products be designed so that the unique qualities of graphene textiles are highlighted?

It is quite a contradiction to highlight the qualities of graphene textiles, given that they are indistinguishable and meant to work as the invisible background technology. The goal is, therefore, that the user should not be able to see the material unless it is purposefully shown in the design. With this in mind, there are a few things to consider when designing products with graphene textiles to ensure a positive user experience:

- Make sure that the product is easy to understand, in particular where the components with active currents are located.
- Include clear feedback to ensure that the user understands when something is activated or otherwise happening.
- Consider the safety of the design and, more importantly, the perceived safety of the user. They need to not only be safe, but feel safe when using the product.
- Consider the textile choice carefully for each product, e.g. do not use stretchy fabric for heatable products.
- Since the material is not used in many current applications, it needs to be tested thoroughly in the development process to identify any limitations.

10.2 RQ2: What are the effects of applying the method Material Driven Design to a material with qualities that are not noticeable by sight or touch?

The method MDD focuses heavily on the sensorial qualities and physical properties of the material. Therefore, to have MDD be a useful method for a two-dimensional material, some activities need to be adjusted. Since most steps are very subjective and meant to be influenced by the creativity of the designer, most adaptations are possible without any major reform. In general, it is mostly the timing of the different steps that should be revised, when comparing to this project.

Step 1 works fine as it is, but the tests and experiments could possibly need to be different from the tests of a physical material. The questions in the Ma2E4 toolkit should also be looked over before use to ensure that all are relevant, since most focus on sensorial qualities. For step 2, the vision can be constructed without problems. However, this step would probably be more helpful if it is conducted when the intended use of the material is defined, perhaps when the company is decided and the long term goal is clear. Step 3 focuses heavily on the physical properties. Therefore, it would be more useful to conduct this step at a later stage in the project, perhaps when the exterior of the product is in development. Then, it would be easier to construct more specific guidelines. In this thesis, when the final products are only conceptual, step 3 could be skipped.
10.3 Future Studies

For any future studies, it is recommended to conduct more tests during step 1 of MDD to properly understand the physical properties, possibilities, and limitations of graphene textiles. The material is very new, and it is not yet known how it reacts in various conditions, which should be rectified before products are developed.

Since the material is still in development, the vision for it should also be developed further depending on the goals of the company. The material experience pattern should be investigated further as well, preferably as Karana, Hekkert, et al. (2009) describe the method, to ensure that more accurate conclusions can be drawn.

The environmental aspects should be properly investigated to compare graphene textiles to other technologies. Given that graphene is carbon based, it could possibly be considered more sustainable than other E-textiles. However, to be able to make a proper comparison, more information needs to be collected about, for example, the origin of the graphite, the other materials in the coating, and the content of any additional coatings.

To further look into how MDD could be used for two-dimensional materials, it would be beneficial to apply it when a product is to be made, instead of only conceptual solutions. Otherwise, the method should be applied to more cases for various materials, by different people.
References


incineration plant”. In: *Resources, Conservation and Recycling* Vol. 91, pp. 109-116. DOI: [https://doi.org/10.1016/j.resconrec.2014.08.001](https://doi.org/10.1016/j.resconrec.2014.08.001)


Appendix 1: User Study 1

In this section, the material used in the first user study is presented. First, the words for the emotions and performative qualities from the toolkit by Camere and Karana (2018) are presented, along with the questions asked at the end of the study. After that, the questionnaire is included, followed by the answers of the four final questions.

**Words for the affective level,** meant to answer the question *How does the material make them feel?* (Camere and Karana [2018]).

<table>
<thead>
<tr>
<th>Frustration</th>
<th>Love</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boredom</td>
<td>Amusement</td>
</tr>
<tr>
<td>Disappointment</td>
<td>Surprise</td>
</tr>
<tr>
<td>Reluctance</td>
<td>Confidence</td>
</tr>
<tr>
<td>Confusion</td>
<td>Enchantment</td>
</tr>
<tr>
<td>Rejection</td>
<td>Respect</td>
</tr>
<tr>
<td>Disgust</td>
<td>Attraction</td>
</tr>
<tr>
<td>Melancholy</td>
<td>Curiosity</td>
</tr>
<tr>
<td>Distrust</td>
<td>Fascination</td>
</tr>
<tr>
<td>Doubt</td>
<td>Comfort</td>
</tr>
</tbody>
</table>

The emotions are also to be estimated on a scale of intensity, see Figure 58.

![Figure 58: The scale which the emotions are perceived to be, and if they are pleasant or unpleasant.](image-url)
**Performative level**, where the words below are meant to answer the question *What does the material make them do?* (Camere and Karana [2018]).

<table>
<thead>
<tr>
<th>How do they touch the material?</th>
<th>How do they move the material?</th>
<th>How do they hold the material?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressing</td>
<td>Folding</td>
<td>Holding</td>
</tr>
<tr>
<td>Rubbing</td>
<td>Lifting</td>
<td>Seizing</td>
</tr>
<tr>
<td>Grazing</td>
<td>Weighing</td>
<td>Pinching</td>
</tr>
<tr>
<td>Compressing</td>
<td>Bending</td>
<td>Grasping</td>
</tr>
<tr>
<td>Poking</td>
<td>Flexing</td>
<td>Grabbing</td>
</tr>
<tr>
<td>Caressing</td>
<td>Picking</td>
<td></td>
</tr>
<tr>
<td>Fiddling</td>
<td>Squeezing</td>
<td></td>
</tr>
<tr>
<td>Pounding</td>
<td>Smelling</td>
<td></td>
</tr>
<tr>
<td>Pushing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At the very end of the user study, the following four questions are asked. The users are instructed to consider all textiles they have interacted with when answering.

- What is the most pleasant quality of the material?
- What is the most disturbing quality of the material?
- What is the most unique quality of the material?
- Can you think of any product that should be made with this material?

See the questionnaire below. Each user filled this out three times during the session, once for each textile type right after interacting with them.
Graphene Coated Textiles Questionnaire

1. Your age

2. Which textile is evaluated? *
   
   * Markera endast en oval.
   
   - Conductive textile
   - Textile sensors
   - Heatable textile

Sensorial qualities

3. How did the material feel/appear? *
   
   * Markera endast en oval.
   
<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. How did the material feel/appear? *
   
   * Markera endast en oval.
   
<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5. How did the material feel/appear? *

Markera endast en oval.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| Matte |   |   |   |   |   | Glossy

6. How did the material feel/appear? *

Markera endast en oval.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| Not reflective |   |   |   |   |   | Reflective

7. How did the material feel/appear? *

Markera endast en oval.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| Cold |   |   |   |   |   | Warm

8. How did the material feel/appear? *

Markera endast en oval.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| Not elastic |   |   |   |   |   | Elastic

9. How did the material feel/appear? *

Markera endast en oval.

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| Opaque |   |   |   |   |   | Transparent
10. **How did the material feel/appear?**

Markera endast en oval.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tough</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ductile</td>
</tr>
</tbody>
</table>

11. **How did the material feel/appear?**

Markera endast en oval.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Weak</td>
</tr>
</tbody>
</table>

12. **How did the material feel/appear?**

Markera endast en oval.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavy</td>
</tr>
</tbody>
</table>

13. **How did the material feel/appear?**

Markera endast en oval.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular texture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Irregular texture</td>
</tr>
</tbody>
</table>

14. **How did the material feel/appear?**

Markera endast en oval.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibred</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not-fibred</td>
</tr>
</tbody>
</table>
15. Did any sample stand out from the rest, in regards to the above listed parameters? If yes, in what way?

The meanings of the material

16. What do you associate with the material? How would you describe it? Pick three meanings from the ones listed or write your own.

*Markera alla som gäller.*

- Aggressive
- Calm
- Cozy
- Aloof
- Elegant
- Vulgar
- Frivolous
- Sober
- Futuristic
- Nostalgic
- Masculine
- Feminine
- Ordinary
- Strange
- Sexy
- Not sexy
- Toy-like
- Professional
- Natural
- Innatural
- Hand-crafted
- Manufactured

Övrigt: □
17. Please motivate your choices. *


18. Thank you for your time, is there anything else you want to add?


Det här innehållet har varken skapats eller godkänts av Google.

Google Formulär
User Study Answers

Below are the answers to the four final questions.

What is the most pleasant quality of the material?
- It is super cool and there are many possible areas of use for it. Extra nice that the fabric can be heated.
- (Most of) the fabrics were very soft while being conductive.
- That the fabric is heatable.
- How the textiles work together and that it can be both waterproof and heatable.
- It looks and feels just like regular textiles.
- You can’t tell that there is anything special going on based on the look and feel of them.
- The possibilities of electrical applications and to have sensors so close to the body.

What is the most disturbing quality of the material?
- The heatable textile does not feel like clothes, and is not something the would look good as the outer layer of clothing.
- Did not like the feeling of the rougher conductive textile, would not want it in direct contact to the skin due to a lack of comfort.
- Some of the fabric felt synthetic, which is not that comfortable to wear.
- That it is both waterproof and see through.
- It feels unnatural to have electricity in fabrics.
- Unpleasant to think of wearing such textiles, will it be dangerous if it gets wet?
- The rougher conductive fabric felt that it could get a static charge if you have it on your arm and have long arm hair.

What is the most unique quality of the material?
- The level of innovation for this material is very high, and the technology is new.
- That it is conductive and can heat up the actual fabric.
- The possibility of electricity in clothing.
- The ability to detect movement with the strain sensors, and that the touch sensor is so sensitive.
- That something as thin as fabric can be conductive and be used in sensors.
- Fabric is not generally associated with electronics.
- It is electric and a fabric.
Can you think of any product that should be made with this material?

- Glove-mouse with pressure sensors for CAD work on the computer.
- Pressure sensors on car seats (buttons) and heating.
- Heatable clothes, blankets, sleeping bags, pillows, ambulance equipment, etc.
- A tent with waterproof roof and walls, and heatable floor.
- Pedometer.
- Sensors in workout clothes so the music can match the tempo/intensity.
- Heating in the textiles in a truck cab.
- Strain and pressure sensors can be used in rehab work to determine a person's recovery, for example after suffering a stroke.
- Cover pockets with the conductive fabrics to prevent thefts of electronic data (by blocking the electromagnetic field).
- Motion capture.
- Controllers for VR-applications.
- Thin waterproof sun umbrellas.
- The conductivity could be useful in safety equipment and clothes.
- Art and theatre plays where electricity can play a big role.
- Sensors that can help people with weak muscles and prosthesis.
- Cords.
- Electrical bikes, e.g. turning the kinetic energy into electrical.
- A tablecloth that can charge your phone when in contact.
- Lights in the curtains.
- Games like laserdome.
- In assembly lines the pressure sensors can help with how hard you need to push something and warn when too much pressure is applied. Common that people press too hard and hurt their fingers.
- In stretching materials, it can change colour or warn when it is about to break.
- Sensors in clothes and shoes which can help sense how the perfect fit should be.
Appendix 2: User Study 2

The work for making the mood boards, and the questionnaire for the second user study are presented below. First, the three meanings that were most popular in describing the material, from the first user study, are reflected upon further as to what they entail. This is shown in Figure 59.

Figure 59: The three meanings are reflected upon further. The meaning are listed at the top as themes, and the words on post-it notes below are meant to help describe what the themes should convey.
The images used for the *futuristic* mood board are presented below, along with the photographer. All images are from the website Unsplash.

Photo by Jet Dela Cruz.  
Photo by Icons8 Team.  
Photo by Sunbeam Photography.  
Photo by Sharon Pittaway.  
Photo by Tim Mossholder.

The images used for the *manufactured* mood board are presented below, along with the photographer. All images are from the website Unsplash.

Photo by Caroline Attwood.  
Photo by Laura Chouette.  
Photo by Rachit Tank.  
Photo by Wesley Hilario.
The images used for the safe mood board are presented below, along with the photographer. All images are from the website Unsplash.
See the questionnaire used for the second user study below.
Louise thesis - associations

Hi! I'm working with graphene coated textiles (with this coating the textiles become electrically conductive). In this part of the project, I'm exploring how different words are associated with/embodied in product design. To help me with this, I would like your opinion on three mood boards, and how you perceive them. Thank you!

*Obligatorisk*

1. What feeling or association do you get from these images? Please choose one of the words below that you think best summarizes this mood board. *

   ![Mood Board Images](image-url)

   *Markera endast en oval.*

   - [ ] Futuristic
   - [ ] Simple
   - [ ] Innovative
   - [ ] Manufactured
   - [ ] Elegant
   - [ ] Safe
   - [ ] Comfortable

2. Feel free to motivate your answer.
3. What feeling or association do you get from these images? Please choose one of the words below that you think best summarizes this mood board.

- Futuristic
- Simple
- Innovative
- Manufactured
- Elegant
- Safe
- Comfortable

Markera endast en oval.

4. Feel free to motivate your answer.
5. Markera endast en oval. Futuristic
   Simple
   Innovative
   Manufactured
   Elegant
   Safe
   Comfortable


   Feel free to motivate your answer.
Appendix 3: Idea Generating Workshops

In this chapter, the setup for both workshops are presented. Workshop1 refers to the workshop with the case study company Grafren AB. Workshop2 refers to the workshop including people without knowledge of the material, but where most have experience in participating in idea generating activities.

Time plan

See the approximate time plan for both workshops below. Each workshop is scheduled for a maximum of two hours in total.

Greetings and introduction
- **Workshop1**: 10 min.
- **Workshop2**: 15 min.

**Exercise 1. Value words**
- Total time: 5 min.

**Exercise 2. Idea drainage**
- Introduction: 4 min.
- **Workshop1**: Writing individually for 1 min, group discussion for 2 min. Two rounds. 10 min in total.
- **Workshop2**: Writing individually for 1 min, group discussion for 2 min. Two rounds. 10 min in total.

**Exercise 3. Swap material**
- Introduction: 4 min.
- **Workshop1**: Writing individually for 1 min, group discussion for 2 min. One round for two products. 10 min in total.
- **Workshop2**: Writing individually for 1 min, group discussion for 2 min. Two rounds/product for three products. 22 min in total.

Break: 5 min.

**Exercise 4. Figure storming - version 1**
- Introduction: 4 min.
- **Workshop1**: Write together while discussing for 2 min. Four rounds. 12 min in total.
- **Workshop2**: Write together while discussing for 2 min. Three rounds. 10 min in total.

**Exercise 5. Random connections**
- Introduction: 4 min.
- **Workshop1**: Write associations together for 2 min, brainstorm products individually for 1 min, discuss together for 2 min. Three rounds. 19 min in total.
- **Workshop2**: Write associations together for 2 min, brainstorm products individually for 1 min, discuss together for 2 min. Two rounds. 14 min in total.

Break: 5 min.
Exercise 6. Figure storming - version 2

Introduction: 4 min.

Workshop1: Write and discuss together for 2 min. Four rounds. 12 min in total.
Workshop2: Write and discuss together for 2 min. Three rounds. 10 min in total.

Final discussion
Total time: 10 min.

The MIRO setup for workshop2

See an overview of the workshop setup in MIRO in Figure 60, with descriptions below.

Figure 60: The overall view of the workshop setup in MIRO for workshop2.

When the participants first join the board, they are greeted by the frame in Figure 61. As seen more clearly in Figure 62 and 63, the agenda and some information are displayed.
Welcome to the graphene coated textiles workshop!

Figure 61: The introductory frame in MIRO for workshop2.

Figure 62: The agenda from workshop2 in MIRO.
Figure 63: Some information displayed in MIRO that the participants can go back to if needed.

For the initial exercise, the entire group is led to the frame shown in Figure 64, where the exercise value words take place.

Figure 64: The frame for the exercise value words for workshop2 in MIRO.
Next, the participants are divided into two groups by pressing arrows at the bottom of the frame in Figure 64. Then, the groups are sent to their respective spaces for the activity *idea drainage*, as shown in Figure 65 and 66. Each person gets their own space to brainstorm, while staying close to their group.

For the activity *swap material*, see the frame for one round in MIRO for the groups in Figure 67 and 68.
See in Figure 69 how one round of the activities *the flower - version 1 and 2* look in MIRO for both groups.

![Image of a frame for an exercise](image)

Figure 69: The frame for the exercise *the flower - version 1 and 2*, for both groups in workshop2 in MIRO.

See in Figure 70 how one round of the activities *random connections* look in MIRO for both groups.
Figure 70: The frame for the exercise random connections, for both groups in workshop2 in MIRO.

At the end of workshop2, all participants are gathered by the frame shown in Figure 71 for the final discussion.

Figure 71: The frame for the final discussion in workshop2 in MIRO.
Appendix 4: Ideas and Selection Process

In this section, the ideas generated from the workshops, the first user study, as well as what the author has collected throughout the project, are presented along with a closer look at the evaluation process.

Before the evaluation process begins, there are 150 ideas from workshop1, 240 from workshop2, and 72 collected from the first user study and throughout the project, meaning a total of 462 ideas. After the ideas have been grouped and the non-relevant ones removed, there are 421 ideas left. After removing all duplicates, there are 204 ideas left. See an overview of the groupings in Figure 72, where each idea is on a post-it note. If an idea has duplicates, the note is orange instead of yellow. As seen in the Figure, there are 14 categories.

Figure 72: Overview of the grouped ideas in MIRO.

Ideas that have been removed at this stage are: socks, batteries, boots, jacket, shoes, t-shirt, textile outer shells for non-electronic devices, flexible resistive heater, iTextile - combine
textile with Apple products, flexible conductive textile, waterproof shoes, rug, gloves, car, battery for wearables, material in stroller that warns before it breaks, composites for safety items with damage detection, water bottle, damage detection in bike frame, cords, graphene used in construction of stroller, moisture removing fabric, rain coat, more sustainable textile, textile pcb for sensors, lighter composites, reinforced bike frame, leave phone at home, waterproof cap for train running, items left in nature (because biodegradable), waterproof clothing, heated clothing, material hardens to protect from injury, GPS-tracker.

See the idea categories in Figure 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, and 86, where ideas with duplicates are orange instead of yellow. Each note is marked with either blue, red, or purple for conductive, heatable, or sensors respectively, depending on what textile type might be needed for the products.

Figure 73: The home-grouping in the affinity diagram of ideas.
Figure 74: The health-grouping in the affinity diagram of ideas.
Figure 75: The fashion-grouping in the affinity diagram of ideas.
Figure 76: The transport-grouping in the affinity diagram of ideas.
Figure 77: The sport/activity-grouping in the affinity diagram of ideas.
Figure 78: The safety-grouping in the affinity diagram of ideas.

Figure 79: The damage-detection-grouping in the affinity diagram of ideas.
Figure 80: The games/controllers-grouping in the affinity diagram of ideas.

Figure 81: The communication-grouping in the affinity diagram of ideas.
Figure 82: The animals-grouping in the affinity diagram of ideas.

Figure 83: The entertainment-grouping in the affinity diagram of ideas.
Figure 84: The electricity-grouping in the affinity diagram of ideas.
Figure 85: The industry-grouping in the affinity diagram of ideas.
Figure 86: The leisure-grouping in the affinity diagram of ideas.
From all the previously stated ideas, 55 are chosen to be included in the \textit{c-box} diagram. This can be seen in Figure 87.

![Figure 87: The c-box diagram of the selected 55 ideas.](image)

From the \textit{c-box}, the following 45 ideas are formed to be voted upon. See these ideas below in Figure 88, 89, 90, 91, 92, and 93.
### Clothes/Fashion

<table>
<thead>
<tr>
<th><strong>Perfect fit</strong></th>
<th><strong>Luminous clothes - Parties</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Special clothes/shoes in stores to try on to find your size. Sensors in the item helps feel how tight it should be.</td>
<td>When at parties/concerts the organizers can do cool effects using the lights of the audiences’ clothes.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Lit up bags/pockets</strong></th>
<th><strong>Luminous safety clothes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Optic fibers in the inner lining of pockets &amp; inside bags so it is easier to find stuff in there.</td>
<td>Jackets, shoes, pants etc. lights up at night for safety.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Information theft preventing bags/pockets</strong></th>
<th><strong>Luminous clothes - professional safety</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene coated textile in inner lining of pockets/bags to block EMF and card info theft.</td>
<td>Higher safety for roadside workers, police etc. at night if they are more visible.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Shocking glove</strong></th>
<th><strong>Luminous workout clothes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Self defense glove that can shock an attacker.</td>
<td>Workout clothes where the light moves to the beat of their music or their movements.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Shocking mosquito clothes</strong></th>
<th><strong>Dynamic/Interactive fashion</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clothes that, when a mosquito sits on them, electrocute it.</td>
<td>Dynamic fashion, i.e. the light moves during use in a pre-determined pattern.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Ice melting shoes</strong></th>
<th><strong>Luminous clothes - message</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoes with heatable outer soles that melt the ice beneath in the winter (anti-slip shoes).</td>
<td>Display messages, e.g. if a kid gets lost parent activate “message” on their shirt so surrounding people can call parents.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Silent alarms</strong></th>
<th><strong>Luminous map/GPS on clothes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Alarm in bracelet/clothes… that squeeze you (some physical feedback) to notify when the alarm goes off. - Possible uses for bracelets, pajamas for waking up, taking medication, leaving meetings etc. but don’t want to disturb others nearby.</td>
<td>- Map (GPS) on jacket arm so it’s easier to see where to go. - When biking, lights go down the arms to show when to go straight, turning etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Luminous clothes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Can make fun and different patterns.</td>
</tr>
</tbody>
</table>

---

Figure 88: 15 ideas within the fashion category that are presented to the company for voting.
Games

VR-controller
Gloves or body suit where movements control the "player" in the VR environment.

Controller
Gloves or body suit where movements control a robot/machine in real time in real life.

Animator suit
Full body suit to record movements of person. To be used in animations, games etc. (Ex having famous athletes to their famous moves in the game)

Textile keyboard
A piece of fabric with touch sensors that works as a keyboard.

Mouse pad
A mouse pad with touch sensors (or glove with sensors), so you control the mouse in the computer with fingers.

Laser dome/Paintball
Game like those above, but with graphene clothes that light up when hit, and sends a shock to the muscles so the hit is felt.

Sport

Portable camping kitchen
A piece of heatable fabric for cooking when camping. Controllers (heat regulation), thermometer?

Performance checking sports wear
Sport clothes for practice so that tell athletes how they perform + possibly give tips on how to improve.

Horseback riding blankets
- Pressure sensors to tell how you sit/move when on the horse.
- Can measure the body values on the horse.

Figure 89: 15 ideas within the games category that are presented to the company for voting.

Figure 90: 15 ideas within the sport category that are presented to the company for voting.
### Home

<table>
<thead>
<tr>
<th>Smart home furniture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Touch sensors in furniture textiles for controlling smart home technology.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outdoor furniture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor furniture that, when used, lights up and gets warm for a cozy atmosphere.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table cloth or plate tablet</th>
</tr>
</thead>
<tbody>
<tr>
<td>The food can be kept warm on the table.</td>
</tr>
<tr>
<td>Pressure sensor to keep track of how much the kids eat.</td>
</tr>
<tr>
<td>Pressure sensor for even distribution of food. (Keeps track of how much you eat &amp; drink)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heatable lunch box</th>
</tr>
</thead>
<tbody>
<tr>
<td>A lunch box that can heat up the food without microwave and keep it warm.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heatable night light cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>A bed cover with heat (and possibly night light).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distance connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>A pair of teddy bears/bracelets... so if one person touches/hugs it, the other person can feel it.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interactive teddy bear</th>
</tr>
</thead>
<tbody>
<tr>
<td>A teddy bear that can give warm hugs back.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Damage detection fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric that senses when it is about to break and warns by sound/light/change of colour.</td>
</tr>
</tbody>
</table>

---

### Health

<table>
<thead>
<tr>
<th>Rehabilitation gloves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gloves that help measure recovery form e.g. stroke patients. Measures strength and movement.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Breath monitor in shirt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keeps track of the pulse through a shirt.</td>
</tr>
<tr>
<td>Uses:</td>
</tr>
<tr>
<td>- Prevent sudden baby death.</td>
</tr>
<tr>
<td>- For those with health problems, can get help easily.</td>
</tr>
<tr>
<td>- Sport.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mimic touch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glove, shirt, pants etc. with touch sensors so it feels when you touch something. Then it sends a small current to the right place to mimic the touch. For people who have lost their sense of touch or with prosthetics.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moving clothes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors that feel when a movement starts and a motor kicks in to help complete the motion (e.g. lift something). For people with low strength, high age, disabilities...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parkinson body suit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A full body suit that shocks the body to help people with Parkinson disease move without shaking (for the future, research is still conducted).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hearing aid gloves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gloves that translates the movements of sign language and says it, so deaf/mute people can more easily communicate with others.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Animal clothes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clothes that stimulates animals with disabilities &amp; difficulty moving.</td>
</tr>
</tbody>
</table>

---

Figure 91: 15 ideas within the home category that are presented to the company for voting.

Figure 92: 15 ideas within the health category that are presented to the company for voting.
Transport

**Stroller**
- Heat in handles and mattress.
- Pressure sensors in mattress that keeps track of babies activity, notify when they sleep or are not there when they should be.
- Pressure sensor in handles, no touch = automatic break.
- Blanket with entertaining moving light show for baby.

**Bike**
- Heat in handles when hands are on.
- Heat in saddle when sitting on it.
- Sensors on saddle and handles to check posture of rider.

**E-bike additions**
- Generator in wheels to charge battery when driving.
- Heater for battery in winter time.
- Bike shoes as locks. Bike doesn’t start unless shoe is on the pedal.
- Phone holder which also is a charger.

**Car**
- Heatable seats.
- Pressure sensors in baby seat that notifies when they are left behind or not there when they should be.
- Dead man’s handle on the wheel.
- Interactive entertainment on the back of the seat. Touch controllers and light show.
- Controllers on the textile of the seat.

Figure 93: 15 ideas within the transport category that are presented to the company for voting.
Appendix 5: Concept Development Process

In the following chapter are the sketch and prototype processes for the final and some of the discarded concepts.

Textile Keyboard

See the sketches of the textile keyboard concept below in Figure 94. Early on, the plan was not to sew lines on the fabric, but to draw on it in UV paint to create the illusion of the keys only being visible when the keyboard is activated. However, the UV-light had to be very close for the paint to be visible, and it did not look as good as expected. Therefore, this idea was discarded.

Figure 94: The sketch process of the textile keyboard concept.
Textile Camping Cooker

See the sketches of the textile camping cooker concept below in Figure 95.

Figure 95: The sketch and prototype process of the textile camping cooker concept.
Smart Stroller

See the sketches of the *smart stroller* concept below in Figure 96.

![Smart Stroller Sketch](image)

Figure 96: The sketch process of the *smart stroller* concept.

Rehabilitation Gloves

See the sketches of this concept below in Figure 97.

![Rehabilitation Gloves Sketch](image)

Figure 97: The sketch process of the discarded *rehabilitation gloves* concept.
Anti-Mosquito Jacket

See the sketches of this concept below in Figure 98.

![Sketches of Anti-Mosquito Jacket](image)

**Figure 98:** The sketch process of the anti-mosquito jacket concept.

Damage Detection Fabric

For this concept, there were no sketches, only notes taken for how to best visualise the concept.
Sign Language Interpreter

See the sketches of this concept below in Figure 99. To properly demonstrate the value of this service, a short film is made for the portfolio. Because of this, physical prototypes were made, though not by the preferred material. For the prototype, thin woollen gloves are used, though they should preferably be much thinner. Unfortunately, no suitable ones were found within the budget’s price range, but it is not a big problem. One of the major benefits of these sensors is that they can be combined with practically any fabric.

The design of the embroidered stitches is not something that needs to be included, but is deemed a suitable design in this case to further visualise the movements of the fingers. This, in turn, visualises where the sensors are located. Given that the sensors are indistinguishable, the design can be adapted to suit many occasions and styles. Therefore, the design is not in major focus here, since that will depend more on the company that decides to manufacture them.

Figure 99: The sketch process of the sign language interpreter concept.
**Smart Carpet**

See the sketches of the *smart carpet* concept below in Figure 100. Due to the larger picture needed to explain this concept, a storyboard or animation became the plan for presenting this concept. However, due to the author having no experience in animation, a storyboard was chosen as the final visualisation.

![Smart Carpet Sketches](image)

**Smart Bike**

See the sketches of this concept below in Figure 101.

![Smart Bike Sketches](image)

Figure 101: The sketch process of the discarded *smart bike* concept.
Smart Couch

See the sketches and models of this concept below in Figure 102.

Figure 102: The sketch process of the discarded smart couch concept.
Luminous Workout Clothes

See the sketches of this concept below in Figure 103.

Message Clothes

See the sketches of this concept below in Figure 104.
Appendix 6: The Portfolio

Below is a pdf containing the portfolio. As it is created as a webpage, the videos can not be shown in the report. For a better viewing, please go to the following website to see the portfolio as it is meant to be viewed: https://louisejosefsson.wixsite.com/minsida/graphene-textiles.