Brunel University London

A framework to communicate radically innovative material properties to designers.

A thesis submitted for the degree of Doctor of Philosophy.

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I. ABSTRACT

This research investigates how radical innovations in material science can be better communicated to designers. In particular it focuses on how language can be used to ensure designers create feasible design concepts when first introduced to a material. The goal being to enable material communicators to reliably share their innovations and empower designers to use them. It was observed that radical innovations despite being significantly different from what had come before had no special support or guidance on how to best be communicated. This is despite radical innovations being seen as distinct in by managerial, design, and communication academics.

By reviewing the existing communication tools and theory on the subject it was found that radical innovation likely would prove a significant challenge to designers. This was due to their reliance on prior knowledge. In the first 10 workshops that reached 127 designers, they were challenged to create concepts using radically innovative materials. The concepts could be for any application though only had to use the materials as part of the design. This testing found that designers struggled to use the existing tools to reliably create new ideas. Of those ideas generated by the designers (n=51) only 49% were feasible. Improving this outcome became the core focus of the research.

To produce a framework that would guide designers a series of tests were completed. Before the initial workshops 40 interviews with designers were conducted that challenged them to communicate radically innovative materials provided the data to be assessed in a thematic review. These tests provided the insight to better understand the language designers use to communicate. Once the initial workshop was completed, focus groups and surveys probed how designers preferred to use the identified language tools. In the focus groups participants were challenged to explore what methods of communication they preferred and why they preferred these approaches. While the survey, which reached 192 designers, focused on asking what method of communication they preferred for specific types of radical innovation identified in the prior research.

A final workshop series, identical to the first workshop series, apart from the inclusion of the communication generated by the framework was conducted. Speaking to 122 designers over 12 workshops found that of the ideas created by the designers (n=72) 84% were feasible. This showed a marked improvement, validating the usefulness of the tool. The value of the framework was further validated by reviewing it through interview with 6 experts, including 3 designers and 3 material communicators who saw it as a valuable tool that would help both groups.

II. ACKNOWLEDGEMENTS

This research was in part sponsored by the EU-funded project L.T.M. Light Touch Matters (NMP.2012.4.0-1) under the agreement n° 310311. I am deeply grateful to those partners I got to work with over the course of the project. I have to say particular thanks to Erik Tempelman for his boundless enthusiasm for my work, Sarah Silve for both discussing her work and allowing me to test in the beautiful UCL Material Library and Veronica Sabrach for allowing me to use her network to conduct testing and making herself available for an interview on short notice.

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1 INTRODUCTION

The specific motivation for this research came from the author's involvement in the Light Touch Matters consortium. In 2015 a group of material scientists, academics and designers came together to create a new material known as 'Light Touch Matters' or LTM. This material was in an early stage of its development, far before its launch to market, and designers were asked to input into its development and imagine applications. The goal was to bring designers creativity and knowledge of what would appeal to consumers into the development with material scientists. However, when the author first attended an event he was led into a room, designers were on one side, material scientists on the other and there was a partition in the middle. This was the first indication that bringing the two groups together was going to be a significant challenge.

Through this project and other research, the author became aware of the gulf of understanding between the two disciplines, which stretched from the use of language to working practices. As part of LTM project work, the author also collaborated with Material Connexion, one of the world's largest material libraries aimed at designers. Conversations with these groups highlighted the challenge of understanding radically innovative materials and how there was currently no proven way to communicate the features effectively. The development of new materials costs a great deal of time and effort, especially ensuring the materials can be produced at an industrial scale. This investment can be lost or dividends from it delayed if the material does not reach the hands of those who might use it.

Designers play a crucial role in specifying the use of materials in their designs as they are responsible for looking for new solutions to problems, including the use of new materials. It is essential that there are as few barriers as possible between designers and these new materials, however communication remains a significant issue. To reduce the barrier communication poses this research was undertaken. The aim is to not only reduce the loss of investment in materials by helping to communicate these materials, but also to arm designers with new materials to help them solve the challenges consumers face.

1.1 LANGUAGE IN THIS THESIS

This study of radical materials and their communication to designers has focused on a few critical areas of research listed below:

Design: The work designers undertake vary significantly both in the work they complete and the mediums they work with. This research focuses on those who work with physical materials, namely industrial and product designers (Lawson, Bryan 2006). To assess the effectiveness of this research the focus of its study will be on designers who have gone beyond being novices, having at least two years of design training or professional experience in the field.

Radically innovative materials: a specific understanding of materials is required to appreciate this thesis. This research is exclusively concerned with materials that fit within the following definition of radical innovation:

Radical innovations introduce new concepts that depart significantly from past practices and help create products or processes based on a different set of engineering or scientific principles and often open up entirely new markets and potential applications. They provide 'a brand-new functional capability which is a discontinuity in the then-current technological capabilities' (Carayannis, Gonzalez et al. 2003).

There is a current surge in the number of radically innovative materials. Entirely new types of material are being created such as smart materials, superconductors, quantum tunnelling composites and many more.

Communication: for this research, effective communication is seen as the accurate transference of knowledge from one entity to another. The communication of radical innovation is the core goal of this approach, not the communication of the materials' every feature.

Framework, tools, systems: in this thesis the end result was the production of a framework, this aim was not apparent at the inception of the thesis, the research could have guided the research to the creation of a tool or a framework. As a result, the term 'system' is used in the research questions and throughout the thesis where it is not apparent if the subject being discussed is a tool or a framework.

1.2 STAKEHOLDERS

This research is primarily aimed at those who take part in disseminating material innovations to designers. The goal is to create a smoother dissemination process that can be followed by anyone with any level of resource. Stakeholder groups are named below.

Designers – Namely those designers who focus on creating functional physical products. This research consistently references industrial and product designers, the remit of these groups can be quite large, even including digital design, however, only those who engaged in the production of physical products were contacted. Consequently, any reference to an industrial or product designer in this thesis should be considered as speaking about those who frequently have to navigate the use of different materials to complete their goals. All the stakeholders below have an interest in communicating materials. In this thesis to group them, they will be referred to as Material Communicators.

Manufacturers – Those who produce materials on a wide scale may not themselves be material scientists, though they have an invested interest in seeing the materials they create be communicated. Marketers may also represent this group of stakeholders.

Materials scientists –This research targets those material scientists who have an interest in communicating their material outside of their discipline.

Those involved with material libraries – Those who regularly create material libraries, who may also be any of the above groups, are also potential stakeholders in this research. This only concerns material libraries that specifically target designers and regularly communicate new materials.

1.3 CURRENT STATE OF MATERIALS COMMUNICATION

The creation of new materials has exploded over the last few decades. In 1999, David Ball estimated that some 40,000 to 80,000 materials were available for designers to choose from(Ball 1999). This number has since grown; with materials communicators the author spoke to openly admitting they have no idea of number of potential materials available on the market but believe 80,000 to be a conservative estimate. These materials include everything from traditional types of wood that have been available to humans for our entire time on this planet to recently developed concrete mixes that better enable 3D printing technologies to use them(Wangler, Roussel et al. 2019). In these last few decades there has been a fundamental shift in both the manufacture and demand for new materials, creating a boom in the field and accelerating the development of radically innovative materials, many of these smart materials(González-Viñas, Mancini 2015). This increases the need for some form of guidance for designers for their options of new materials are going to include more of the unfamiliar.

Materials communication is currently achieved through processes that have not changed significantly for decades. The core of this communication is the product data sheet, sometimes known as technical data sheet or spec sheet. These sheets consist of a collection of information, tailored by the author to explain the material and provide information they believe to be essential to anyone who wishes to use it. This process largely lacks standardisation. With companies only emerging in the last 20 years, such as Icecat, to start standardising this kind of technical information. Despite these attempts to start standardisation the data sheets are very different between materials. This is a reflection that each material can be significantly different and require different data, but this issue is also contributed to the differing needs of markets, a data sheet for the EU market might need to highlight how the material meets EU standards, while a data sheet for the US will need to explore how it meets US standards. This lack of standardisation means that data sheets need to be read by those who are experts, not only familiar with the properties the materials discuss but also the regulations they reference. This limits the communication potential of these sheets.

To support the data sheets material communicators, use a variety of tools, some of which have been used for decades, including workshops, samples, and videos. Others have capitalised on the digital revolution and use websites and other interactive services to better communicate their materials. The non-interactive services, such as videos offer a chance to provide more information about the materials but are limited in that they need to be digestible by those using them, often limiting the depth into which the discussions of the material properties can go into. The interactive services, including online tools and workshops are a highly valuable resource but come with a high cost. In particular workshops which may only reach a handful of designers and may require multiple experts in the material to attend are a high cost high reward approach and are usually reserved for only the most lucrative contracts. Currently no one approach is resolving the challenge, and companies are trying to use multiple approaches to get the best results, as long as they can afford it.

These communication challenges can increase when the material is radically innovative, as this can shift how those being communicated to understand the material. No longer are they comparing to somewhat similar data sheets to understand what has changed or using their personal experience to gauge how a shift in tensile strength might change how they use a material. Now they are trying to understand how a completely

Proactive and consistent communication of materials can lead to positive outcomes for the materials, both incrementally innovative and radically innovative. Mycelium bricks, a highly sustainable material that is made from mushroom roots and developed first in 2007 (Bayer, McIntyre et al. 2017) was a radical innovation. The material is constructed in a completely new manner, has a unique construction and has unique properties, and has shown exceptional growth and uptake by the design, construction and commercial industries. Many materials take decades to have the penetration that Mycelium has achieved in 13 years, this is ignoring that fact that the materials development cycle itself can often stretch into decades (Atwater 2019). To achieve this success those involved with the mycelium production have endeavoured to constantly reach out. Offering ‘make your mycelium at home’ kits, workshops on how to make mycelium and it how it can be used and creating an open lab in which they explore how mycelium can be used. The material is now making its way into construction, replacing polystyrene packaging and is regularly featured in new sustainable designs.

Even with diverse attempts to communicate materials the communication of materials can still fail. A good example of a material that has been communicated through many channels but has not lived up to the expectations many had of it is graphene. Graphene, another radically innovative material, has many valuable properties. It has extreme conductivity, strength, two-dimensional nature and other features were seen as making it as the next 'wonder material', however it failed to live up to the hype(Barkan 2019). The communication of the materials potential raised the hopes of those who heard about it, spreading this information out from the scientific community to the surrounding industries. This spread lost the nuance of the material and the understanding of the challenges associated with it(Konrad, Alvial Palavicino 2017). This led to the material to become a frequent study for how materials can over promise, even when the claims are actually truthful as the materials limitations are not honestly represented. The challenges the material faces mean that recently the EU pledged and additional billion euros in development and yet even with this the future of the material is in question(Johnson 2019).

These examples help illustrate how challenging the communication of radically innovative materials can be a significant task. The quantity of communication isn't the only factor to consider but the approach and methodology can also influence the materials ability to be taken up by commercial enterprises. This adds to the motivation of this research to create a system that can reliably provide support communication to ensure the best possible outcome for the materials.

1.4 Supporting Designers

The need to support designers and others seeking to use new materials has been long understood. Failing to communicate radically innovative materials with designers cuts off a key avenue to seeing new materials reach their full potential. If designers do find a new material and build it into their products, it can lead to significant benefits for consumers, designers and materials manufacturers. While some tools exist to communicate new innovative materials, current systems have no specific system to communicate radical innovations, despite them being distinctly different from other forms of innovation.

Outside of tools like data sheets and workshops, whose qualities are discussed in the previous sections, material libraries are the core method by which materials are disseminated. These institutions collect and communicate about materials, providing support for those designers looking for new solutions. Materials libraries in addition often have a specific focus on a particular industry such as architectural, design, academic or engineering. The focus of these material libraries tailors how the materials are communicated. In the literature review a discussion of those material libraries that specifically cater for designers is explained in more detail.

All the methods of support provided to designers have both advantages and weaknesses. This thesis in general will mostly focus on material libraries that aim at designers. This is due to the fact that these tools are tailored to be effective for them. As covered in the above section workshops/talks are also a viable option for communication but because of their limited reach and the fact that they are mostly unique to the situation they will not be factored in as there is not a consistent measurable impact to them. Before the focus is brought down on to the libraries it is important to address the data sheets. Data sheets are not tailored to designers but are the tool designers may be expected to use to understand a material. Currently data sheets, no matter their design, make a number of assumptions about the reader. They use language and measurements that focus on objective measurements of the material, covering details such as tensile strength, in addition to referencing key standards the material might meet. This language is only helpful to the reader if they are familiar with those measurements and standards. However, this is not necessarily something that designers will understand as their education focuses more on the application of materials in a more natural sense. As designer's education does not necessarily include an understanding of these terms, leaving designers unable to interpret the data sheets (Sörensen, Jagtap et al. 2016). Material libraries role is as a translator, taking these complex data sheets and converting them into a useful output for designers. The approach taken by each of these libraries is different and with no obvious testing as to if one approach is more effective than another, let alone an approach that focuses on the communication of radically new materials.

This research aims to build a framework that will enable the communication of radically innovative materials to designers, enabling them to use the materials in their work. By targeting the initial design phases, this system will help support existing material libraries and be a framework that anyone who wishes to communicate a new material might use. The introduction chapter discusses the research goals, scope and structure of the thesis. It also outlines the significance of this work to the broader academic discipline.

1.5 Research aim and Questions

This research aims to create a new system that allow the communication of radical innovations in material science to designers. This accurate communication will allow designers to use the materials in designs more reliably. The research questions are below, to generate these a process of reflection was undertaken. This included speaking with designers and material communicators as well as conducting research around how material communication is currently conducted. Much of this research is described in the literature review. This research identified three key areas of investigation; the current state of materials communication both to designers and amongst designers, the effectiveness of this communication, and how this communication could be improved. With these identified the research questions were formed, each aiming to target a manageable and specific element from within these topics which could result in measurable results.

Research question 1: What communication techniques exist to communicate radically innovative materials to designers?

Research question 2: How effective are the communication materials aimed specifically at sharing radically innovative materials with designers, at enabling them to create concepts that are feasible and use that knowledge accurately?

Research question 3: What written or spoken communication techniques enable designers to better understand radically innovative materials?

Research question 4: How can these communication techniques be applied in a systematic fashion to enable design communicators to reliably communicate radically innovative materials through text?

Research question 5: Does this new communication system function notably better than the systems currently used by material communicators?

1.6 Significance of this study

The research contained in this thesis aims to establish how communication of radical innovations to designers could be more effective. The objective is to create a system, a tool or framework that can be engaged that allows for more consistent and effective communication of materials. This system will then be disseminated to those who need it through channels that have the necessary connections.

A useful system will benefit all the stakeholders listed in the above section. The development of new materials is costly and time-consuming; any material that does not reach its full potential because it is not communicated has wasted a considerable amount of resources. Any reduction of this is an impactful change.

It would also allow designers to expand their knowledge base effectively, allowing them to increase the number of known materials. A more extensive range of options in the design phase can directly contribute to better design. As such the diffusion of the material may also improve the quality of work that designers produce which could lead to further earnings through better products.

Beyond improving the diffusion of innovation, there is also the benefit of further understanding of design communication. As the research explores how designers communicate, it will expose the systems and preferences of the industry. These communication systems can then be used in other research projects. Since if they are useful for radical innovations, already established to be challenging to communicate, there may be a potential that the same systems can be used to communicate other sources of knowledge effectively.

1.7 THESIS STRUCTURE

There are nine chapters in this thesis:

Chapter One – Introduction: An overview of the research, looking at its scope, aims and research questions covered in the thesis.

Chapter Two – Literature Review: Examining the existing research on the topic and offering an analysis of that prior research to establish what is relevant to the communication of radical innovation to designers. The chapter explores innovation, design thinking and communication theory.

Chapter Three – Methodology: A look at the methods used to ensure the research is robust and in line with the respected academic process.

Chapter Four – Descriptive Study 1: Initially, it covers two tests that looked to establish if radical materials did provide a unique challenge for communication to designers. This is then followed by an analysis of a series of workshops that put radically innovative materials in front of designers and used existing communication tools to establish how useful the systems are in communicating the innovation.

Chapter Five – Prescriptive Study: This chapter discusses the further studies completed in this research, including the thematic review of innovation types, a questionnaire investigating what forms of communication work best for each innovation type and focus groups that discuss how comparison and other forms of communication work for designers.

Chapter Six – Development of the communication framework: This chapter explores the creation of the communication system, initially choosing between the construction of a framework or tool, before exploring how the framework can be shaped to improve the communication of the radically innovative materials. It focuses on bringing together the research elements from the rest of the thesis.

Chapter Seven – Descriptive Study 2 and Validation: This chapter is focused on the new communication system created from the prior research in this thesis and the analysis of its impact on communication through the second set of workshops. The tests sought to provide evidence that validates the effectiveness of the framework, this was further supported by a series of interviews with experts who provided feedback on the system.

Chapter Eight – Final Version of the Framework: Explores the final version of the framework, along with providing explanations of how each part of the framework can be best used.

Chapter Nine – Conclusion: Summarises the research and findings set out in previous chapters. The chapter discusses the applications, limitations and potential areas of future research.

2 LITERATURE REVIEW

2.1 INTRODUCTION TO LITERATURE REVIEW

This chapter covers a literature review of key aspects that this research concerns. It focuses on answering **research question 1** of this research, 'What communication techniques exist to communicate radically innovative materials to designers.' There is some additional focus on gaining insight into **research question 3** 'What text-based communication techniques enable designers to better understand radically innovative materials. 'To fully answer **research question 1** knowledge surrounding innovation, and specifically 'what the differences in innovation are', defining radical and incremental innovation, and innovation dissemination must be explored. This helps establish the exact boundaries of this research.

The second topic of discussion is material science, the nature of it, and how it can communicate these new materials which are fundamentally different from materials which have now saturated the market. The material science section also looks at how radically innovative materials in the development and use by designers, represent a similarity to developing materials in open innovation projects. Followed by an examination of how open innovation can struggle with the nature of radical innovations between communication groups, and how they think and act. At the end of this section, research is also highlighted that states the importance of creating a system for communicating innovations and the very basic requirements of a system to be effective. A review of Design Thinking follows this. Design thinking is the process with which designers complete design tasks and is an overall view of how designers are believed to think. It is its own branch of research and has been supported by numerous publications. The review focuses on how radical innovation conflicts with the normal flow of design thinking principles and why radical innovation will be difficult for the processes to absorb.

The next element of the review is a discussion on communication. Communication is the method with which humans can accurately provide information from one to another. This is a focus on the different communication methods that exists, and a discussion of why certain communication methods are more valid or unique to designers or unique to material scientists. This is followed by research that discusses why it can be particularly challenging to communicate radical innovations.

Finally, there is assessment of the current forms of communication, that currently facilitates the communication of materials to designers. These being material libraries, specifically designed for the use of designers. An examination of them shows what common aspects are shared by these tools for this task. In table 1 there is a summary of what is covered in each sub-section of the literature review.

The methodology of the literature review focused on exploring these topics in more detail. The focus on the topics to be explored stemmed from exploring the wider topic areas, such as design thinking. With these areas explored specific phrases that allowed for the deeper exploration of that topic where identified, in the case of design thinking the exploration of 'Ill-defined problems' topic arose from the initial review. Once each topic had been reviewed texts were hand selected to be explored to in more detail, focusing on those which had a significant reach, direct application to the topic and appeared in well reviewed publications. More information on the methodology of this review and how these topics were developed is in appendix F.

Introduction	
Innovation	• What is innovation: This section expands on what innovation is and its general role in industry. • Differences in Innovation: Exploration of the different types of innovation and examples of these innovation types. • Innovation Diffusion: A look at the current method of innovation diffusion which aims to share innovations so companies can use them.
Design	• What is design: A discussion on what design is and how it functions as well as highlighting the nature of designers. • Design Process: Design thinking is a specific method of processing challenges that designers use. This has implications for the rest of the research. • Why aspect of design thinking is being targeted and why: Design has many different stages and this section highlights which are being targeted in the thesis.
Material science	• Material science introduction: This section introduces material science and systems behind it and its practioners. • Material science and the open innovation process: Radical innovations demand that people work openly to share knowledge, this section looks at the open innovation tool that supports this process. • Knowledge transfer issues and implications: There are challenges for open innovation, this section discusses them in detail.
Communication	• What is communication: Exploring what communication is and how it can be assessed. • Communication definition in this thesis: A specific definition of communication is provided in this thesis to ensure the accuracy of the work. • Tool use and limits on tools used in this thesis: Tools are essential to communication, however not every tool is accessible. • Communication methods: An assessment of existing communication methods was also conducted.
Current forms of communication	• What is being assessed: A number of libraries exist that aim to communicate materials to designers. These are outlined as well as the criteria that was used to choose them for assessment. • Attributes, advantages and disadvantages of each system: Each system is assessed to establish what tools it uses and how the system may be effective or challenging to use. • Similarities between libraries: This was a discussion on what tools were used consistently across libraries.
Summary	

Table 1: Summary of literature review

2.2 INNOVATION

Innovation is a key force of change in our world, allowing us to effectively apply ideas that help and support others (Dodgson, Gann 2018). It provides a more efficient way to convert resources into products or services. This though is a shallow term for innovation as an overarching definition is elusive since innovation can occur at any point from researching a product to the delivery and use of a product.

For decades groups have argued that because innovations are so structurally different between organisation and technology, they should be labelled differently. This argument is grounded on a solid base and argues that a universal theory of innovation is an incorrect goal (Satell 2017). However, this confusion mostly relies on the broader study and modelling of innovation, not merely understanding it. What must be understood is that innovation is not purely technological; it may be social or meaning-based (Verganti 2013). The wide variety of innovation research says there are many definitions for innovation, growing organically from their work the meaning is often used as a lens to aid the view of the avenue of innovation the writer pursues. The work of Bargheh and Rowley (2009) was exceptional in that its goal was to pin down a single universal meaning that arose from a reading of swathes of the most respected innovation literature. The definition is listed below and is the best tool to view the rest of this thesis's discussions on innovation. While the example is a little dated, it does combine many of the seminal works on innovation over the last few decades and is more than valid.

> "Innovation is the multi-stage process whereby organizations transform ideas into new/improved products, service or processes, in order to advance, compete and differentiate themselves successfully in their marketplace." (Baregheh, Rowley et al. 2009)

The quest to better understand innovations comes from the fact that innovations can pose a threat to innovators, as it is possible to destroy existing strengths or create new opportunities for competitors to link their strengths together. This importance of understanding how innovation will affect a business has led to a discussion on how to categorise innovations to avoid risky scenarios (Nechaev, Ognev et al. 2017). This work has led some academics to see innovation as a sliding scale, and others see it as more of a mix of different qualities. In the seminal paper on different forms of innovation by (Abernathy, Clark 1985), they developed a matrix that described the different forms of grouping them based on their ability link existing tech and resources and the potential disruption of established concepts.

The transilience map from Abernathy & Clark (1985) looks at the division of innovation on two scales, Creation/Destruction of linkages and the entrenchment/disruption of competence because of the innovation. Linkages mean that the way components of their business worked together, these components are seen to be anything from how material parts link together to accessing the existing customer base. Using innovation to apply technology across sectors can reap huge benefits. As for the other scale of competence, the company needs to be aware that innovation may improve output, but they will have to build up their knowledge in that area and potentially lose the benefit of competency in existing products.

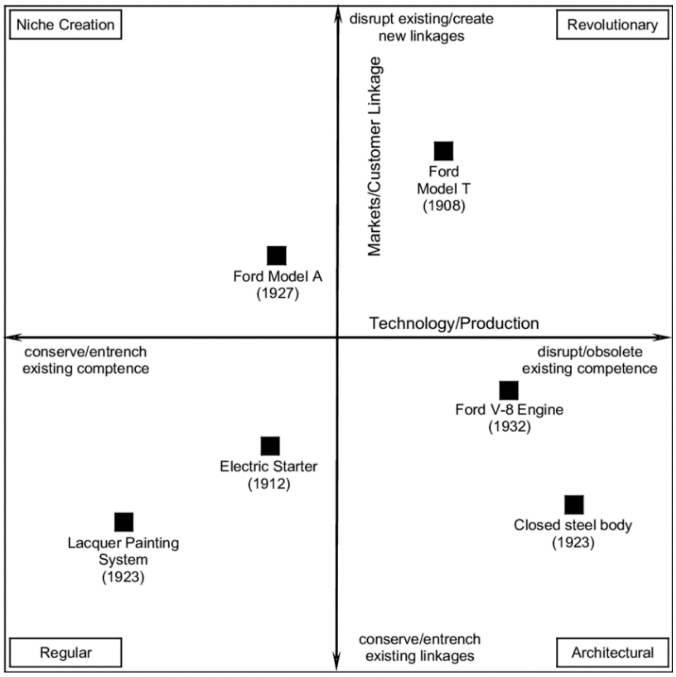


Figure 1: Abernathy and Clarkes' (1985) transilience map

The goal of the work was to look at the potential impact of innovation on the market and the company, assuming that the innovation affected the company developing it. Henderson and Clark (1990) also used a very similar map to plot out their view on the different forms of innovation. They used the same scale of linkages that Abernathy and Clark used but altered the second factor as 'core concepts.' In their description, this is very similar to the competencies factor; however, the difference here is that Henderson & Clark (1990) in a paper that followed on from the seminal 1985 paper were focused on a company's internal structure and were less concerned with the external market.

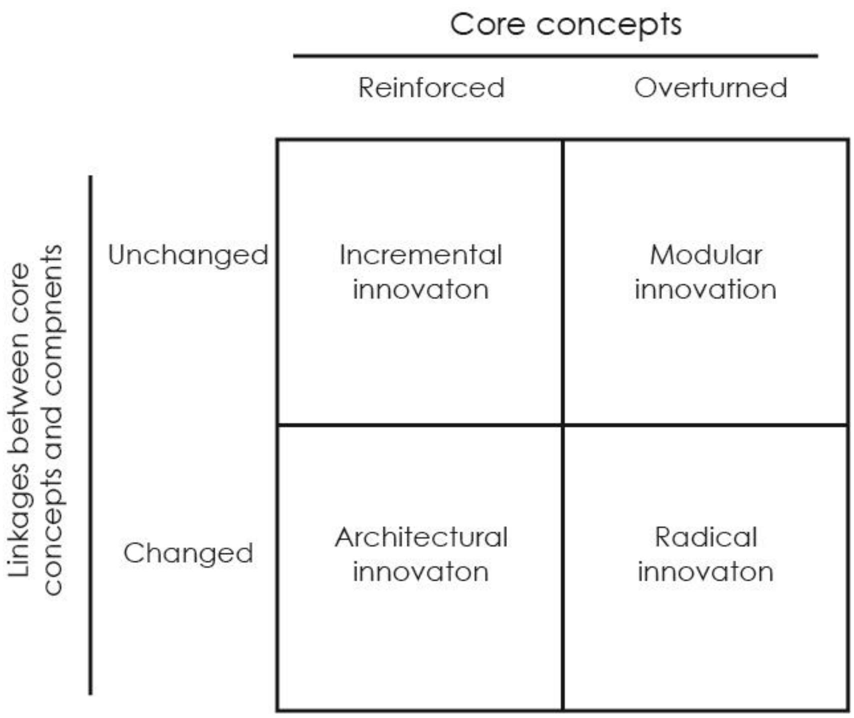


Figure 2: Henderson and Clarks innovation map

Importantly both groups see that their scales are defined by a disruption or entrenchment to the status quo be that in linkages or elsewhere. The importance of disruption was expanded upon by Christensen and Clayton (Christensen, C. 2013) who saw the ability to use disruptive innovations as an indicator of company success and effectively seeing it as a dominating difference between innovations.

This has since developed further innovation is now seen to include a wider range of possible stake holders. While the terms coined in Abernathy, Clarke, and Henderson (1985,1990) live on, with radical/incremental innovation in particular remaining relevant, innovation considerations now focus on how the different stages of a products life. This focus now leads to an exploration of the different types of radical innovation and incremental innovation (Dodgson, Gann 2018).

2.1.1 **Differences in innovation**

The differences in innovation are still up for debate with many labels being proposed; however, to limit this to a manageable scale for this research, just the dominant theory will be expanded upon. The difference between radical innovation and incremental innovation is perhaps the most established in academic research. Radical and incremental appear in the texts of many papers on innovation that differ significantly in context and application. This includes a great many papers that look at how incremental and radical innovations create productivity (Guisado-González, Vila-Alonso et al. 2016), how they differ in R&D(Beck, M., Lopes-Bento et al. 2016), and how companies should be structured to support these innovation types(Sheng, Chien 2016). This builds on decades of research that looked at how innovations develop, and broke innovations down into different types (Abernathy, Clark 1985, Ettlie, Bridges et al. 1984, Henderson, Clark 1990). This research is seen to remain relevant and influences modern theory (Rip 2018).

It is vital to bring clear definitions to these terms. While there is much debate about the exact nature of each innovation, it is possible to provide a clear overview. This is supplied by Carayannis and Gonzalez (Carayannis, Gonzalez et al. 2003) who worked to bring together the different terminologies around innovation in a literature review to develop clear definitions. They use the same academic reports that Rip (2018) identified as still being relevant to the discussion on innovation.

Incremental innovation is best defined as:

> 'Incremental innovations exploit the potential of established designs, and often reinforce the dominance of established firms. They improve the existing functional capabilities of technology by means of small-scale improvements in the technology's value-adding attributes such as performance, safety, quality, and cost.'(Carayannis, Gonzalez et al. 2003)

Incremental innovation is perhaps the most common form of innovation, in fact, Abernathy and Clark (1985) described it as 'regular' innovation. This is how firms compete within the same market making small steps to keep an edge on their competitors constantly. Incremental innovation while often seen as uninteresting are profitable for a company(Berggren 2019). Reducing costs or increasing the desirability of the product and allowing the company to defend its market position by increasing the barriers to entry to other potential competitors while maintaining an edge over the established competition(Pappenheim 2016).

Radical innovation is best defined as:

> 'Radical innovations introduce new concepts that depart significantly from past practices and help create products or processes based on a different set of engineering or scientific principles and often open up entirely new markets and potential applications. They provide 'a brand-new functional capability which is a discontinuity in the then-current technological capabilities.' (Carayannis, Gonzalez et al. 2003)

Radical innovation creates something that is different from established offerings. An essential part of this is that radical innovation does not have to be an entirely new idea but can take an idea that already exists and apply it into a new market or function. Radical innovation is a higher risk than incremental but can offer a significantly higher pay-out opening new markets and allowing companies to leapfrog their competition(Colombo, von Krogh et al. 2017).

The focus on these terms is due to the fact that while much of the research uses different terminologies for innovation types; radical and incremental are the most consistent terms. Radical and incremental are also useful as they remain relevant even when viewed about either purely technical innovations or administrative innovations and remain relevant when seeing innovation purely on a scale of disruption (Clayton 2013). The radical vs incremental study remains relevant in so many contexts that it makes these labels some of the most robust terms in all the literature.

The reason for focusing upon these robust terms is that this study investigates an external group using innovations from another company, and as a result, large parts of the subtler pieces of innovation literature will not apply. An example of this is architectural innovation which appears in numerous works on innovation including earlier works by Henderson and Clark as well as more contemporary content (Hofman, Halman et al. 2016). Seen as distinct from incremental and radical innovations, it was originally described as 'the reconfiguration of an established system to link together existing components in a new way' (Henderson, Clark 1990). As an outside group purchasing a product-based innovation from a company, such as designers buying materials, this reconfiguration will have already happened by the time it is accessed and as such technology cannot be architectural as it is not internal. Architectural is not the only innovation term that does not apply if seen from this context. To avoid confusion and ensure that the literature remains relevant to this study only radical and incremental will be used to evaluate technological progress.

To better understand how incremental and radical innovations apply to materials, examples of those materials that when released, provided incremental innovations and radical innovations are described below.

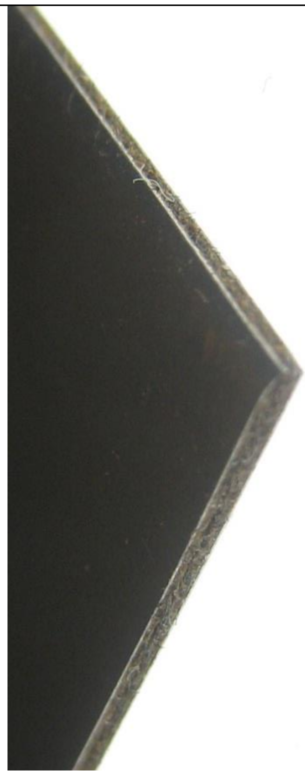
<table>
<tr><th colspan="2">Incremental Example</th></tr>
<tr><td>What is it?</td><td rowspan="4"></td></tr>
<tr><td>Hybrix steel is a sandwich of steel around a fibre lattice. A material that looks like regular sheets of stainless steel but is only two-thirds of the weight. However, it does not retain the full strength of solid steels or its durability (Pimentel, Alves et al. 2016).</td></tr>
<tr><td>Why is it incremental?</td></tr>
<tr><td>Hybrix while very different from steel, does not fundamentally change what is possible with the material. Achieving the lightweight material comes at a significant compromise, and that means that it cannot achieve much of what real steel can achieve. If, however, the Hybrix had similar material properties to steel retaining strength, it would be a radical innovation as the significantly reduced weight combined with full functionality would change what is possible with steel entirely.</td></tr>
<tr><td colspan="2">Incremental Characteristics Summary</td></tr>
<tr><td colspan="2">Incremental change is a change that allows the progression of existing technology by;
Improving upon existing technology.
Using predominately existing technology in production.
Does not fundamentally change the functionality compared to the previous design.
Allows existing knowledge to be used to access the innovation by consumers.</td></tr>
</table>

Table 2: Incremental example

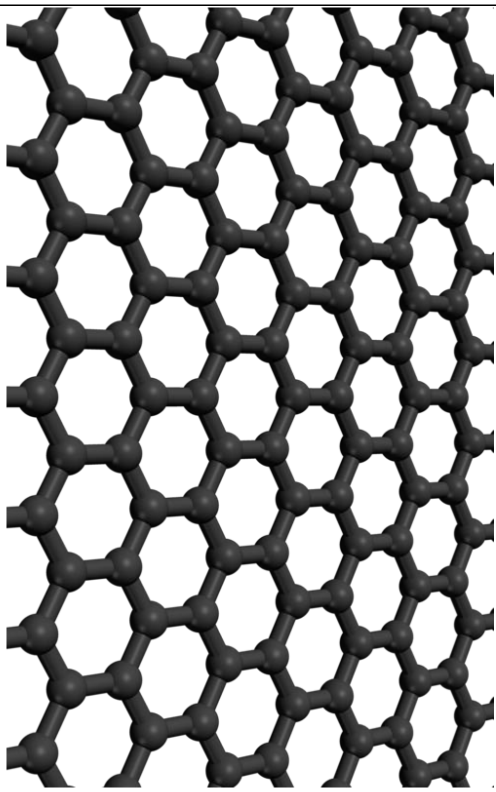
Radical Innovation Example	
What is it?	
Graphene is a nanomaterial, being made up of a single layer of carbon atoms arranged in repeating pattern that provides a unique set of properties. It has a wide range of innovative material properties including being an exceptional semiconductor, very strong, extremely thin and light wight weight (Papageorgiou, Kinloch et al. 2017).	
Why is it Radical?	
Graphene was unlike practically any other material when first discovered and remains one of a very small group of materials that display the abilities it currently has. It looks to enable a series of new technologies, is produced in a unique fashion and is opening up new avenues for product development(Xiao, Li et al. 2016).	
Radical Characteristics Summary	
Radical change disrupts the existing technologies on the market. • Creates new technology that supplants existing technology. • Uses new technology in production, (or a combination of new technologies). • Fundamentally changes what is possible compared to existing technologies on the market.	

Table 3: Radical example

2.3 INNOVATION COMMUNICATION AND ASSOCIATED TOOLS

The body of research present in the area of innovation communication is not insignificant but is not overly developed and does not focus on any specific topics in great detail. There is not a clear definition of what innovation communication is, with some bodies seeing it as the process of management instilled by corporations to spread information about their portfolio (Pfeffermann 2011), some see it as the interactions with which innovations spread out between corporations and their stakeholders (Mast, Huck et al. 2005), others still see it as an extension of the innovation process itself(Heinemann, Matthews 2018). There is also research focusing on how innovations are communicated internally within a business, covering how innovations can be enabled through the management of communication by leaders (Zerfass, Huck 2007). As this research is primarily interested in how communication can enable interactions between designers and material communicators, innovation communication is seen as the interaction between two groups of stakeholders most closely represented by the work of Mast.

This concept of Innovation communication builds on the idea of innovation dissemination which posits that innovations spread need the support of communication to initially spread to a specialist selection of early adopters and then further communication to reach a broader market (Rogers 2010). The basis of innovation dissemination was first outlined by Rogers in his seminal work in 1962, updated in 2010, which stated that "Diffusion is the process by which an innovation is communicated through certain channels over time among the members of a social system." (Rogers 2010) Innovators supporting this process require other elements of a social group, be that industry or profession, to use their idea to make a profit. Dissemination is of crucial importance as, without it, innovations can be produced and then fail even if they are valuable because they never reach the right people. This idea has become so pervasive that it has evolved into a core practice in for most organisations which pursue innovation (Beausoleil 2018).

In addition, without publication, discovering innovations becomes exceptionally difficult. This is such a severe issue that some governments have funded organisations to help improve the dissemination of local innovations, with a green paper commissioned by the EU that found: *"It is the dissemination of new techniques, products and services to the whole of the economic fabric which allows full benefit to be gained in terms of competitiveness." (European Commision 1995)*

The path to innovations becoming diffused is more complicated than merely communicating with the target audience. Rogers (2010) lays this out in his 'Phases of innovation process'. In this process innovations go through stages. Stage 1 is Development and is defined by control as the innovation is developed by researchers. In stage 2: Start-up, an early version of the material, is shared to interest potential stakeholders. Stage 3: Adaptation is a collaboration stage; this is where the developers of the innovation must work with early adopters to refine the material. Stage 4: Expansion, it reaches either back to control or to consultation (Rogers 2010).

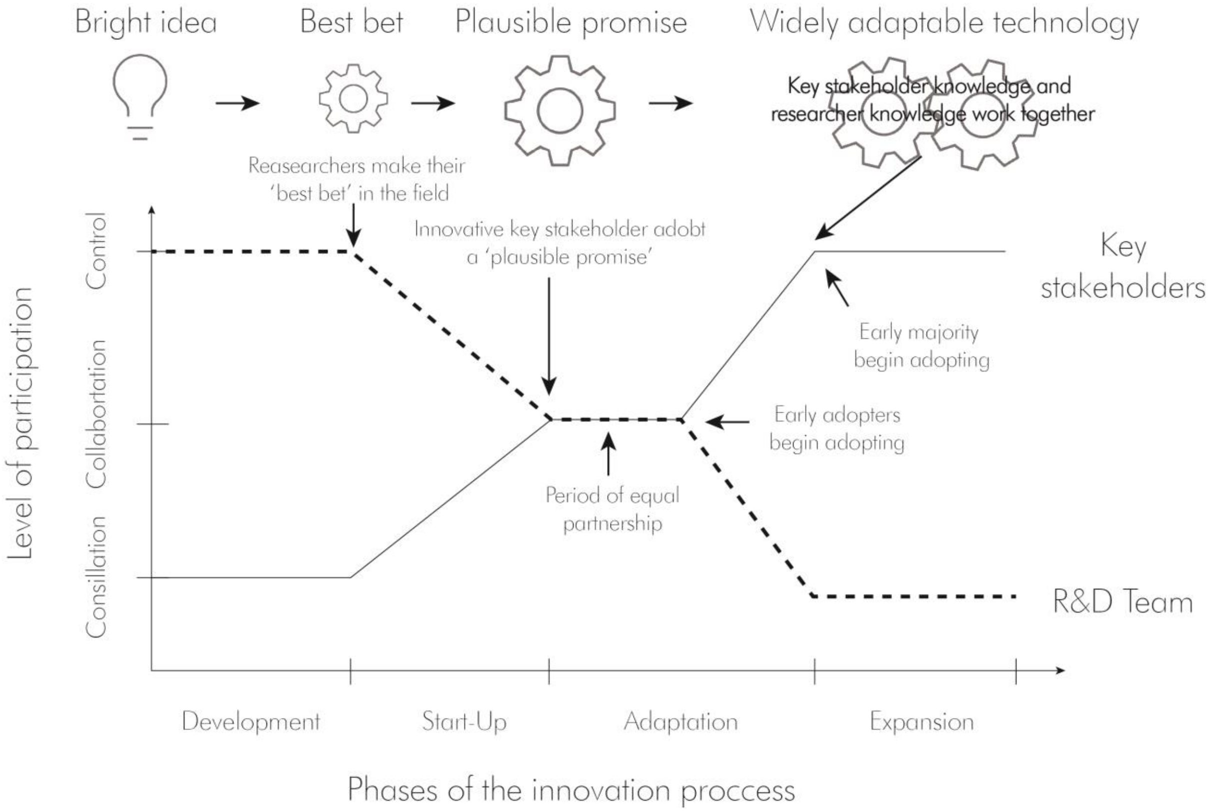


Figure 3: Roger's (2010) innovation dissemination graph

Of interest to this research are phases 3 and 4, which describe the periods where radical innovations in material science could be used by designers. This shows that to a degree, the innovations are disseminated in part due to a level of collaboration between designers and material scientists. Innovations can increase their usage through excellent communication of the innovations qualities and potential to profit the organisation is essential (Murray, Hanlon 2010). Increasing the likelihood of use of innovations offers new chances for profits.

To better enable this dissemination, concepts around how to communicate these materials has continued to expand from its early beginnings where it focused more on the expansion of how marketing could be used to change short purchase intent (Arndt 1967). A great deal of this work is tied to innovation journalism, which aims to spread information around new innovations. This can be motivated both by the innovator or independent journalists. Both groups aim to spread information to help drive the dissemination of innovation to enable it better to succeed in the market place, supporting those who would benefit from it (Nordfors 2014).

The spreading of this information is not limited entirely to journalistic support, a great deal of research indicates that innovation communication is driven by the networks that those looking to innovate have and that this word of mouth spread, (that includes electronic word of mouth through online sources) is core to effective dissemination(Chapman 2018). Delre argues that this effect is so pronounced that the impact of a handful of highly connected individuals can determine the final diffusion of innovation (Delre, Jager et al. 2010). Considering the vast body of research that aims to explore and provide tools to more effectively create conversations that enable the individuals within teams and those part of collaborative groups to explore innovations, the goal of creating more effective social interactions cannot be ignored (Pfeffermann 2011).

Both innovation journalism and the communication of innovations through social networks rely on the ability of communicators to explain the innovations to uniformed stakeholders who may then utilise the innovations. This focus on communication has led to the development of several tools and frameworks that aim to help spread this information more effectively, and these can be seen as belonging to three groups. It is essential to clarify that these frameworks and approaches are focused on only innovation communication, not the broader subject of enabling the development of innovations which can be conflated by some groups.

2.3.1 **Existing communication tools in journalism**

Innovation journalism offers tools to help communicate new technologies across industries without the emphasis being placed on designers. Effective innovation journalism offers tools to help communicate innovations, while this has started to become more democratized with innovation bloggers also adding value, traditional journalism has examined how it can keep up.

The focus of innovation journalists and innovation bloggers alike tends to focus on communicating in ways that are accessible to the average reader. This approach though is fluid and requires specific routines to gain the best possible outcomes (Huck 2006). Despite this lack of exact approach, this category was examined to find examples of frameworks, tools and recommendations that help support this communication as it most closely related to the key questions of this thesis. Three innovation communication approaches are described below.

1. Innovation communication recommendations for Innovation Journalism by Mast (2005)

In the guidelines set out for how journalists should communicate innovations, several vital methods are outlined. The first goal is to plan to ensure the explanation is easy to grasp and can be seen as relevant by the reader. The next advice is to place the material in an understandable frame of reference, targeting current issues and scenarios that allow the audience to place the material in evaluating the usefulness of the innovative product. This stretches to the application of the innovation into examples and applications that show concrete examples of the innovation's abilities. Finally, the recommendation is to support this work with a vision, using stories, personalisation and visualisation to make the content feel more relevant to the audience and provide additional points of reference. The topics covered in this area are touched on lightly with limited resources to support how these suggestions can be actioned. The work does provide some key areas for further thought though.

2. Innovation readiness – Master innovation communication (Zerfass 2005)

Zerfass (2005) argues that for innovation communication to be effective, it has to be planned and fit within the corporate communication structures working with internal communication, market communication and public relations approaches. There are several recommendations as to how to get the best out of such an approach.

In this it is argued that the production of communication should be a collaboration between the innovator and the other stakeholders involved. This helps leverage the skills of both groups. The communication should aim to work within 'News Values'. The communicator must work to build in the values; easy to explain, topical, clear, unexpected, negative or sensational. This approach not only makes the communication more likely to be featured in the news helping it spread but also enables individuals to more readily engage with learning about the innovation. The explanation should also avoid specific, non-newsworthy values. These include; lack of clearness, lack of notable change, ensuring the significance is apparent, and lacking in clear usage examples. These values increase the likelihood an audience will fail to pay attention to the communication.

3. The Innovative Journalism: Enhanced Creativity Tools approach (Andreassen, Polden et al. 2018).

This research has most recently been championed by the Innovative Journalism: Enhanced Creativity Tools (INJECT) program funded by the EU. This program sought to build on innovation journalism to create additional understandings of how to effectively communicate innovations. Whilst the research highlights the need to build, strategy, clarity and relevance this approach focused on the use of a 'creative discovery engine', an approach that highlights the need for creative exploration of the topic by those who understand it. This INJECT system aims to bring journalists closer to the innovations by giving new angles to view these innovations from to make them relevant and accessible to others. These 'creative sparks' are generated by an algorithm and work to help provide additional connections in which users can ground users understanding of the innovation. The INJECT system supports this creative by connecting journalists with resources which make the innovations more understandable by using open source content and existing educational resources such as YouTube videos(Andreassen, Polden et al. 2018). By reviewing these three different approaches to innovation communication, some consistencies could be observed.

Strategy – The need for a planned strategy to make communications effective appears in each innovation communication strategy. This ranges from planning a communication campaign, to plotting how specific communications should be attempted. This strategy involves an assessment of both the audience and the innovation being communicated, with the goal to understand how the audience may react to the concept and how complex the innovation is. A good strategy will encompass a clear understanding of the innovation's nature, how it fits with the audience's understanding and works to target the audience's specific needs and interests clearly.

Clarity – The clarity of the communication is paramount. The ability to produce clear communication lessens the energy that must be invested to understand the innovation by the audience, maximising its' potential to be used. Clarity can be provided by careful consideration of what is being communicated along with supporting the communication with multimedia approaches that aim to provide multiple methods to understand the innovation.

Relevance – The communication of innovation must be relevant to the audience to be successful. Each tool focuses on how innovations need to meet the audience's understanding and adapt to work with that frame of reference. This requires the communication to work within their knowledge and for the explanation to help them visualize the innovation enabling them to meet their goals. This helps the communication be understood and be given priority so that it might overcome concerns such as risk to the business.

Creativity – The communication of innovation must be creative in how it is approached; a single direct approach risks a lack of clarity or relevance to all. Being creative in not only how a concept is explained but also how it connects with other resources to help readers understand the content.

An example of a piece of innovation journalism that embraces these factors is the BBC's continued coverage of the radically innovative smart material graphene. Graphene is referenced earlier in this literature review as being a source of confusion as those who communicated focused to highly on its capabilities rather than limitations. However, the BBC has consistently covered graphene for over a decade and in this has shown it can exemplify effective innovation journalism.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The little graphene dress unveiled in Manchester

An innovative dress made from graphene has been unveiled.

Cute Circuit have designed the dress, which can change colour and design, in conjunction with scientists at the National Graphene Institute in Manchester and intu Trafford Centre.

Graphene, which has been hailed as a "wonder material", is tougher than a diamond but stretchable like rubber.

A form of carbon, it was discovered in 2004 by Andre Geim and Konstantin Novoselov who were awarded the 2010 Nobel prize in physics for their work on the material.

25 January 2017 | BBC News | Manchester

Figure 4: Little Graphene Dress report (BBC 2017)

At the earliest stages graphene was communicated in general terms, example of potential uses were provided and the possibilities were explored lightly, over the last five years in the BBC has consistently shared graphene based content, not only exhibiting examples of it in practical use such as dresses and cars, but also in examples of more technically challenging concepts such as power packs. There is a clear strategy in the communication with a diverse nature of content ranging from articles and videos that focus on educating children to content entirely aimed at business. In most of these documents there is a clear goal to make the content clear and relevant to those it is targeted at, while also a creative use of metaphors and examples to make the content connect in different ways. To achieve this education, they do everything from pulling in experts to using pop culture references to make the content land with the maximum amount of people.

2.4 Design

'What is design?' has been a topic of debate since at least the 1960s when design research was first formalised. While this might be the beginning of the academic debate, it is hard to understand the actual age of design practice, exactly why will become apparent through discussing the definitions placed upon it (Cross 2007). In the seminal work 'Design Methods' by Jones (Jones 1992) initially published in 1970, he looks over the ten years of definitions supplied by the respected academics of the time and found minimal consensus as to what exactly design is. This confusion has not yet abated. With the subject being the focus of entire thesis' even in the last year, which found that not a single method to define design but instead produced a model to define the different elements of the design ecosystem(Stevens 2019). In short the nature of design as a single definable concept is impossible as it encompasses so much (Design Council 2009).

2.1.2 **Design thinking**

A designer's way of thinking is so different from other forms of thought that a whole industry exists to now teach design thinking(Wrigley, Mosely et al. 2018). Design thinking lacks consensus as to what it is, with design academics, management consultants, and designers all having a different view on the topic (Carlgren, Rauth et al. 2016). The roots of design thinking are connected to a study by Lawson and Bryan (Lawson, Bryan R. 1972), where they found design thinkers differed from others as they seek the most favourable solution to a problem rather than trying to understand the full details of the systems involved. This unique method reflects what problems designers are trained to deal with. Many professions concern themselves with well-defined issues which require an entirely different form of thinking than ill-defined problems which designers routinely face.

Design thinking produces solutions that are very creative, often using elements from outside of the systems involved. The ability to apply concepts that are not fully understood but work, creates ideas which are not apparent to others. This creativity though is not unbounded. Design thinking consistently seeks results in the ideas it generates, hoping to solve the problem efficiently(Black, Gardner et al. 2019). To ensure the ideas are appropriate, designers use their prior knowledge and transfer that to the current challenge (Roy 1993). Designers are very capable of applying their past experiences to the design challenge that they are currently facing even when those experiences are not directly relatable. This knowledge can be experience or a direct precedent, a solution they have seen in the past to this problem. Designers use this knowledge knowingly or unknowingly to guide their work (Pasman 2003). Designers say though, that the vital element to their thinking is intuitive assumptions which guide their work, enabling them to explore new ideas and create possible options without complete certainty of their applicability, to be refined later (Taura, Nagai 2017). This reliance on intuition is no surprise as past experience and intuition are one and the same (Klein 1999).

Developing a reliable system to communicate radical innovations may be a challenge given how designers think. Nigel Cross (1997) defines that design thinking while seeming at times chaotic is a repeatable process that uses prior knowledge to create new ideas. This process of design thinking has been developed to such a degree that the global consultancy of IDEO sells training as a core way to build value in companies (Johansson-Sköldberg, Woodilla et al. 2013). Design thinking follows the idea that the challenges and briefs designers face tend to be undefined and somewhat fuzzy, in that there is no clear goal. This means that designers are often developing their understanding of the problem and the solution simultaneously, while this may appear counter-intuitive to some it has been shown to help generate the 'creative leap' which is how designers can create something new (Dorst, Cross 2001). Table 2 describes the differences between well-defined problems.

Well defined problems	Ill-defined problems
• Present all elements of the problem, • Are presented to learners as well-defined problems with a probable solution (the parameters of problem specified in the problem statement), • Engage the application of a limited number of rules and principles that are organised in a predictive and prescriptive arrangement with well-defined, constrained parameters, • Involve concepts and rules that appear regular and well-structured in a domain of knowledge that also appears well-structured and predictable, • Possess correct, convergent answers, • Possess knowable, comprehensible solutions where the relationship between decision choices and all problem states is known or probabilistic, and • Have a preferred, prescribed solution process.	• Appear ill-defined because one or more of the problem elements are unknown or not known with any degree of confidence, • Have vaguely defined or unclear goals and unstated constraints, • Possess multiple solutions, solution paths, or no solutions at all, that is, no consensual agreement on the appropriate solution, • Possess multiple criteria for evaluating solutions, • Possess less manipulable parameters, • Have no prototypic cases because case elements are differentially crucial in different contexts and because they interact • Present uncertainty about which concepts, rules, and principles are necessary for the solution or how they are organised, • Possess relationships between concepts, rules, and principles that are inconsistent between cases, • Offer no general rules or principles for describing or predicting most of the cases, • Have no explicit means for determining appropriate action, • Require learners to express personal opinions or beliefs about the problem and are therefore uniquely human interpersonal activities. • Require learners to make judgments about the problem and defend them.

Table 4: Differences in problem type - summarised from the work of Jonassen (Jonassen 1997)

Well-defined problems suit systematic evaluation and can be assessed with an identified objective scale and most importantly have a ‘correct’ answer, Ill-defined problems however do not have an objectively correct answer (Pel 2018). Designers do not have this goal as there is no ‘correct’ answer so they must search for the ‘best’ answer (Cross 2001). As a result, the designer’s method of thinking does not concern itself with a complete understanding of the problem. Designers instead look to other sources to make their decisions. They become “ill-behaved problem solvers” (Cross 2001). This is the process where instead of finding all the data, the designer performs ‘problem-scoping’ to gain an overview of the challenge facing them and prioritize the criteria they must fulfil. While designers are problem solvers, they are not problem-focused, instead, designers mostly focus on the solutions, and this can be seen in expert designers (Cross 2004).

Designers do not see the challenge issued by a client as a rigid brief, but as starting point to explore potential solutions (Cross 2011). The designer uses their problems solving skills to discover the extent of the problems faced by the client and resolve them. This ties the problem and solution together as they do not necessarily follow one after the other, instead the problem may support the creation of ideas and concepts that can then be developed further (Taura, Nagai 2017). To explore the brief designers will balance their understanding of the problem and their ideas for a solution upon information gained throughout the process

(Kruger, Cross 2006). Designers find this balance to be different and their focus may be roughly grouped into four types depending on a designer's preference for how they gather information, described below. This division is by no means rigid and a designer contains aspects from all four types to come to the right design solution. Some are surprised that information gathering is not considered more important in design especially with large ill-defined solutions but in the process of design thinking, there is an issue with design fixation, where designers create a concept and then hold on to that concept against all others (Lawson, Bryan 2006).

Problem-driven design	Problem drive designers focus on the brief and providing definition to the problem that must be solved, gaining a good understanding of the whole problem.
Solution-driven design	Solution-driven designers focus on collecting the necessary requirements from the brief and only delve deeper into the information if it is required for a specific solution. They prioritise production of solutions either producing many or iteratively working
Information-driven design	The designers prioritise collecting information related to the problem. They try to define the problem as strictly as possible; this reduces the number of solutions.
Knowledge-driven design	In knowledge-driven design, the brief is read carefully, and the designer compares the brief to similar known problems. Mostly past experiences are relied upon unless proven wrong and entirely new aspects are explored through gathering information.

Table 5: Types of design - Extrapolated from Kruger (2006)

Designers cycle through their connection with each of these values with iterative designs that is essential to the design process. Iterative design is the process of producing concepts and then revising problems as they become visible. This has long been a core understanding of how design functions and continues to explored in models and academic discussion (Camburn, Auernhammer et al. 2017). For many designers, the production of visual representations is essential to this process and plays an integral part in bringing order to the diverse information (Pei 2009). The reason that this needs visual representation is that design is mostly cyclical; a single solution is not produced and developed unless it is weighed against the other three factors. This constant weighing of factors is part of the design process which will be discussed in more detail later, but it is essential to understand that designers are often said to tackle problems in a process that resembles the graph below.

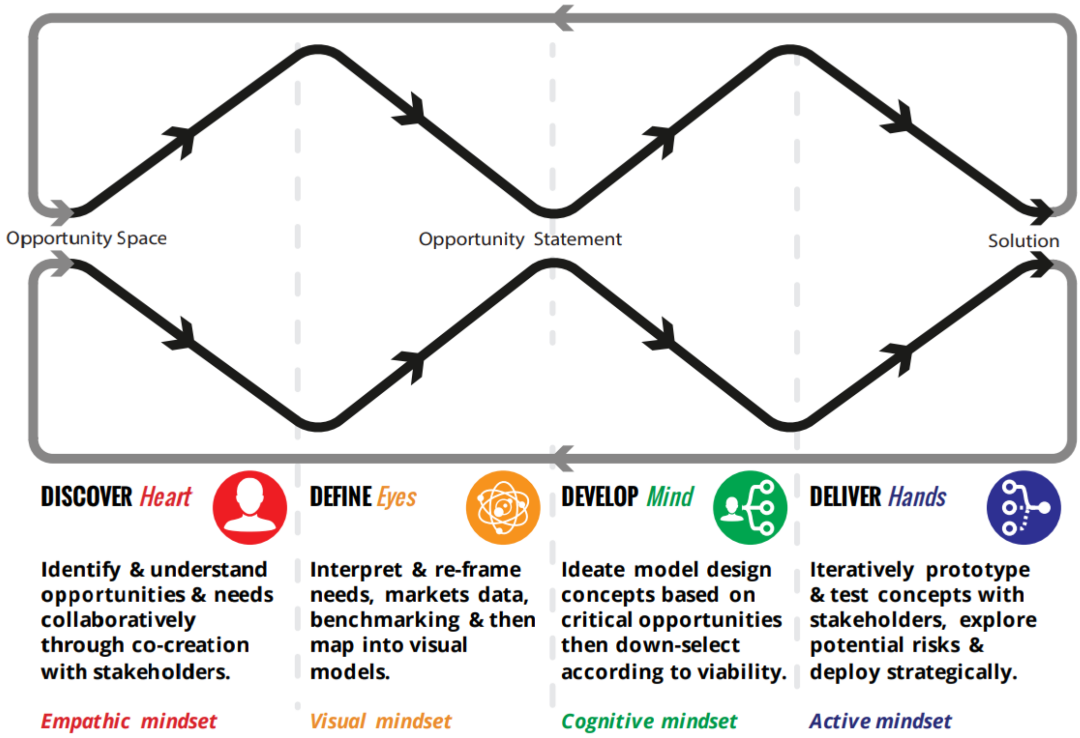


Figure 5: Modified version of the UK Design Council's design model from Camburn and Auernhammer et al. (2017)

The cyclical nature of design thinking is an essential component that enables design thinking to function. Each stage acts as period where designers are either exploring new ideas or re-evaluating the ideas that they have developed. In each of these stages designers can be pulling on the knowledge from other design challenges they have been involved in previously, bringing those part experiences in to increase their idea creation or improve their refinement of those idea (Press, Cooper 2017).

Designers are very capable of applying their past experiences to the design challenge that they are currently facing even when those experiences are not directly relatable. The prior knowledge can be from a related experience or a direct precedent, a solution they have seen in the past to this problem. Designers use this information knowingly or unknowingly to guide their work (Pasman 2003). Designers believe that intuition guides their actions, this is not only a belief but is also something seen in practice (Hamilton 2019). Intuition can be described as 'deciding advantageously before knowing' and is a proven psychological concept (Bechara, Damasio et al. 1997). Intuition can be responsible for very complex decisions and is based upon layered past experiences. It is used by people who need to make decisions under pressure with inadequate information (Klein 1999). The decisions are made by process of satisficing. This concept was first suggested by Simon in 1955, and involves mentally finding a satisfying solution that will suffice for the situation at hand by subconsciously looking through potential solutions and comparing them to prior knowledge(Simon 1955). The process of satisficing continues to be relevant today as it shown to be an effective tool for enabling the flexible behaviour of the design process (González-Valdés, de Dios Ortuzar 2018).

2.1.3 What aspect of the design process is being targeted and why?

While there has been extensive research on the topic of design process there remains little consensus on how to describe the method by which designers create (Clarkson, Eckert 2010). There have been numerous attempts to describe the process and many approaches have been posited. These processes consistently break up the design process into numerous stages, with each stage offering a distinct function that helps support the creation of new designs (Aspelund 2014). The work of Bobbe et al. (2016), looked to assess the different processes that had been developed to pick out consistencies. Their work found that there are five distinct stages, 'analyse', 'define', 'design', 'finalise', and 'implement'. When looking to build materials into design in a way that will help the development of the material and allow its nature to be capitalised upon, it is essential to focus on the early stages of design. This is where the material is likely to make the most significant impact as the design will still be mostly unformed and able to be open to alteration (Van Bezooyen 2014). As such this places the first explanation and use of the design is likely at the 'analyse' or 'define' stages. This is the point at which designers are looking at the problem before them holistically and working on trying and selecting possible solutions to the challenge before them.

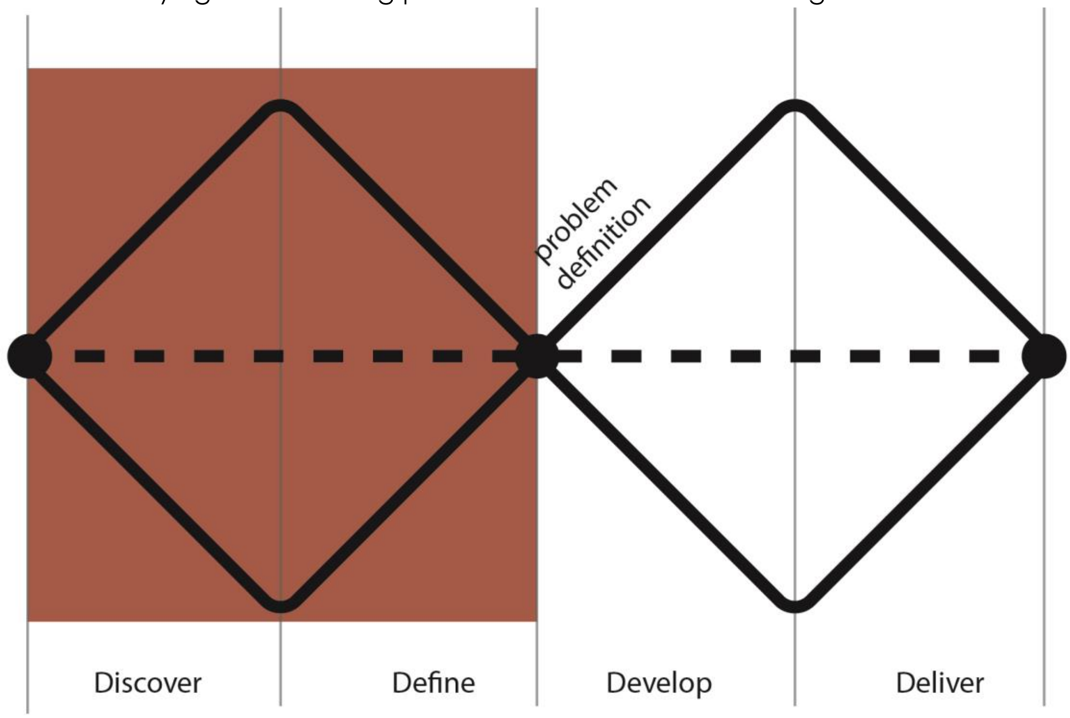


Figure 6: Design double diamond from the Design council (Council 2005) red emphasis added. The design double diamond was updated in 2019 to include a more detailed exploration of the surrounding support structure which has not been featured.

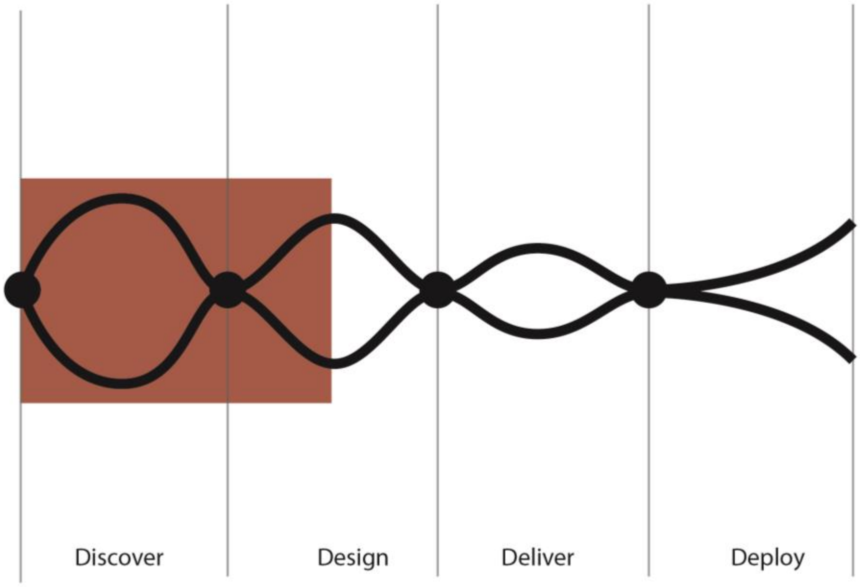


Figure 7: Design process proposed by Frog (2014) red emphasis added.

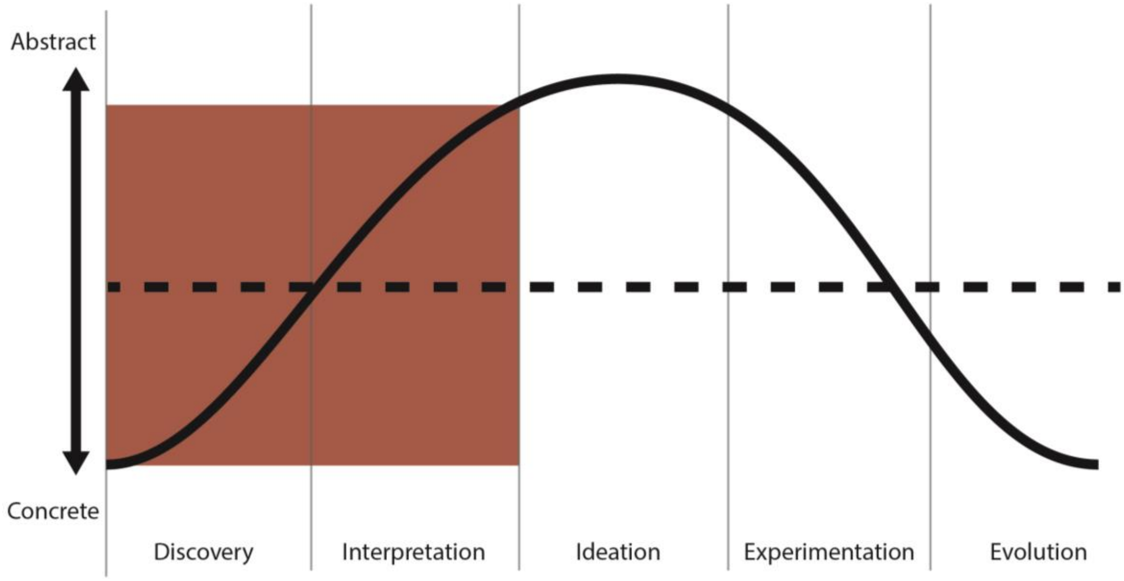


Figure 8: Design process from IDEO (Ideo 2014) red emphasis added

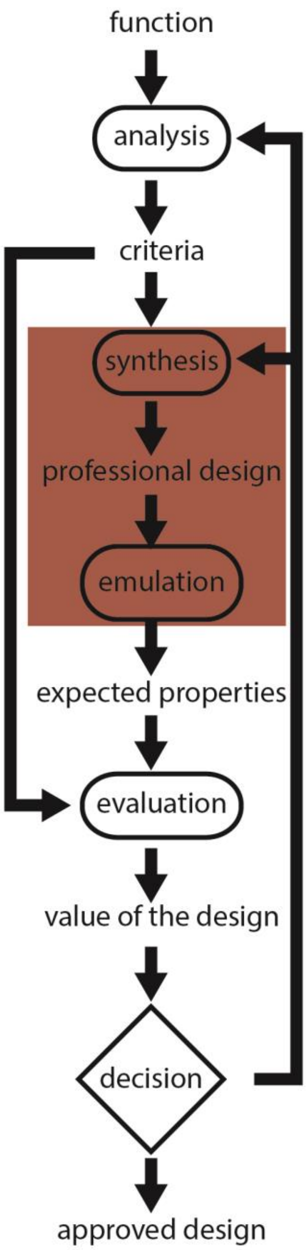


Figure 9: Design process from Roozenburg and Eekels (1995) red emphasis added.

As discussed in this literature review the focus on the early stage of design highlights the importance of accurate communication. Highlighted in red is the area in which a new material would benefit most from being introduced. These stages are often called ‘discover’ or ‘explore’. These stages are critical to the creation of the initial designs as it allows the designer to both explore the needs of their audience and the methods by which that need could be met (Aspelund 2014). Encountering new materials at this stage offers the designer solutions and informs the designs at later stages. Poor communication at this stage risks the designer moving forward with incorrect designs without realising that the communication is flawed. The images above show how far it is possible for the concept to progress with this flawed understanding, often only being stopped when prototyping and practical evaluation of the concepts begin in a ‘design’ stage. The ability of miscommunication to progress into the design process wastes designer’s energy and effort on the false concept, leading to a need to evaluate all the designs that have been created and potentially force significant changes to the designs if indeed they are still feasible.

2.5 MATERIAL SCIENCE

Material science is the process that creates new materials or alters existing materials from their natural state. This process can in some way thought to have begun 2 million years ago when our earliest ancestors found ways to sharpen rocks, how progress now allows for the creation of better solutions for every product-based industry from medical tools to microchip components. Material science has benefitted massively from the recent scientific developments which has rapidly accelerated the process of exploring new materials. Much of material science is now focused on changing small details of both organic and inorganic structures, however sweeping changes remain possible as new frontiers are found (White 2018).

Material science focuses around three primary materials groups; Metals, Ceramics and Polymers (Callister, Rethwisch 2007). These material groups are based around the type of the chemical bonds produced, and the goal of material scientists is to find stable solutions which provide beneficial material properties. These properties are balanced between needs for changing the structure, processing, performance and properties of the material. While some of the work completed in material science is simple enough to be conducted at home, many developments can only be completed with state-of-the-art equipment(González-Viñas, Mancini 2015). This necessitates a rigorous scientific culture that shapes those who work within it.

Materials science offers a widely varied way to create new materials, and the practitioners of this skill can differ in the extreme. The research, production, experimentation and goals of the scientists can all be radically different. With their topics so split the practice of material science can take individuals down very different and specific paths the unifying feature is the pursuit of these new materials or refinements to known materials.

Producing innovative materials is a very time-consuming process. It often takes twenty years or more to develop a material to the point it is commercially viable. Innovations also then need to be tested by companies who will use the material which may take additional time that can range into years. As such, innovations in material science are on a very different schedule to product and service innovations (Boren, Chan et al. 2012).

A vital issue with material innovations is that the initial discovery is done under lab conditions in tiny batches. This new material while engaging requires further development to be made suitable for the mass production scale required by the market. Scaling this up can be a more significant challenge than discovering the material and often contributes to the long innovation cycle (Jia, Wei 2019). Throughout this period, the material is unlikely to be producing income and means the development is running at a loss, relying on investment and external funding. This can limit the innovation dissemination material (Colapinto 2014).

Numerous issues stem from this long development cycle as often materials get their significant reveal years before they are publicly available. A lot of the press about new materials can appear years before they are available, allowing them to become forgotten or for the limitations and abilities to be misreported. This can be clearly seen in the case of the material 'graphene', a radical innovation, which has been talked about for over a decade but is only now becoming widely commercially available (Guasch, Cortiñas et al. 2019). The initial hype overvalued certain aspects of the material and misled some about the strengths of the material. As a result, cluttering the materials innovation field is information that does not accurately represent it. The usual methods to share innovations cannot account for the difference between material science's innovation cycle and the product innovation cycle (Nanlyze 2017).

David Ball estimated 20 years ago that there are some 40000 to 80000 materials for designers to choose from (Ball 1999). With this number almost certainly grown, it is essential to specify what kind of materials this research will cover. As designers may use any materials in their work, the research will not exclude material types. Equally, what stage of material processing designers start to choose and influence the materials they use can differ wildly. To ensure the materials picked reflect what designers regularly use, this research will use materials that are likely to appear in materials libraries at the stages of processing presented in those libraries. These existing resources are built to cater to designers and as such, could be considered a good reflection of the kind of materials they are interested in and used to dealing with. This is discussed in more detail later in the literature review.

2.6 MATERIALS AND DESIGN

Materials communication to designers has up until very recently lacked support from researchers. The new research has expanded though over the last ten years to explore in far more detail the role of materials in design. This research focuses on how to communicate specific material attributes in a language that is useful to designers (Karana, Hekkert et al. 2009). This focus on design has also spurred on the concept of materials as a motivator for design has only recently been explored with 'Materials Driven Design' (MDD) becoming an expanding area of research. MDD focuses on how designs can be motivated by materials rather than designs specifying a need and then looking as to which materials can meet that need (Van Bezooyen 2014).

Current research on how best to communicate materials and bring them into the design process has generated several different approaches. This diverse array of approaches reflects the full range of materials that are of interest to designers. Much of this research focuses on material 'experiences', which cover how the physical sensation of interacting with the material can elicit responses from users (Karana, Hekkert et al. 2009). This research while important is not necessarily directly relevant to the communication of radically innovative materials. However, a review of those topics has found that there are some consistent recommendations that are important to factor into future research.

Use of material samples – Material samples are a core tool by which materials are communicated to designers. The use of such samples is not just recommended but is seen as vital to communicate material experiences effectively. This is due to designers requiring the sample to explore the available experience fully (Wilkes, Sarah Elizabeth 2011). Using samples also offers the ability to unify design understanding in a way that other methods may struggle to equal. However, merely providing samples is not enough to drive a comprehensive understanding of the material and there is a need for supplementary information to support the material for the communication to be effective (Akın, Pedgley 2016).

Use of designer focused language – Designers think like designers when encountering new materials, the language that is used to communicate the material to them should reflect this. Much of the available research looks to avoid language which is engineering-based which can leave designers with little support in the early stages of the design phase (Karana, Hekkert et al. 2010). Different researchers have come up with different approaches, but these tend to be specific to a category of materials such as textiles or aim at a certain form of interaction such as emotions. The specific teachings do not apply to innovations, but there is a consistent recommendation to use language and wording that fits with designers' understanding of the world and to avoid language that is not intuitive to them (Rognoli, Levi 2004).

The need for a different approach when dealing with smart materials – Literature on the use and communication of smart materials within the design process highlight how different these materials are from other materials. Bergström, Clark et al. discuss that due to the transitional nature of the materials, designers must have a higher level of engagement than other materials, requiring the materials to both be thought about and discussed differently (Bergström, Clark et al. 2010). This pressure is not just on the communicator but also on the designers, with research indicating that the process they need to follow to use smart materials is also different, and different questions need to be asked of smart materials to get the most out of them (Nilsson, Vallgårda et al. 2011).

2.6.1 Designers using radically innovative materials functions like open innovation

Using radically innovative materials is different from using conventional materials because radically different materials require additional knowledge to comprehend their function due to their difference from established norms. Established materials that are already in use in a great many applications or incremental innovations on established materials, can be explained by those who used it previously and in case of very traditional materials such as wood practitioners can pull on thousands of years of experience to guide them.

To use these radical materials, designers often need to connect with those who created the material or represent them. By doing this, they can help accelerate the development of material science. This knowledge exchange is potentially in both directions as the designers explain what they want, and the materials team explains the potential and limitation of the material. This may also be only a one-way conversation with the material scientists providing reams of guides and other data. This need for collaboration is also a recognized part of innovation dissemination.

This knowledge exchange is very similar to the process of open innovation, which was initially championed by Henry Chesbrough (2003). Open innovation is the concept that innovation can be boosted through the free sharing of ideas, stating that competition should come from business models and practices rather proprietary ownership of patents. The concept has seen widespread popularity, and a wealth of knowledge exists on how to utilise this innovation and business model fully, institutions and practices have even been built to capitalise on the idea (Bogers, Chesbrough et al. 2018). This use of radically innovative materials is similar to open innovation, as designers are reliant on sharing concepts with manufacturers, as they are unlikely to be able to control access to the material, and when they release the product, it may be copied or improved upon by competitors.

Chesbrough(2003) summarised that open innovation begins by creating relationships that allow for knowledge flows. This allows the companies involved to absorb external technology into the company while sharing ideas to others in their market. Finally, this leads to a change in the business model, shifting to support an open rather than closed research practice and relies more heavily on integration with other sources (Leitão 2018). This maps relatively closely to the relationship between designers and materials scientists. It, however, is not present in conventional materials used.

Open innovation stage	**Role in radical material use**	**Role in conventual material use**
Network connection	Requires a conversation between manufacturer and designer	Not necessary, can be an entirely one-way dialogue between designer and supplier.
Knowledge transfer	Requires the manufacturer to communicate limitations and potentials to the designers. The designers may also request changes.	No new knowledge gain is necessary.
New technology absorbed	Understanding of new technology is built into the designer's skill set.	While additional skills may be developed, it does not require new technology
Ideas shared to market	Design can be inherently difficult to copyright. Sharing finished products may be considered as doing this, but it is not the goal.	Design can be inherently difficult to copyright. Sharing finished products may be considered as doing this, but it is not the goal.
Change in the business model	Depending on the success of the venture, a different partnership may be considered.	Even if a product is thriving using a conventional material, there are minimal benefits to partnering with a single manufacturer.

Table 6: Open innovation compared to use of radically innovative materials by type based on stages outlined by Chesbrough (2003)

While the similarities are not complete, core parts of open innovation apply to the use of radical materials. In addition to similarities, there is support for design to use an open innovation structure to get more significant results out of new technology like radical innovations. However, this support comes with the warning that open innovation structures cannot be applied to every project in the same way (Christiansen, Gasparin et al. 2013).

Open innovation has been established to be a useful tool in supporting the creation of radically innovative products (Inauen, Schenker-Wicki 2012). It is often used as it allows for the flow of knowledge that is essential when using radical innovation to travel from one group to another, tackling issues such as cognitive distance. Any open innovation needs a structured approach to be useful though, without an effective structure the benefits of open innovation can easily be lost to aggressive competition or internal frustrations(Bogers, Chesbrough et al. 2018).

An example of this open innovation practice within product development of a radically innovative material is mycelium packaging. Made from fungal growths it has properties that make it suitable for replacing plastic packaging (Karana, Blauwhoff et al. 2018). It has been the focus of several open innovation sessions to look at how plastic packaging could be replaced. In addition, the companies producing mycelium have embraced collaboration. One supplier (Evocative) has cooperative labs with which customers can tweak the product and discuss the material with experts. Changes like this have allowed IKEA and Dell to start producing packaging from the material which suits their needs (Gosden 2016).

Academic institutions also leverage open innovation for material development. 'The materials project' an online resource that combines open computing with a design for inorganic compounds and it is the subject of considerable research and has helped to develop new material applications through design (Jain, Ong et al. 2013). It is crucial that scientists can take up a roll of enabling communication as it is seen to add to public knowledge of these ideas significantly (Jucan, Jucan 2014). Including designers in this process also boosts the potential in the market. Including designers in the dialogue about the use of material, innovation is helpful because they can deliver a competitive advantage to new technology. Designers have been proven to add value to companies in some ways.

Some add value through being the creation of innovative designs that make companies services or products more appealing. Others offer effective product design does not just make a company more competitive it can also increase the return on investment over the project lifetime (Hertenstein, Platt et al. 2005). But most importantly, considering the focus of this research being upon the creation of products with new materials, it is essential to note that one of design's greatest strengths is in improving the chance of new products' market success by making it more appealing to those who will use it. This value comes from the ability to tailor products to customers' needs by understanding those needs and how to meet them (Heskett 2017).

Open innovation and the material sharing process mix people from different academic backgrounds. When looking at designers using new materials, the groups that need to be targeted are designers and materials scientists. This process of communicating how the technology works and how it can be applied is called knowledge transfer, a term that was championed by Argote & Ingram in 'Knowledge Transfer: A Basis for Competitive Advantage in Firms.' They point out that the ability to transfer knowledge has a direct effect on the success of a business that wants to use new technologies (Argote, Ingram 2000).

Effective knowledge transfer is essential to the success of a new innovative material (Alisantoso, Khoo et al. 2006). However, the need to transfer the knowledge of materials scientists to designers poses a challenge. This issue arises from the different way their disciplines work and how that shapes their minds and expertise. Each group is notably different. This stems not only from what they know but how their knowledge is applied and the processes they use. This difference is sometimes referred to as cognitive distance as defined below.

'Reversely framed as shared cognition, describes the degree of similarity among actors concerning their representations, interpretations, and systems of meaning or beliefs about the types of issues perceived to be important, how such issues are conceptualized, and alternative approaches for dealing with such issues'(Cohen, W. M., Levinthal 2000).

The higher the cognitive distance, the more likely there are going to be issues in knowledge transfer. Just reducing cognitive distance is an imperfect solution though. Having cognitive distance between groups is essential in open innovation projects; it is a pivotal way to produce new forms of innovation as those with different mindsets work together to produce never seen solutions (Filiou, Massini 2018). This is the main reason that multi-disciplinary groups are formed in the first place (Muscio, Pozzali 2013). The challenge of knowledge transfer is best looked at as pieces of information that must be communicated effectively from one party to another. This communication is also the expectation of understanding; the source and recipient must be able to use the information once it is communicated.

2.6.2 **Innovation in businesses**

Radical innovations are linked closely with disruptive innovations. Radical innovations create new capabilities which can create a new market or value, the two factors which define disruptive innovations. This close link can make companies wary of radical innovation. Companies and entire industries have been wiped out in the past due to disruptive innovations. An example of this has been the complete coup by the LED lightbulb over the incandescent bulb. Originally seen as a niche option, LED bulbs continued to evolve to offer better energy efficiency longer life and provide more colour options (Udovychenko, Suprun

2019). Incandescent bulbs not only started to lose their edge on value but as the world moves towards a more sustainable system, they were in fact legislated out by the EU and other countries, with more joining each year. This disruptive innovation began with a radical shift in how the bulbs were made which interested few but now is routing incandescent bulbs from markets all over the world (Wei 2016).

The goal of this research is concerned with the development of a system which would allow designers and materials specialists to transfer knowledge between their disciplines with greater ease and less cost when working together. This will potentially allow better innovation at a lower cost. This interaction is being improved by reducing one of the main challenges of knowledge transfer 'absorptive capacity.' Connected to cognitive distance, this is a measure of the ability of the company to properly understand the communicated information (Egbetokun, Savin 2015).

This is targeted in three ways;

1. Transfer: What information is transferred is very important; relevant & applicable information must be prioritised, and irrelevant information should be removed.
2. Tools: A careful selection of tools brings the source and recipient in a knowledge transfer scenario together and allows for a better learning experience.
3. Method: How the transfer of knowledge happens must be based in traditional and relevant teaching methods as due to the difference in disciplines radically new information may need to be learnt (Szulanski 1996).

Key to transferring this knowledge is the process of selecting what to transfer. As part of this transfer process it is essential to understand what can be transferred and outline exactly what it can be transferred. It has been argued by Nonaka (Nonaka 1994) that for information to be transferred it must change from a tacit unformed knowledge base to an explicit definable knowledge base, setting clear boundaries and limits on what needs to communicated for comprehension. This converts the information into a useable structure that can then be fully communicated to those with different knowledge bases. This builds on the need to develop clear systems of communication that is prioritised by modern organisational learning approaches. These approaches highlight that a clear system for communication is built upon the codified knowledge base and tested system for communication (Basten, Haamann 2018). This process helps create systems that can enable companies and individuals to reliably understand the threats and opportunities.

2.7 Communication

In this thesis, communication is discussed frequently and improving communication is considered a core goal of the research. As such, it is essential to specify precisely what is meant when this document refers to 'communication' and what is meant by 'successful communication'. This research will tweak the definition provided in the introduction to provide a more tangible goal for testing. In addition, a description of what shall be considered successful communication is listed below. This is based on the observation that communication is the exchange of thought, knowledge or ideas (Littlejohn, Foss 2010). As such the definitions are listed below.

Communication: Communication is the process of imparting knowledge from a source to an individual or group who previously did not have that knowledge.

Successful communication: To be considered successful, those who have been communicated with must be able to use the new knowledge accurately when called upon to do so. Using the knowledge in this thesis focuses on the application of material knowledge to create designs that use the new material in a feasible manner.

Communication is what a reader is currently experiencing as they read this sentence. Defined as 'the act or an instance of communicating; the imparting or exchange of information, ideas, or feelings' communication imparts knowledge of some degree (Collins 2020). This definition though is lacking as communication is hard to define in a meaningful manner fully (Littlejohn, Foss 2010). While overall communication deals with a variety of information, in this body of work communication is focused on technical information — specifically, the accurate dissemination of radical innovations.

In any communication, there are at least two participants: the communicator and the recipient. For communication to be successful, the recipient must accurately gain the information the communicator is sharing (Beck, A., Bennett et al. 2013). Ideally, the recipient is then able to use that information and potentially spread it further. In this research, communication deals with imparting technical knowledge, aiming to reduce the cognitive distance between the two groups (Filiou, Massini 2018).

For this communication to happen, the communicator needs typically to understand the recipient. Their skills and knowledge will affect their ability to understand what is communicated. An effective communicator is not only aware of the subject they are trying to share but also how they can tie it to the recipients existing knowledge (Suter, Arndt et al. 2009).

This method of passing on information could be considered teaching (Hodge 2014). Teaching is its own area of communication, and this research project does not intend to focus on teaching due to the sheer scale of the academic literature, which does not explicitly target innovation, materials or design. Teaching is a vast area of research, not only defined by what is being taught but also who to and who by (Joyce, Weil et al. 2003).

The reliable and accurate communication of radical materials is a core concern in this thesis. The ability to consistently communicate new material abilities is essential to their dissemination to designers and future use in new designs. Without communication, the potential of radical innovations can go unused, and the innovation underperforms or worse, falls entirely out of use. This diffusion of innovation requires the designers and materials communicators to communicate in some form. This does not have to be direct personal contact but can be a written summary, demonstration or other systems that display the innovation's potential. If materials scientists create a concept and then do not let information leave the lab, it will remain there. Equally, if designers are not looking out for new innovations through press releases, media or demonstrations, there cannot be diffusion. Both sides are required to engage for innovations to spread (Kapoor, Dwivedi et al. 2014).

Established paths for the communication of innovations, including materials innovations, already exist. For materials, it is materials libraries and other online resources, as well as dissemination amongst manufacturers who can then recommend new materials when designers come to them with prototypes. However, these methods of distribution are not codified and not every material innovation can be accessed through them. Looking at effective means of communication for all radical material innovations is a core element of this research. Excellent communication leads to a greater diffusion of innovation. Any method that provides better communication tools for innovation can then be a method to improve the diffusion of these new materials (Andergassen, Nardini et al. 2017). As such the improvement of communication is paramount to the success of this thesis.

The first and most straightforward way to improve this communication is focusing on the media used to communicate. The capacity for knowledge transfer, no matter the content, will always be affected by the media used to communicate it. When transferring the knowledge, the form it takes is an essential part of the process of shaping how and what information is transferred (Haskell, ScienceDirect (Online service) 2001). A method to select communicative tools is being explored that would provide a way for engineers and designers to bridge the cognitive distance between them, as it forces communication down specific routes. This limits the extraneous information that might otherwise be introduced to the conversation and conflict with either disciplines capacity. This effectively removes some of the challenges of selecting the correct information to transfer. If both a designer and engineer can understand and engage with a specific system, either party can then select that system and be sure the information communicated in this form is understandable to both parties.

When the initial examination of tools used by both disciplines started it became clear that both groups had a lot of similar tools or the groups used the same tool in very different ways. The similarity is quite natural considering both groups concern themselves with the production of physical artefacts. The way the groups differed though was apparent, designers tools are mostly 'Uncertain' meaning that the tools leave room for interpretation, Engineers tools are almost all 'Certain' meaning that they communicate unambiguously though this does not mean that the tools do not provide options (Lenard, Pintarić 2018). This apparent difference in tools reveals a core difference between the two disciplines showing the challenge that exists in uniting these two groups. The most useful overlap with tools lies where both certainty and uncertainty are present. While this combination sounds improbable it is clearly present in tools which have a physical presence such as prototypes. Prototypes can be interpreted differently depending on the mindset of the onlooker. To an engineer they are a physical representation that shows what the designer wants to achieve, even low fidelity prototypes which bear little to no resemblance to a real working of a product may communicate this effectively. Equally, a high-fidelity prototype produced by an engineer will reveal to a designer the limitations of the system and allow them to see how it works without strictly restricting their imagination.

Any resources that bring both groups together within their comfort zone will be ideal to be expanded upon as it not only motivates those involved but also makes learning easier. While there are a number of other tools which both groups share the ease of using physical examples compared to other methods was witnessed by the author in practice and is used elsewhere by the likes of IDEO in their 'Tech Box' (Ideo 2014).

Figure 10: Ideo Techbox

One reason this was so effective was that each group could take the desired information from the physical product and question their counterparts effectively. This meant that the beginning of their conversation started with both groups happily in their area of capacity; if a question was asked which stretched their capacity, they could use the physical artefact as a tool to help improve their understanding, resulting in a 'step by step' increase in capacity tied to a core understanding that the recipient is comfortable with.

2.7.1 **Design communication**

Design communication is a large field that covers focuses on communicating different topics with designers. This communication includes a great deal of tools meant to enable designers to speak with companies and enable companies to speak with them. However comparatively few tools focus on the communication of the real-world limitations of the physical tools and materials they use. So as to not lose focus on the topic of this research this section will not examine the larger design communication in detail but instead focus on how design communication enables discussions about materials and production methods.

Before focus is brought to the more relevant design communication methods it's important to highlight what the larger design communication topic can impart. Key to challenge of design communication is the fact there is a lack that of formalised tools that enable this communication effectively. When those involved with design seek to communicate, they are often trying to explore ill-defined problems (see the design section of this literature review for more information) and provide solutions and options that don't have an objectively correct solution. These communications may also require the collaboration of multiple stakeholders who may all have different views on the topic which causes confusion around these unspecified topics (Sawyer 2020). This complexity isn't helped by the fact that designers communicated differently with users, suppliers and clients, let alone the fact that designers communicate differently based on industry they are in and the industry they are speaking with (Eckert, Stacey et al. 2013).

Attempts to better understand these challenges and create solutions focus around codifying the content to be communicated as well as creating processes to communicate this data. In this review two approaches will be explored but it is important to note that at the time of this publication no one system dominates, despite many being suggested. This highlights the challenge faced by those who seek to improve the general design communication. Much of the work on design communication focuses on the language used and knowledge base of designers. While exploring language there is a focus by design communicators to work with or around the visual nature of design. Some sources look to see how sketching, CAD and even virtual reality can complement design communication (Chalhoub, Ayer 2018). Much of this comes from the fact that these groups believe the best way to communicate designers' vision is to embrace their visual nature. Other tools highlight that visual mediums are not always the best resource to communicate with other industries and instead focus on normalising design language and bringing a formality to how designers communicate (Lee, Ostwald et al. 2020).

The language of those who do not prioritise visual communication connects with second priority of many design communicators, building a codified knowledge base. Those who focus on creating this codified knowledge base prioritise finding ways to bring specific and repeatable understanding to designers often ill-defined practices and processes. By doing so they aim to standardise how designer communicate, benefitting designers and clients. This process of codifying elements is currently sectionalised, as designers remit is so widely stretched that no one approach aims to codify all that designers do (Dong 2008). When looking at the communication of materials the current focus of much research is how to communicate the nature of that material, this doesn't focus on the objective qualities of the material but instead the sensations, and character of it, aspects that might be considered a subjective experience (Eckert, Stacey 2000). This research highlights how important these aspects are to designers who frequently focus on the materials attributes outside of its technical abilities.

In this specific design communication certain aspects of the designers thinking must be considered. One of the core considerations is that there needs to be different form of interface to communicate the materials nature as designers demand a more visual and intrusive system than is provided by data sheets (Lenau 2002). To meet this demand Ashby (2013) whose work has been much referenced and even help structure the CES material selector, a resource to select material for engineers and designers (Sörensen, Jagtap et al. 2016). This book, the 'Materials and Design: The Art and Science of Material Selection in Product Design" highlights numerous different pieces of information that help designers not only understand materials but also how to communicate their needs (Ashby, Johnson 2013). What is important is that this document does not itself rely on a specific formula or framework to communicate, instead it focuses on bringing together resources in a way that is design focused, prioritising comparison, and examples of applications. As part of this design process it uses lots of graphs and tables which are graphically stimulating and meant to better engage more visually focused designers. This is similar to approaches taken in the highly reviewed 'Materials for design' by Chris Lefteri and which embraces a similar approach (Lefteri, Sermon et al. 2014).

When it comes to specific strategy's or frameworks two approaches stand out as providing unique frameworks to aid communication. The first system focuses on the meaning of materials. This research by Elvin Karana (et al) (Karana, Hekkert et al. 2010) focuses on the exploration of the 'meaning' of materials, this being what those who handle materials think of them. This meaning includes, the values users attribute to sensations they experience as they interact of them, physically visually and auditory.

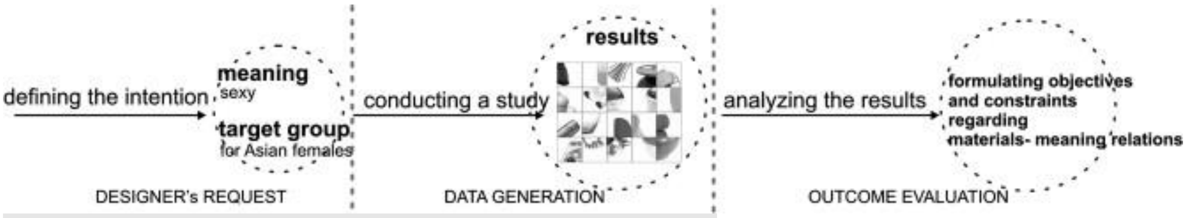


Figure 11: Steps in Karana's materials communication process

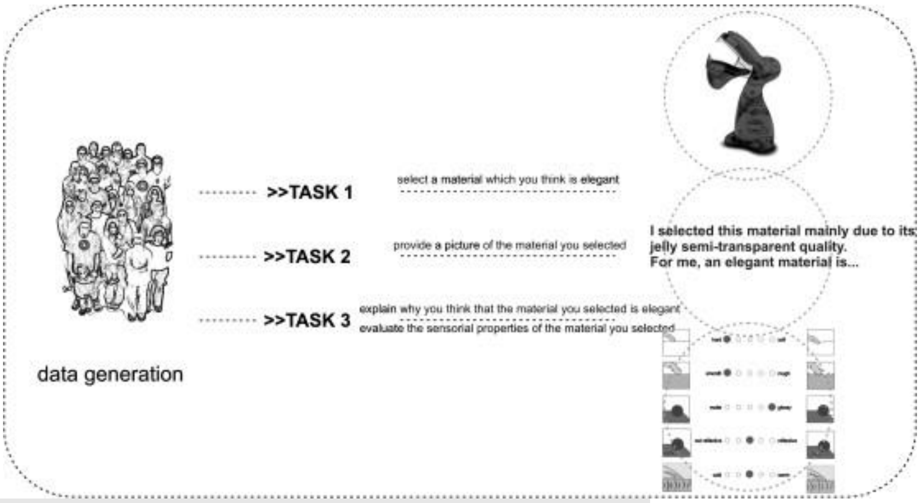


Figure 12: Overview of Karana's material communication process

The approach targets specific users to explore materials and highlight those they feel excel at creating a desired value. In the first stage the users are challenged to select a material they think has a specific meaning, one of 76 meanings defined by Karana and her team(2010). In the second stage the users are then challenged to produce a picture of the material they selected exhibiting the meaning, and finally they are challenged to explain their choice and evaluate the material on sensorial scales. These scales use images and a combination of objective and subjective language to help users explore their thoughts on the subject.

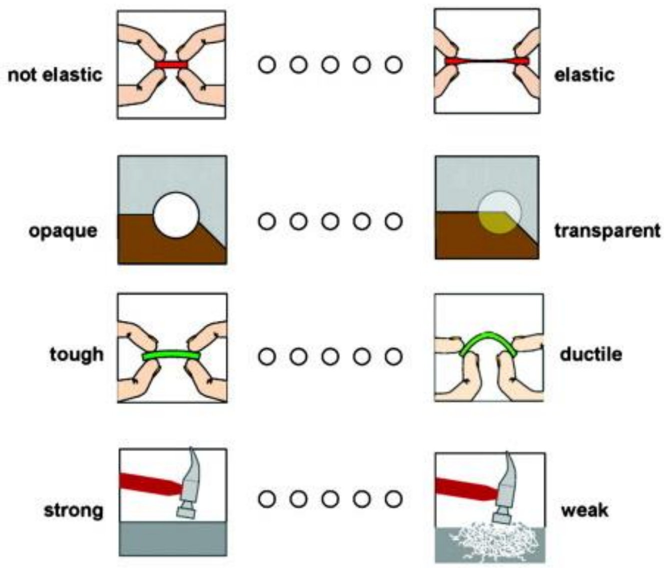


Figure 13: Examples of materials communications

This ‘meaning led’ communication allows designers to better understand the subject perspective of those they design for. This system though does not focus on communicating the capabilities of new materials to designers though, instead it focuses on their meaning. No part of this resource helps to communicate innovative materials to designers or helps materials communicators explore these materials with designers. It does remain one the most detailed frameworks for materials communication and undoubtedly has learnings that can be brought to the larger questions explored in this thesis.

The next tool is a collection of tools outlined in the ‘Design tools for interdisciplinary translation of material experiences’ developed by Wilkes et al (Wilkes, Sarah, Wongsriruksa et al. 2016) and combining work over several years to create a series of sensorial tools to communicate material properties. These practical examples to focus on standardising physical experiences. These physical toolkits standardised examples of samples that help explore auditory, taste and touch sensations. See images below for examples.

Figure 14: Taste material examples

Figure 15: Tactile material examples

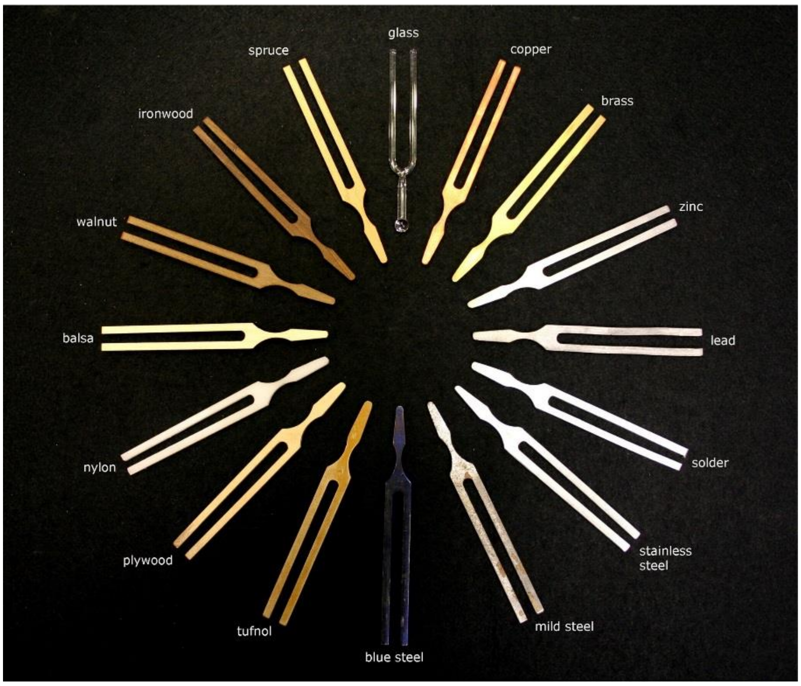


Figure 17: Auditory material examples

This offers a very different approach to Karana (2010), where users did the talking now materials lead the way. By creating standards that can be compared the toolkit enables discussion and communication. The benefit of these kits is they offer a universal language that can be shared by designers, clients, material communicators and users. The challenge of the kits is in need for customisation, as a specific example a communication set was made for the Light Touch Matter Material, a specific sensorial tool kit needed to be assembled to explore the specific abilities of the material. The challenge of this approach is the diversity of materials that must be communicated, and radically innovative materials often lack materials they can be easily compared against due to their nature. This does not mean the learnings cannot be actioned, instead it highlights the importance of including samples to as a means to communicate.

Established methods exist to support designers in communicating materials, these include concepts like the 'Materials in Products selection tool' and the 'Sensorial Atlas' (Rognoli 2010, Van Kesteren, Stappers et al. 2007). Both these examples focus on educating users in how to communicate the sensorial experiences they experience when handling the material, either so they can better communicate with clients or so they can better understand the connection to objective language. Both these examples focus on bringing a codified system or language to the sensorial properties of the materials, combining the elements seen in Karana (2010) and Wilkes (2016) work.

In all these examples there is little role for education about new sensation or abilities. No system seeks to engage designers with a new concept, instead it aims to bring a standardisation to known concepts. The only approach that does highlight new concepts is in books like those by Ashby (2010) and Lefteri (2014)which do not have a specific framework instead focusing on visualisation, comparison and contextual examples to explore the topics. This highlights a clear need for research that bridges that gap, providing a system that can help support these resources to bring new materials into designer's lexicon in a standardised format. The examples here also build upon the focuses outlined in the wider design communication discipline, the examples aimed to bring clarity to language used, and aimed to codify the knowledge that was being gained. Any future system generated by this research needs to have strong clarity on the language used, and what codify to some degree the knowledge being shared.

2.7.2 **Limiting knowledge representation in this research**

Designers commonly use visual methods to represent their thinking, knowledge and ideas to each other and others. This reliance comes from training, client expectation and the fact that designers are often working in a visual medium that needs communication. While this allows designers to communicate their design reliably, it is a challenge. Skill is required which places a pressure on the thinking of both those sketching (Song, Agogino 2004). Nearly all the tools for visual communication rely on the skills that must be developed over time. Designers develop these skills as part of their training but those wishing to communicate with them cannot be assumed to have that resource.

As such visual communication methods included in this research have been limited to the iconography that is already in use and images accessible to all. This includes imagery that can easily be sourced online. More accessible tools of communication are needed to ensure that this research is accessible to all those who would wish to use it. As a result most communication in this research is using verbal or written communication with samples. Neither of these tools requires specialist training to use. The ability to write and speak fluently in at least one language is something that can be expected of that anyone who works in materials science.

The ability to communicate in written or verbal communication is something that can be refined though, and numerous guides to how to improve this skill already exist. This research will join those guides in aiding otherwise fluent speakers of the language, in communicating radically innovative materials properties.

2.8 CURRENT RESOURCES FOR COMMUNICATING THE MATERIAL'S QUALITIES.

To understand what current resources exist to explain materials to designers, a study of the available tools was completed. This looked at all the major online materials libraries and books which were accessible and geared towards designers. Material libraries have become necessary due to the wide variety of available materials and the fact that designers lack a formal education in material science that would enable them to navigate these options effectively (Wilkes, Sarah Elizabeth 2011). Other resources do exist to select material, but these tend to be engineering-based, often full of technical assessments which are more targeted to the later stages of the design process and do not fully support designers (Karana, Hekkert et al. 2010). Requiring both specific knowledge and expensive access, these methods will not be reviewed.

The goal of this research is to assess the current on-demand information available to all designers, looking at how information is communicated currently and if there are any unifying factors in the existing system. Identifying key elements would provide an understanding of what tools designers are used to and what information they have come to expect.

Currently, a list of four primary resources have been identified as both accessible and geared towards designers. Some online resources have not been included, most notably Wikipedia. Resources like Wikipedia which are not being featured as they lack two core elements. Firstly, they are not explicitly targeting designers and secondly; it is not consistent in its content. A lack of consistency has also ruled out many magazines and other online spaces which feature new materials as the entries are not consistent, being written by many different authors with different goals.

The four resources being reviewed are;

- Institute of making's online library
- Granta: CES materials sampler
- Chris Lefteri's series of material books
- Material Connexion's online library

2.2.1 **Institute of making online library**

The Institute of making's online material library has grown out of the physical samples that library owns. With a strong history of sharing these materials with others through events and lectures, the organisation has a strong motivation to share knowledge.

Information presented

The information that the Institute of making begins with a large block of text that explains the product. This information is joined by a gallery of pictures. This gallery also has a couple of videos that further demonstrate the properties of the material. There is also minimal material property information that varies, based on what materials family the material being described belongs to. This includes the manufacturer. Finally, there is a list of associations that the materials had with other organisation uses and other materials.

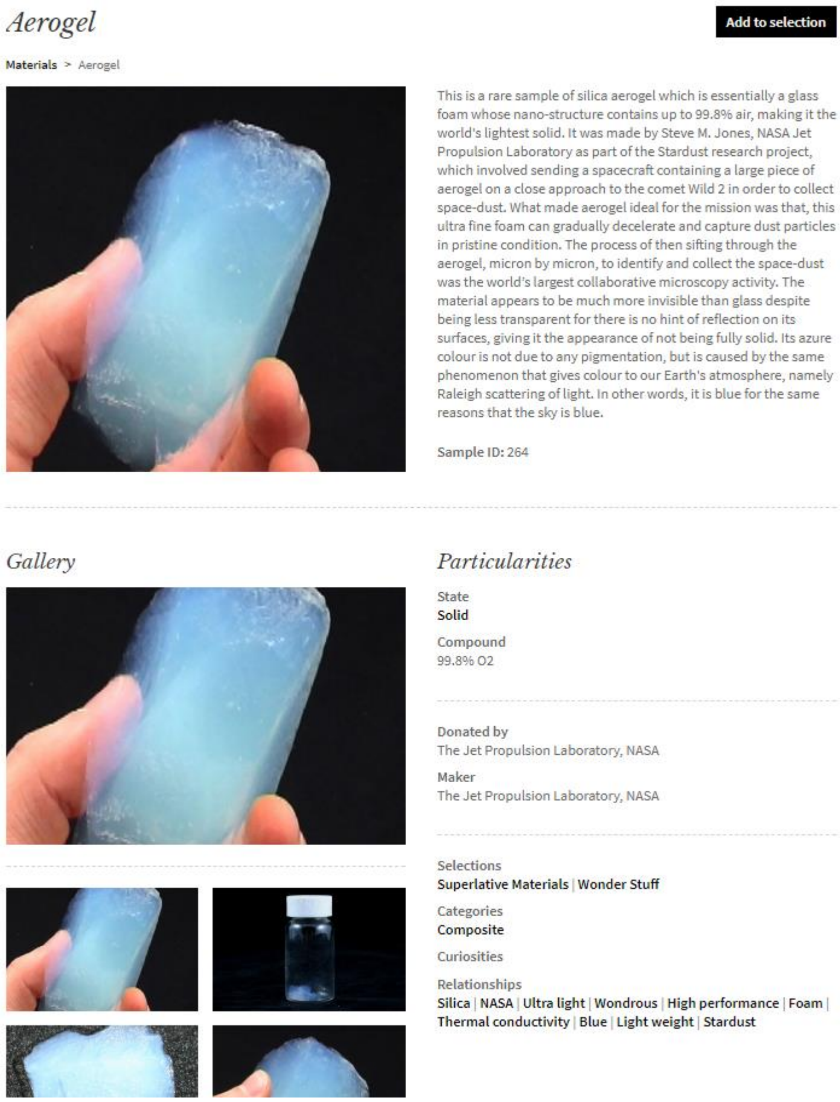


Figure 17: Screenshot of Institute of making online library

Advantages and disadvantages of this system

The advantages of the system are that:

- It illustrates the material and clearly connects it to its unique, innovative value.
- It allows the reader to see what class of material the featured material belongs to, allowing them to apply their knowledge of that class to it.
- Provides clear pictures that illustrate the material in reference to its actual size and composition.

The disadvantages are that:

- The information is not very detailed and what information is presented can focus on the history of the product, leaving it somewhat unrelated to the use the material in practice.
- Some information presented such as 'material state' which lists the material as solid, liquid or gas is somewhat redundant given the other resources presented.
- Lack of detail on manufacturing or use cases can lead to questions as to how the material can be used.

2.2.2 Granta: CES materials selector

Granta is different as it has several levels, the first level is the one which will be examined here. The detail about the materials increase per level as does the specification, a material which might just be labelled polypropylene in level 1 may be broken down into several separate types of polypropylene in level 3.

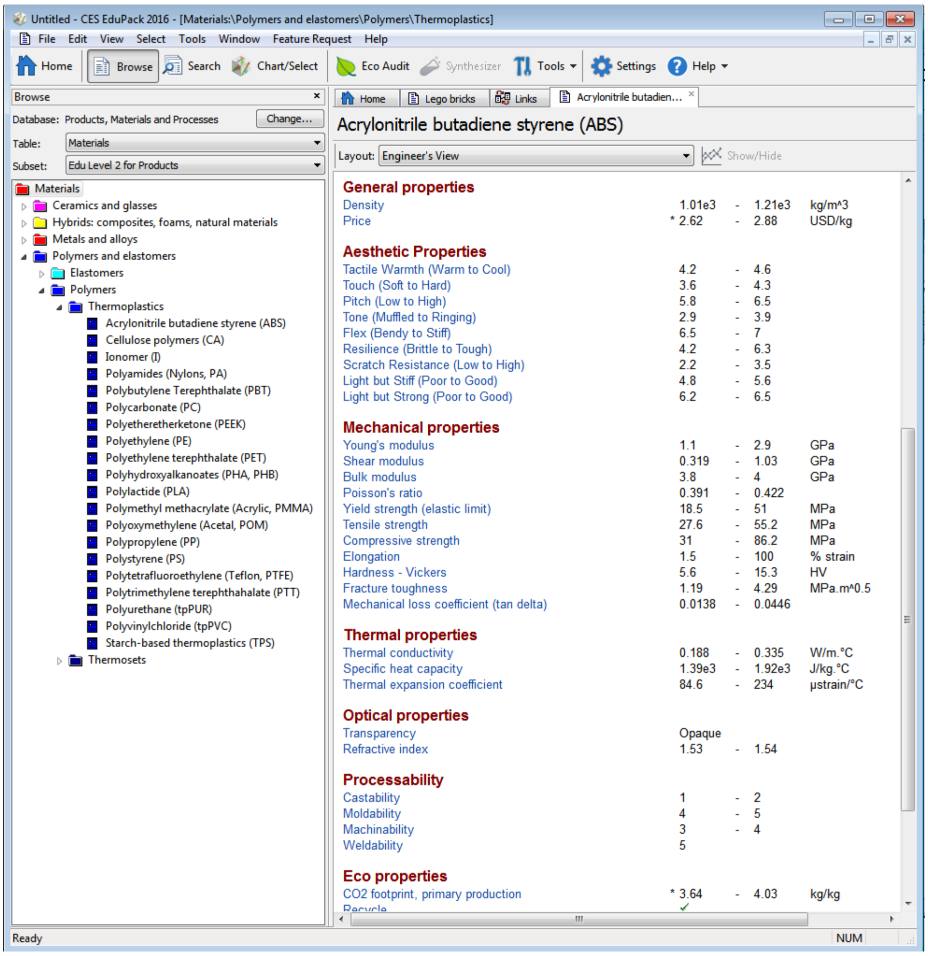


Figure 18: Screenshot of Granta CES materials selector tool

Information presented: The CES materials selector begins each material with Explanation text which covers what the material is, what is special about it and something about the process of the manufacturer. This gives an overview of the material; with some objective and scientific information about the materials origins/properties mixed with some subjective descriptions as well. It also provides info on the composition often giving the exact chemical combination. It then proceeds to list the general properties providing density, price, and mechanical properties. The list of properties is extensive including:

- Young's modulus, yield strength, tensile strength, elongation, hardness, fatigue strength, fracture toughness.
- Thermal properties including Melting point, Maximum service temperature, Thermal conductor or insulator. The information gives the temperature ranges that the material can effectively function within.
- Electrical properties; this section just states that the material is a good/bad conductor or insulator, excellent may also be involved; this is subjective.
- Optical properties; provides the quality of transparency.
- Eco property is a summary of how much energy is used up in production.

Finally, the summary ends with some supporting information, including a section on typical uses and links to providers and further examples.

Advantages and disadvantages of this system

The advantages of the system are that:

- It contains incredibly detailed information on the material. Including a wide range of mechanical properties.
- The explanatory text introduces the material in a high-level overview that brings attention to its innovative properties.
- Offers an overview of how the material might be processed and used.

The disadvantages are that:

- Lacks images of the material so it can be challenging to visualize what's described.
- Information provided can be inaccessible to designers not familiar with scientific terms.

2.2.3 Material Connexion Library

Material Connexions online library is perhaps the most varied of all available libraries. The company is a consulting firm that provides insight to companies that need to know what materials they can use and what options they have.

Information presented

Material Connexion begins with a paragraph explaining the material as a brief overview. It then proceeds to explain the potential processing applications and the usage properties of the material. This information is quite minimalist, often being just a yes or no. There a gallery that accompanies this information with shots provided by the supplier or taken by the company. Finally, there are two sections that cover the sustainability of the material and the physical properties. These properties are mostly talked about subjectively and are not explained in scientific terms like the CES materials selector.

Advantages and disadvantages of this system

The advantages of the system are that:

- It illustrates the material and clearly describes the innovative of the material.

- It shows how the material can be processed via a list of process methods, which designers will be familiar with.
- It also explains how the material might work in specific usage scenarios that can help inform designers if it is appropriate for an application.
- Describes the physical properties in accessible language that should be familiar to all designers.

The disadvantages are that:

- The language used is subjective and could be open for misinterpretation.

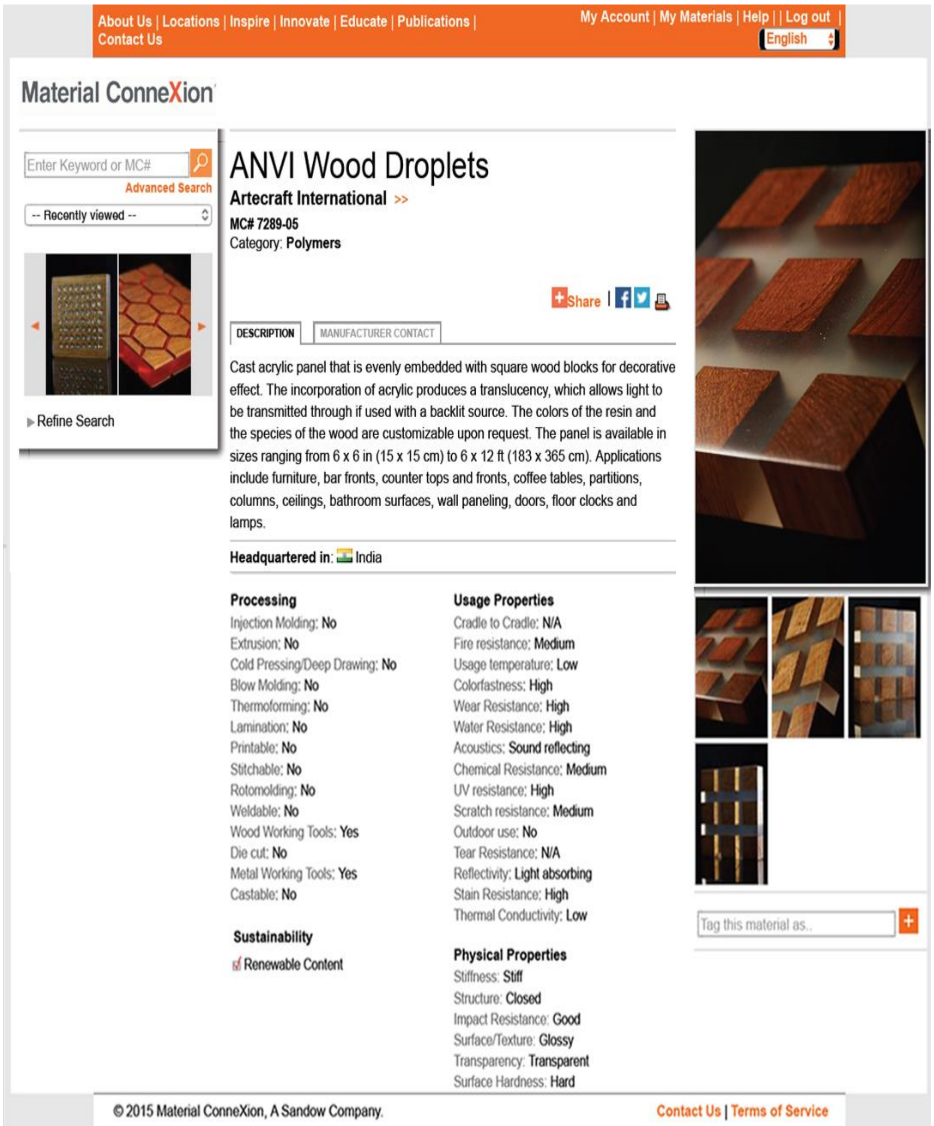


Figure 19: Screenshot of Material

2.2.4 Chris Lefteri's books

Chris Lefteri released a series of books covering different materials. Of the various books covering materials, this was meant to appeal to designers and was written specifically for them, which is why this featured, and some other entries are not. In addition, Chris Lefteri's entries are consistent, each material appears with the same information stretching across the multiple books and this makes it perfect for this exercise.

Information presented

The most prominent feature of Lefteri's work is a picture showing the material. Often this material is shown being used in a product. There also paragraphs explaining the background of the material and the background of the example, covering briefly what the material offers that is different, but do not go into exact detail.

It also includes the dimensions of the example and critical features of the material. These are displayed as bullet points. It is focusing on the bits of information which explain the unique or exceptional features of the material. It generally goes into little detail and information is mainly subjective stating 'low-tooling costs' or 'flexible' with some objective qualities where relevant such as 'chemically inert'. At no point does it use an objective measurement.

Figure 20: Photo of page of Chris Lefteri's materials book

At the end it provides a link for where to go for more information, often giving links to manufactures or the producer of the example. This information is listed alongside typical applications and an overview of where the material is used, industry and applications.

Advantages and disadvantages of this system

The advantages of the system are that:

- It shows the material being used for a practical application that illustrates its strengths.
- The text clearly explains the value of the innovation and how it might be used by designers.
- Extra information is provided to explain the material properties.

The disadvantages are that:

- There is a lack of detail on applications that are not illustrated in the book.
- The material properties are described in a subjective manner that could be misinterpreted.
- Additional information about the context of its use sometimes does not add to an understanding of the material and could be confusing to readers.

2.2.5 Similarities between libraries

	Material Connexion	Granta	Chris Lefteri	Institute of making
Pictures	X		X	X
Explanatory text	X	X	X	X
Key features	X	X	X	X
Current use	X	X	X	X
Usage properties	X			
Manufacturer	X		X	
Physical properties	X	X		
Processing properties	X	X		
Mechanical properties		X		
Aesthetic properties		X		
Eco properties/sustainability	X	X		
Thermal properties		X		

Table 7: Table assessing tool use by material libraries

The libraries of Chris Lefteri, Material Connexion and the Institute of making all showed some core similarities. The outlier that had little commonality to the others was the CES materials selector. This is in part because it is built for "engineers, scientists and industrial designers." (Granta 2020)

List of components presented in material libraries

The other resources are all focused primarily on design and so have a different style and goal. Even with this fundamental difference, there are still some similarities that appear. Across the design-focused libraries, there were some apparent similarities that appeared in all. The same methods being used to present and communicate the materials. The most common are listed below.

- **Picture:** Images were an essential part of the explanation of the material. This makes sense with how deeply visual designers are. It also provides a quick and effective way to communicate Aesthetic properties.

- **Explanatory text:** A block of explanatory text that served as an overview of the material was also seen in every example. These blocks were also very consistent in content, providing a background of the material as well as some additional detail about its key features.

- **Information on critical features:** Each material had some key features. But information was often limited to one feature; it is a key innovation. When it was the key innovation of the material, the resource highlighted how it could be useful. When it was more essential features, sometimes describing multiple innovations, the resource was highlighting the primary properties that the resource imagined the designers using. (Appears in Granta)

- **A current use:** All the resources named at least one current use of the material. This might have been in part illustrated by the picture of the material but was a critical repeating factor across all the libraries. (Appears in Granta)

2.9 THE LANGUAGE USED IN COMMUNICATION

In this section, the goal was to explore how language can be used to increase understanding. To understand how tools might be used, the tools which had emerged as necessary through the research in earlier sections of the literature review were examined. These include:

Subjective: Subjective descriptions were used consistently by the material libraries and designers. This tool puts forth an opinion of a materials quality from a personal viewpoint.

Objective: In the reviewed methods of communication, objective terms commonly appeared. These were usually accurate measures of certain material qualities and are intended to give an unambiguous understanding of those specific concepts.

Context: A situation where the material is placed in a scenario which shows how the material properties could allow it to achieve a specific goal that uses its radical innovative property. The goal is to allow the audience to understand the needs of the scenario that the material is placed in and see that the material meets those needs.

Comparison: A recommendation that stems from innovation communication studies is to find relevant content that is known to the audience to help draw comparisons to, aiming to find relevant and engaging content that could help bring attention to innovation properties.

Analogy: Analogy is a form of comparison. Analogous learning is seen as a crucial element of learning new topics; it is both heavily involved in the creation of models of understanding scientific concepts and the comprehension of new topics. Analogous learning has been included here due to the focus on ensuring that designers are able to create workable models of the material as a model for successful communication.

Subjective communication

Subjective communication is an opinion led description of how an individual or group sees a concept. The Cambridge English dictionary describes subject terms as 'influenced by or based on personal beliefs or feelings, rather than based on facts.' Subjective terms use language that is used in many natural language processes to communicate not only the speaker's opinion but also the evaluation of a target and speculations of the future (Wiebe, Wilson et al. 2004). Subjective communication while a natural part of language is not consistent. Even when individuals are tasked with using specific language, how people apply that language can differ significantly. This is a constant challenge for researchers, who mostly focus on inferring positive or negative sentiments around specific opinions (Singh, Dubey 2014). This leaves subjective communication a sophisticated tool that must be handled carefully.

Examples of subjective description include phrases such as 'pretty' and 'pleasant to the touch', both these terms are entirely based on opinion as there is no factual basis to call something 'pretty'. Other statements which at first may seem factual such as 'warm' or 'elastic' can also be argued to be subjective. For instance, while some may assess an object as 'elastic' because it has a specific young's modulus, others may be using the material with their hands and describe it as 'elastic' since in their opinion it feels more elastic than the average material. In this thesis, statements such as 'elastic', 'flexible' and 'hard', all of which could be objective are treated as subjective statements. This is due to the fact that statements from those designers interviewed about materials as part of the testing in the first descriptive study used terms such as 'very flexible' or 'pleasantly soft'. The combination of the ambiguously subjective/objective statement of 'flexible' and 'soft' with the subjective evaluations of 'very' and 'pleasantly' shows that the designers are using this language not as an objective assessment but as a method to communicate their opinion of the material.

Subjective communication is useful because it allows for emotive descriptions that can evoke specific ideas in the audience's mind. Not only allowing the communication to elicit a strong response but also allowing the communicator a great deal of freedom of expression. However, this ability to create emotive concepts is limited by the aforementioned issues with the clarity of the communication, which can lead to confusion between the communicator and the audience. This can be intensified by cultural differences. Both those between those, of different cultural backgrounds and those from different industries; this is in part because these cultures have different understandings of what the language being used might be indicating (Risager 2007).

Currently, in materials, subjective terms appear in all the material libraries communications around the materials and in the communications produced by the material manufacturers. This use of personal communication also stretches back into history. Looking at Bakelite(1925), which as explained earlier in the literature review was the first commercially available plastic, the language used in the 1925 advert includes 'lightweight', 'strength' and 'hardness' as key attributes.

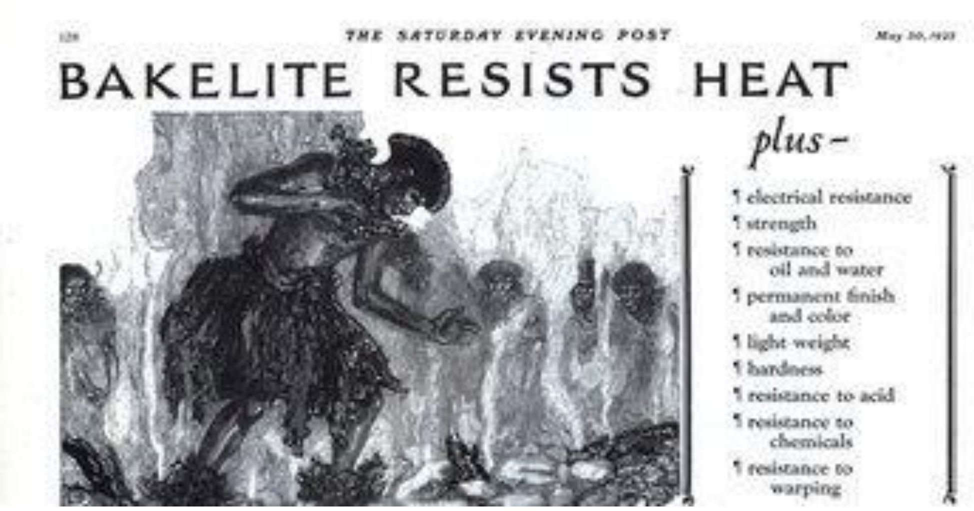


Figure 21: Example of communication of Bakelite material from 1925

This language is not that dissimilar to that used in the book 'Materials for inspirational design' by Chris Lefteri from 2005 which uses the phrases 'Excellent sealing', 'lightweight', 'hardwearing' and others, to communicate the material properties of cork. With this, it can be seen there is a continued and consistent use of subjective phrases in materials communications.

Excellent sealing

With its warm, waxy and spongy feel, cork is another one of nature's wonder materials. It has been harvested and utilised since the time of the ancient Greeks, when its ability to float was exploited by fishermen. Today, about half of the world's cork is produced in Portugal. In the north of the country 30 million cork stoppers are manufactured every day.

It is grown in 14-sided cells in the bark of the tree. These are then impregnated with suberin, a waxy material with sealing properties. The bark is carefully removed in strips, which take nearly six months to dry. These strips are then boiled and left to dry for a further three weeks before being shaped into the end product.

Cork is the only tree whose bark reproduces itself after harvesting, which means it is a totally renewable resource ↘. Typically, a tree will produce several hundred kilos of cork at each harvesting and will survive for many generations. But with plastic elastomers increasingly taking its place in the wine-bottling industry, new uses need to be discovered for this lightweight ↘ natural wonder. Contemporary designers like El Ultimo Grito have demonstrated creative applications of cork in modern furniture ↘ without the usual garden fête associations.

Dimensions	**50 x 69 x 61.5cm**
Material Properties	**Lightweight; Buoyant**
	Good elasticity and compression properties
	Impermeable to both liquids and gases
	Good insulator; Fire retardant
	Hardwearing; Renewable source
	Hypoallergenic; Chemically inert
Sources	**Portugal; Algeria; Spain; Morocco; France; Italy**
Further Information	**www.woodfibre.com; www.corqinc.com**
	www.granorte.pt/properties.htm
Typical Uses	**Footwear; travel cases; handle grips; safety helmets; shuttlecocks; dartboards; bathmats; buoys for fishing nets; wall and floor tiles; vibration dampeners; insulation; furniture**

Chair
Designer: El Ultimo Grito

Figure 22: Example of communication from the book 'Wood: Materials for inspirational design' (Lefteri 2005)

Objective descriptions are factual statements about the world, based on assessments or factors that can be tested. Objective terms are the opposite of subjective terms which is made clear by the definition provided by the Cambridge English dictionary which states objective means 'based on real facts and not influenced by personal beliefs or feelings.' Objective communication about materials is advanced. A massive range of different factors can be used to assess everything from a material's flexibility to its resistance to exposure to acid. Objective communication offers an unambiguous assessment of these factors by correlating them with a specific measurement. This allows for objective communication to have exceptionally high clarity, ensuring that both the communicator and audience have the same understanding of the topic thanks to this shared knowledge.

Objective communication is so ubiquitous that nearly every material will have some of materials property sheet that covers the abilities of the material. This can be understood across different industries and cultures if they understand the terms being noted. The knowledge of these terms is the main limitation of this form of communication. Each term requires unique specialist knowledge to fully comprehend what that assessment is stating, for complex materials. This can require an incredible range of specific knowledge. For instance, a datasheet for Hybrid Steel contains more than 50 distinct assessments of the qualities of the material, most of which require distinct pieces of knowledge (Ovako 2019). Objective communication remains essential to material communicators but as a tool used to communicate to those who are novices in material science and not familiar with their assessments used the is a considerable limitation on how useful this tool can be. What it gains through its unambiguous nature it loses through the knowledge requirement needed to access that information.

Contextual communication is a term distinct to this thesis. In this thesis, contextual communication focuses on applying the material to a product to illustrate how that material would function effectively as part of that product. An example of this might be, "D3O *(a material-efficient at absorbing impacts)* would work well as the lining of a helmet." This process of application requires applying the material to a scenario that is familiar to the designers and challenging them to reason as to why that material is a good fit in the scenario. This process is similar to the Case-Based Reasoning (CBR) discussed in the feasibility assessment section which aims to *'to identify the current problem situation, find a past case similar to the new one, use that case to suggest a solution to the current problem, evaluate the proposed solution, and update the system by learning from this experience.' (Aamodt, Plaza 1994)*. In this case the communicators are aiming to find a problem that the material they wish to communicate can aid with by nature of its properties. With this done, they find a past application of a material with similar properties, update the application to use the new material and submit that to the designer to help them understand how the material can function(Goel, Diaz-Agudo 2017). This is backwards to the regular application of this thinking, but it still demands that the designers complete a similar reasoning process. They must identify what role the material is playing in the situation, evaluate how it effectively complements the design with its attributes and understand why the updated system is better or equal to the original system.

This system offers the ability for users to apply their own knowledge and reasoning to the material and better enable them to learn. CBR is already a respected teaching tool and is used to help construct an understanding of complex theories. What limits this communication method is that to be effective the context being used must be familiar to the designer to be effective. This places high pressure on communicators to find relatable scenarios that will work with the maximum number of people.

While not used as extensively as subjective or objective communication, most material communicators do use contextual communication to some degree, often listing current examples of the material in use. In addition, nearly all the material libraries surveyed (the only exception being Granta) included examples in their text of the material's current commercial uses. This existing practice may not be to facilitate this CBR style thinking, but it does allow designers to approach the materials and think in this manner.

Comparisons can be used to communicate, by drawing on similarities or distinctions between two concepts, the audience can apply their knowledge of one concept to the other. The exact nature of this comparison though can differ with many different forms of comparison offering distinct benefits and limitations to what they are best at communicating. These different forms are listed below.

2.9.1 **Literal similes, literal comparisons**

A simile is a statement that establishes similarities between two items, explaining how the qualities of one item can be seen in the other. While similes usually aim to create an interesting connection between two topics which are not literally the same (Fishelov 1993), a great deal of literature has explored their difference to metaphors which often aim to achieve the same goal. However, it is a clear distinction. Similes are statements that follow a specific pattern, using the words the 'like' or 'as' to draw attention to the similarities. The main goal of this comparison is to draw attention to and create an interesting comparison of the two concepts. The published study of these similes stretches back centuries, and the use of them is millennia-old with academic work still exploring the similes of some of the earliest written works we know of (Silk 2016).

While most similes are figurative, the literal simile aims instead to describe a factually correct likeness. The study of literal similes is comparatively rare with and highly respected voices have long argued that a literal simile is a contradiction in terms (Addison 1993). However, the language used by those studied in this thesis found that consistently, designers were drawing comparisons using the same 'as' and 'as' statements of a figurative simile. In this thesis the literal similes are referred to as 'Literal comparisons. This is to avoid confusion with the far more frequent use of similes to create emotive connections between two topics.

Literal comparisons are very effective at communicating when two items are very similar. A literal comparison can, for instance, state that, 'this plastic is as hard as steel.' This is effective for the same reason that figurative similes function in that If the listener appreciates the hardness of steel, they can then apply that understanding to plastic and know that the two are similar (Israel, Harding et al. 2004). Literal comparison is potentially limiting when used this way though, requiring the creator of the statement finds directly correlated items which are very similar. The use of additional descriptors in the statement can provide more options. Descriptors can establish that the similarity is not direct. Instead, the relationship is altered by a known quantity contained in the descriptor.
An example of a literal comparison with descriptor is, 'This plastic is half as hard as steel.' While the statement pulls on the same knowledge as before, it now allows the listener to understand that they must use their knowledge of steel as a method of measurement that they then change according to the descriptor, halving it in this case. This method is useful but not as good as using a literal comparison, since it requires an extra level of thinking and calculation on behalf of the reader.

2.9.2 **Analogy**

Analogy is a type of comparison, unlike similes which aim to compare two concepts and transfer some attribute from one to the other, analogy focuses on transferring systems (Anttila 2019). Analogies are also true; they aim to be literal in their comparison unlike metaphors which are figurative. For instance, saying that the inside of the atom and the way that electrons orbit a nucleus is analogous to the orbit of a planet around a sun aims to apply the system of an atom to the solar system. The statement, while not entirely correct has literal similarities between the two allowing for the expansion of understanding by the audience and allowing them to apply their knowledge accurately (Holyoak 2012). These types of analogy are effective enough to be used consistently in the education of scientific principles, working to help expand the knowledge of students by connecting unfamiliar and often unintuitive concepts to clear and known concepts (Hallyn 2013).

The use of analogy as a tool of assessment utilizes the fact that as humans, the audience will try to connect new experiences with old experiences intuitively. The aim is to save on the mental energy of learning a new system (Silverman 1985). Designers may benefit from this process more than other groups as the process of applying prior knowledge to new challenges is a crucial tenant of design thinking and so is something they are practised at (Cross 2011). Both analogy and literal comparison aim to bring literal understanding from something the designers know to something they do not. This use of past experiences is beneficial for radical innovations as those innovations are new and the content of them may be wholly unfamiliar; the ability to use prior knowledge gives many options for exploring the attributes of the material.

2.9.3 **Metaphor**

Notably, analogous comparisons are distinct from those using metaphors which deal with empathy taken from existing experience. A discussion of comparison would not be complete without some examination of metaphors. Metaphors are a form of figurative comparison that is not literally true but helps to explore or emphasise the concept being explored (Silk 2016). They are often confused with figurative similes, as both tools concern themselves with comparing figurative concepts; however, metaphors do not follow the use of 'like' and 'as' which structures a simile. In literature, a metaphor's purpose is often to create an emotive connection with the audience, exploring how concepts and systems, complex and straightforward have similarities to something the reader will recognize and make an empathic connection to.

Metaphors play an essential role in teaching and despite their lack of real clarity are used to explore scientific concepts (Hallyn 2013). However, they do not appear in any significant amount in this research; this was due to an examination of designer's language, which occurred in the first descriptive study. When exploring the language that designers used to describe materials there was very little use of figurative language, either as a simile or as a metaphor. Designers focus on accurate comparison brought the focus of the research into those tools.

2.9.4 **Existing Analogy Tools**

Analogy is a much-studied area of interest due to its effectiveness in teaching and communication. A variety of academic tools already exist for constructing analogies. Many are based off systems that break down the two key elements of an analogy; the known concept 'base' and the unknown concept 'target', into systems that can be compared for similarities. The goal of these tools is to ensure that communication is as effective as possible (Richland, Simms 2015). Other research on analogy does exist, focusing on the literary content and intent of the writer. This study of analogy strays outside of the literal education focus of this research, which aims to ensure the accuracy of the comparison and that it is scientifically sound, as such tools that focus on scientific analogy are of most importance and are explored in more detail.

Of these tools the most consistently used methodology is the process of structure mapping which has been applied effectively to educational areas including maths, science and history, as well as being used in many others (Richland, Simms 2015). This was originally a scientific analogy tool created by Genter. In a paper from 1983, she described a process of breaking up scientific concepts into 'maps' that could then be compared to another concept to evaluate if it worked as an analogy (Gentner 1983). Not only is the work respected academically with many thousands citing the work but it has also spawned new systems that look to expand on the process such as the 'Structure-mapping engine' which looked to create a digital process to build analogies using it (Keane, Ledgeway et al. 1994). These different tools all use the same base of structure-mapping in different ways to deal with specific challenges or work within a specific system. The effectiveness of structure-mapping isn't diminished though, and as none of the new systems is specific to designers, materials communications or explicitly applicable to the work discussed in this research, the research will focus on using the updated version provided by Genter. Genter's work on analogy contains both a system on how to break down concepts into maps that can be compared and a guide to assess the potential effectiveness of the analogy. As the current research points to a need to create useful analogies, the ability to create and assess them is paramount to its success. Genter's work offers a premade and established solution that requires minimal adjustment to be applicable to this work.

2.9.5 **Genter's Mechanism of analogical learning, a summary and application of the tool.**

When looking for tools that could help furnish those using the tool with an effective method to create analogies, Genter's work was identified as offering a reliable method to generate accurate analogies. In addition, it furnished the researcher with the tools to examine the analogies used by designers when communicating. It also helped establish critical terms for the processing of all comparisons including adding the terms: Base and target, Objects, Relationships, Attributes

Base and Target: The very first step in any analogy production is to understand what is being compared to what. The target is the concept that is intended to be explained, and the base is the concept that is having the listeners understanding of it leveraged. The initial selection of the base is controlled by several concepts. Though these do not exist in isolation, the majority of the ability to assess whether a base will be productive comes from comparing it to the target.

To assess the two different elements, they must be mapped into how each concept functions and then the two can be compared. This does mean that a specific element of creative thinking from the modeller is required; it is not possible to map every possible base and then compare it to a target. Those creating the analogy are expected to use their intuition to select two systems that appear close and then evaluate how effective an analogy between the two may be using these tools.

The first step in creating an analogy this though, is to map the target, as this is a known quantity that will not change. Mapping the target first can also help guide the intuitive selection of the base.

The process of mapping concepts asks that they are broken down into a series of objects, relationships and attributes. To start mapping a concept, the target must be chosen and then broken down into its components.

Objects are the different components in the system. They do not need to be physically separate entities, as seen in this example, the first object is the material in its soft state and the second the material in its solid-state. The different objects in the system have to be connected to each other through some form of interaction, called a relationship.

Relationships are the connections between two or more objects. They often represent a force; someway one object acts upon another. They can equally represent a change that is invoked in an object by another object. These relationships are perhaps the most crucial element of the analogy as they often describe the systems change, providing the information the analogy was created to convey.

Attributes are the physical properties of the objects. They are the least important part of the analogy but must be included to ensure they do not cause confusion when used in the analogy. As analogies often have no aesthetic resemblance between the base and target, many attributes are immediately discounted as not being similar.

Sometimes though this overlap of content must be looked at if the two systems share aesthetic similarities that could confuse the analogy. An excellent example of this is in a classic science analogy of a nucleus (target) being like the solar system(base). A solar system has a large body (sun) in the centre which due to gravity means smaller bodies (planets) orbit it. An atom has a large central body (nucleus) that due to its charge, causes smaller bodies(electrons) to orbit it. While the relationships are the same, some attributes could be confused to be affecting the system. Looking at the base those who understand gravity know that the size of the central body is directly connected to its ability to affect the smaller bodies. This not the same for the nucleus its size has is not the reason it attracts electrons. Inconsistencies like these need to be identified and clarified as part of the analogy so as not to confuse those using it. This can be as simple as stating that the similarities in scale are incidental and are not be considered as part of the analogy.

Evaluating the comparison

Structure: The structure of the objects and relationships should appear in a similar fashion; this perhaps the most prominent issue. If for instance a base has an object A with relationships with object B and object C and the target has relationships between object A and object C but not between object B the structure doesn't line. This shows a clear sign that the analogy won't work as the interactions are not similar.

Clarity: The clarity comes from how effectively the base and target map to each other. Perfectly clarity has a similar number of objects connected by a similar number of relationships. This is often not the case with the target or base having unique relationships or objects that don't map, these don't necessarily ruin the analogy if most of the elements of the target are similar enough to create a direct map. It does, however lower clarity and can confuse the analogy.

Richness: The richness of the map is how much of the analogy maps. If only the core aspects map and there are other elements of the target which are not covered wholly, then there is a lack of richness. The ideal situation is to have the whole of the system accurately map to the other, matching all the relationships and objects of the target to the base. This can be rare though, so if two potential bases are available that map correctly, the one that is richer that should be the preferred option.

2.10 SUMMARY OF THE LITERATURE REVIEW

There are more materials being released now than ever before. Despite this increased availability of new materials, the tools used to disseminate these innovations to designers, who play a crucial role in material use, have not significantly changed. This lack of change has continued even as the number of radical innovations has increased, including the development of smart materials. While this wouldn't be a problem if these innovations were entering into designers' hands anyway they are not, with many materials failing to penetrate the market (Trebilcock 2017).

While not every material has a good use case or fits current design needs, many will never be seen by those who might be able to use it. A better method of sharing these materials with designers is needed to ensure these developments are not wasted. The goal of this research is to develop a method to explain radically innovative materials properties to designers in a reliable manner that enables them to apply them to their design thinking. If this can be achieved, there is the opportunity to both reduce the potential loss of innovative work and to enable designers to solve problems more effectively. The key points laid out in each section are as follows:

The Innovation section discussed how radical innovation poses a unique challenge, being very different from what came before it. This needs a different approach than incremental innovation. The value of these innovations and the importance of communicating them was also discussed. In addition, it discussed that for innovation to be disseminated, collaboration/communication is required between those parties who intend to use the innovation and developers of the innovation.

The Materials section establishes that radically innovative materials are a unique communication challenge. The process though has similarities to the Open Innovation process and learnings can be taken from that process. What is essential to take from this section is that there are multiple sources who see a codified system of communication with a supporting tool as an effective method to improve communication.

The design section discussed the challenge of building radical innovations into design thinking. A process that intrinsically relies on prior knowledge, which is tough to apply when radical innovations do not easily connect to past experiences. It also introduced the issue of the 'fixation' where designers can get locked on a concept early in their design process.

Should the information that they build this 'fixation' on be flawed, it can lead to severe issues. This shows the critical issue that this research is attempting to avoid through better communication.

The communication section discussed how to communicate and looked at possible tools for communication — establishing that the best tool to use was written or verbal communication. This section also established limitations on what forms of communication would be used in this research, aiming to make it accessible and useful to all. Design communication was also explored in relation to materials finding systems that while not covering radical materials highlighted the importance of using experiences as part of the communication. In addition, an analysis was conducted of existing communication methods in this space. It found some similarities between the existing libraries and books that provided a structure for future work. The research in this section answered wholly or added understanding to several questions highlighted in this thesis. A summary of those points is below.

Research question 1: What communication techniques exist to communicate radically innovative materials to designers?

Currently, there are no academic systems aimed at communicating radical innovations in materials, and none which specifically target designers. Some tools do exist that aim to communicate materials correctly. This communication process can be supported by research in the open innovation process which is analogous to the process of designers using new materials by looking at their need to collaborate with material producers. In the process of open innovation, the ability of both parties to benefits is often is limited by the ability of groups to transfer knowledge (Szulanski 2000). To resolve this, it is recommended that the communication focuses directly on what information should be transferred ensuring that the differences between the two parties is fully accounted for and while the system to improve this exists, they aim at making institutional change rather than alterations to the specific communication (Lichtenthaler, Lichtenthaler 2009).

Academic systems do exist to communicate materials sensorial properties, these offer some insights on how to communicate materials. Focusing on the creation of formal language using language that is common to designers. This commonly includes the comparison and examples of the material in use. This help provide some understanding of what methods are already seen to be effective by the communicators in the design sphere. Books and other online commercial tools exist that look to communicate innovative materials to designers. These tools included a list of material libraries that aimed to communicate materials to designers that they might not have heard of previously and are updated with new materials as they enter the market. While the academic tools aiming to communicate radical innovations are limited, those that do exist make recommendations on how to communicate generic, radically innovative concepts though. A review of this advice showed that three recommendations are consistent. The strategy should be clear aiming to understand the audience and the context in which they will be absorbing the communication (Zerfaß 2005). There needs to be clarity in what is being said, this involves careful consideration of what is being said and how it can be as accurate as possible (García-Morales, Matías-Reche et al. 2011). The communication must also be relevant and creative to the audience, matching their interest (Andreassen, Polden et al. 2018)

The tools used by commercial entities aimed to try and communicate their materials in different ways, but there were four consistent methods that were used by designers to communicate the materials. These were the use of pictures, a block of explanatory text, a list of information that covered the key material features and examples of the current use of the material.

Research question 3: What text or speech-based communication techniques enable designers to understand radically innovative materials better?

When looking at the research that aims to communicate materials the past research by Karana, Hekkert et al (2010). was surfaced. This research provides evidence that the language used needs to fit in with the language that designers use, making it emotive and straightforward, rather than focused on engineering terms. Smart materials are an innovative branch of materials that are evolving quickly, in part due to their nature and in part due to their complexity. Bergström, Clark et al (2010). recommend that the communication around these innovative materials must be different to their more traditional cousins. Essential to this discussion though is the inclusion of experience of the materials. Without experiencing the materials the communication will likely fall flat no matter how polished the text or speech (Veelaert, Du Bois et al. 2020).

Research question 4: How can these communication techniques be applied in a systematic fashion to enable design communicators to reliably communicate radically innovative materials through text?

The literature review found that there was a gap that could be filled for a system. It also found that there were researchers calling for systems to target specific forms of knowledge transfer, which aims to reliably transfer knowledge and experience (Brown, Duguid 2000). Nonaka (1994) suggests that the first step to creating this kind of communication is through changing this knowledge from a tacit state to an explicitly definable knowledge base. This step will help bring clarity to what is being communicated and set clear boundaries and limits to what is being communicated.

To support this communication, the review highlighted evidence from Wilkes et al., (2016) who established that having physical samples which are supported by discussion is an essential part of having a meaningful learning process. Without these samples, the communication may be stymied. This information will be factored into the development of the system.

This literature review has identified some core gaps in knowledge that this research hopes to fill. The most crucial area where no knowledge currently exists is in the communication of radically innovative materials to designers. This specific gap is the core issue that this thesis hopes to resolve. Less specific gaps in knowledge have also been identified in a number of supporting areas; this is space where the research will also need to expand knowledge to help support that primary goal.

- Innovation theory recognizes radical innovation as a type of innovation that is distinct from other forms. Despite noting the distinct nature of the innovation, the innovation diffusion theory does not ascribe any specific systems around the material.

- Design research has many tools that help designers communicate with others but has limited tools for communicating to designers. This lack of established tools means that it is a limited platform to build from. Outside of specific communication tools, designers do have their own systems that allow them to understand new concepts, but this doesn't fit the nature of radical innovations.
  Overall there is a missing area of knowledge on how to communicate innovations to designers which they cannot use their intuitive systems to assimilate. This research will need to resolve this question in part to ensure the accurate communication of

radically innovative materials.

- Material science hasn't got a system that allows for communication of materials to designers. Codified systems to communicate materials to novices, in general, are not present either. There is the potential to use open innovation to support this process, and it is already used.

- Communication tools exist to help bring people's knowledge together. These though are not aimed at radical innovation or the design/ material producers' sector. There are plenty of tools out there to support future development of the tool though.

The next section will be a study of how designers comprehend innovative materials, the language they use to describe those materials and to test how effective current communication techniques are. This aims to investigate those gaps in knowledge highlighted above.

3 METHODOLOGY

This part of the thesis covers the methodological approach of the research. The section details the overarching research methodology used, covering what methodologies were considered and why design research methodology was selected. It then goes into detail as to how the design research methodology has been applied to shape the research covering each step of the methodology. With that overview in place, the general methodology of the thesis is also described, covering how participants were selected, research ethics was built in, how the materials were selected and the limitation of testing. This is then followed by an in-depth assessment of the methodology applied for each research tool used over the course of the research. The work covers how the methodologies have been shaped and what actions have been taken to ensure the tests and data collection are as effective as possible. In addition, the system of assessing feasibility is covered in detail, as this assessment is core to answering research question 5.

3.1 SELECTING A METHODOLOGY

The research methodology dictates the approach to how the investigations and tests are conducted by the researcher. The choice of research methodology can have a profound effect on the outcomes of the research as it shapes the steps taken (Crotty 1998). To ensure the best possible outcome for the research, a methodology that compliments the topic and goals of the research should be selected. To select an appropriate research methodology questions needed to be resolved.

Research purpose: The purpose of this research is to explore how to communicate radical innovations in materials to designers effectively. This goal aims to understand what the current state of communication is, how it could be improved and what that system might look like. These questions demand that the research be exploratory, descriptive and explanatory. To achieve all three of these goals, a variety of approaches must be used to explore each stage. Any methodology chosen must, therefore, be flexible enough to use multiple approaches. What is essential is that the chosen methodology must allow the different phases to shape each other with exploratory phase to shaping the descriptive phase and the exploratory and descriptive phases shaping the explanatory phase. This is because the outcomes of these phases are mostly unknown and will shape the research methods needed to make the most use of data gathered at each stage.

Research strategy: Most research studies are quantitative or qualitative. Traditionally quantitative research aims to measure while qualitative research aims to investigate (Choy 2014). Qualitative research allows for the pursuit of a central research question supported by smaller supporting questions that allow for a general concept to be explored. Quantitative research focuses on exploring a hypothesis that supports a research question (Blessing, Chakrabarti 2009). As the intent of this research is to broadly explore the challenges and potential solutions to a communication issue, qualitative research is best placed to enable this. It not only allows for the exploration of the core question, but it places no demand for a hypothesis as a quantitative approach might.

For this research, a methodology that was tailored to support both communication and design thinking was necessary. As both topics are highly fluid and often without objectively correct answers as discussed in the literature review the research questions an approach was needed that reflected this focus on a more subject output. In addition, the research would benefit from being adaptable to the specifics of research to enable design; this topic has shown to need support that is distinct from other approaches. To find the right methodology, several possible options were assessed.

Literature review	• **Information gained:** What current communication systems exist, how design works and how materials feed into design process. • **Outcome:** Creates clear goals on how to improve design understanding of materials and allows for the development of future tests
Interviews and workshops	• **Information gained:** Established there is a difference in how designers understand materials based on innovation type. Found out how designers talk about radical innovations and understood the current limits of conventional tools. • **Outcome:** With the specific tools that designers use to discuss radical materials identified, the research on how to use these tools can now use them to try an improve communication.
Thematic review, focus groups and questionnaire	• **Information gained:** This section exposed how the tools designers use to communicate about materials could be harnessed to improve understanding. Creating potential methods that could be used in the final tool. In addition, a method to divide up radical innovations was explored that should help create a more tailored system for discussing materials. • **Outcome:** A clear system was outlined that could become part of the final tool. Using design language this repeatable method could be refined and applied to final
Workshop	**Information gained:** This workshop established the validity of the communication system developed in the previous two steps, outlining a more effective system for communication of radical innovation. **Outcome:** A new system of communication can be used to communicate radical innovations to designers.
Validation	In this final section all the previous work was assessed, both through tests and speaking with experts. This explored the weaknesses, strengths and future opportunities of the research. This allowed for the final version of the tool to be stronger and more robust, while clearly outlining its limitations.

Table 8: Summary of how the design research process compares to the process of this thesis

2.2.6 **'Looking for information' a research process.**

This methodology focuses on providing a generic platform for many types of research to begin. It focuses on a simple process of picking research questions and determining data needed to answer those questions. It then follows on to choosing research methods that are then conducted to create data that can be analysed and interpreted to create compelling results (Mai 2016).

The process is best at supporting open research questions which do not have a specific answer, as it allows for the process of identifying the data needed to answer questions as well as supporting obtaining it. This is a marked improvement over more prescriptive research methodology. With communication not having a clear objective answer to its success, the ability to define the data based on the larger research is critical.

The challenge of using this process is that it may be too generic for the specific focus on design. As the approach is broadly applicable to all types of research, it means that nuances of design research may have been overlooked by the process. Design research is distinct from other forms of research and this needs to be accounted for (McKenney, Reeves 2018).

2.2.7 **Design research methodology**

Design research methodology (DRM) is a structured method for those trying to develop an understanding of designers and design practices. The basis of design research is a multi-stage research process that seeks to bring academic rigour to design which is a fundamentally dynamic and complex area of study (Blessing, Chakrabarti 2009). The process was initially conceived to provide the growing number of design academics with a shared methodology. So far this has been somewhat successful with a rise in academic papers that use the techniques, with over 1300 citations for the updated version of the original 1995 publication.

This process may be more relevant than the other approaches listed, as a design research methodology is applicable to other forms of research. This is compared to Design Research which states explicitly it aims at design (Barab, Squire 2004).

2.2.8 **Design research**

The methodology called 'Design Research' focuses on recognizing design research as distinct from other forms of research and in need of specific tools. It is made up of seven distinct stages and does not hold researchers to any particular methods of research or data analysis (Easterday, Rees Lewis et al. 2018).

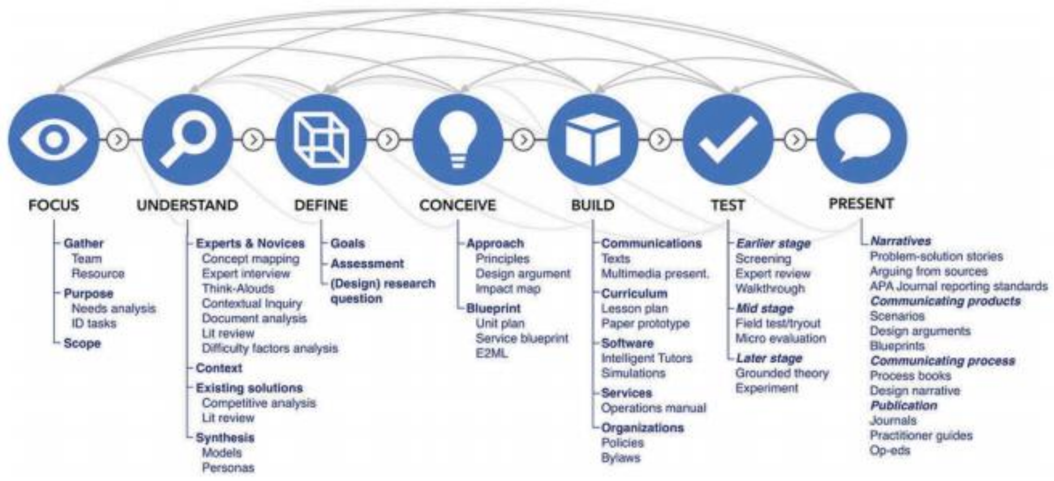


Figure 23: The design research process by Easterday, Rees Lewis et al. (2018)

The seven stages are designed to take the research from an identification of the problem through to conceiving and building a new concept, with a final test and presentation (Easterday, Rees Lewis et al. 2018). This research methodology is significantly more detailed than 'Looking for information' and at each step describes the core steps that should be taken, though how those challenges are resolved is based off the individual research's demands.

This process, while relevant to the design, maybe too specific to reflect the focus on innovation and communication. The tool focuses on the production of a concept, whether that be a physical thing, service or software. It doesn't actively support the production of a system that is core to research questions 4 and 5. Considering this research aims to develop a tool for designers but not a tool to create designs, it is likely that this tool will not be applicable.

2.2.9 **Selecting a methodology process**

Considering the challenges posed by the research, DRM was selected as the approach for the research. The reasoning behind this came down to an analysis of the needs of the research. For the research to be successful, the chosen methodology had to…

- Based on qualitative research: The research methodology needed to focus on qualitative research to be effective in helping explore the challenge as it was no hypothesis to support a quantitative approach.
- Maps closely to explore, describe, explain goal: The research questions of this thesis focus on the aim of exploring the communication challenge, understanding how it might be improved and then creating a system that explains how to use that knowledge.
- Allow each research stage to shape other stages: As the issues surrounding communication are unknown, as are the methods of design communication, there needs to be the approach that allows each stage to shape the next and inform previous research.
- Supports the creation of a system: methodologies that embrace the creation of a system are essential to the research's success, as a core goal of the research is to create a tool to aid communication. Methodologies that do not support this goal are not likely to be effective.
- Support design thinking: Design thinking is known to create a nuanced approach to challenges. This nuance could be overlooked by methodologies that are not specifically tailored to collect design thinking.
- Supports research outside design: While design thinking is core to the research the focus of the topic is on communication and materials innovations, a system that cannot cater to the broader topic will not be effective at creating useful research.

Requirement	**Looking for information**	**Design Research**	**DRM**
Based on qualitative research	X	X	X
Map carefully to explore, describe, explain the goal	X	X	X
Allow each research stage to shape other stages	X	X	X
Supports the creation of a system			X
Support design thinking		X	X
Supports research outside the design	X		X

Table 9: A review of research methodologies

Considering the results, the research contained in this thesis was guided by the DRM process as it was deemed most relevant as the subject profoundly concerned designers and the design process. The methodology is specifically designed to be appropriate to both design groups and individual researchers. It allows for a variety of research tools; all of which are essential for this research to be considered valuable to designers.

3.2 The design research methodology process

Below is an outline of the design research methodology process which outlines the four main stages of the research process as well as the intended outcomes. The image below provides a map of the process.

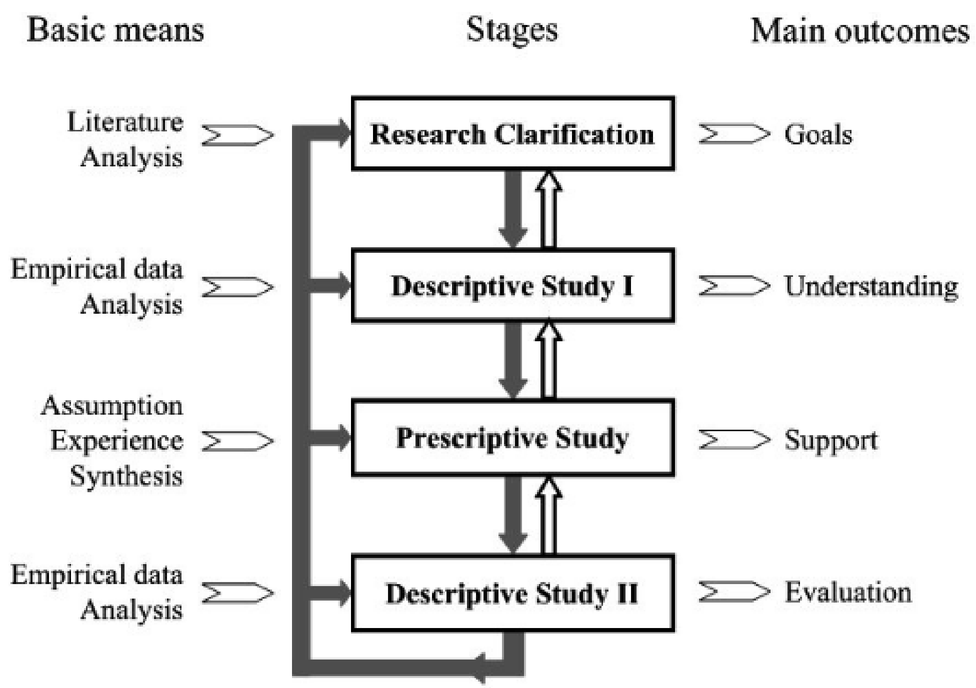


Figure 24: The design research methodology process

Research clarification – Literature review: The first step in this research was the literature analysis that outlined the major issues that faced communicating radical innovation to designers. This wide-ranging literature review followed established literature review guidelines, looking at existing research to develop a better understanding of the existing knowledge and to expose a knowledge gap which the study could close.

The literature analysis found that there was a significant flaw in current communication around radically innovative materials. It also exposed the challenge of correcting this flaw due to the radical innovation's nature conflicting with the process of design thinking.

Descriptive study 1 – Interviews and workshops: In this study, there were two main research tools that aimed to develop an understanding of the challenges surrounding the communication of radical materials with an empirical study on how designers communicate and how effective communication is.

The first test studied how, in short interviews, designers communicated incremental and radical innovations. The goal was to discover what language they used and if there was a tangible difference between how they communicated the two materials. In the second study, a series of workshops were used to establish what language was used when designers discussed radically innovative materials in groups and how effective current commercial and academic methods are at communicating radical innovations.

The second study in the descriptive study phase 1 has an additional purpose. Its results will be used in comparison with an almost identical workshop completed in the Descriptive Study Phase 2. These studies will fit with the scientific method, which is one of not the most established tool for conducting experiments with a long history in many fields (Skinner 1956).

A comparative experiment conducting at least two tests which are almost identical, with the exception of one factor being altered, known as the independent variable. With only this factor altered any changes that occur between the two tests must stem from the impact of that altered factor. The test will often be aimed at seeing this independent variable's impact on a specific variable, known as the dependent variable. Any other changes are extraneous variables; changes in them may provide useful data but are not the focus of the test. While this form of experiment is more conventionally used in scientific tests, it is still applicable to sociological/psychological tests (Gauch Jr, Gauch et al. 2003).

The benefit of this form of data collection is that is it will be objective. By showing cause and effect, it is possible to remove the bias of the researcher. The challenge, especially for sociological research, is to keep all the variables the same for each test. Unless this is done, it will lead to a reduction in the validity of the results or lead to incorrect deductions. The chance of errant variables affecting the test can be reduced from repeating the experiment a large number of times. This helps to ensure that any change does stem from the independent variable (Cohen, M. F. 2011).

Prescriptive study – Thematic review, Focus Groups and Questionnaire: Having discovered that the current methods of communication aren't reliable and don't reflect designer's heavy reliance on comparison to explain RI, the next round of study focused on what techniques could use this information to improve the communication. A thematic review of a wide range of RI materials was completed to help create groups that could be targeted to provide specific communication guidelines. This was because the range of RI materials is enormous, and it was unlikely that anyone rule of communication would benefit them all equally. Once that was completed a focus group that was shaped by a supporting questionnaire was developed. The questionnaire exposed what communication techniques designers found most useful and focus groups then expanded on this to understand why that was.

Descriptive study 2 – Workshop: With research supported by the prescriptive study, a new methodology for explaining RI materials was developed. The test was identical to the earlier test that established that designers were failing to understand RI materials. Through doing a test on a similar scale and with the same materials and methodology, it allowed for results to be evaluated against the original research. The test showed a marked improvement in the designers' ability to understand the materials. The results also led to a review of the tool that was developed in a prescriptive study using feedback from the workshops to develop it further. This resulted in a final tool that tested as far more effective than the current methodology.

Evaluation: The evaluation of the thesis considers all of the studies outlined above. This will be summarised in the conclusion.

3.3 GENERAL METHODOLOGICAL PRACTICES AND LIMITATIONS

3.3.1 Selection of participants

In all tests, the criteria for those taking part was nearly identical. Participants needed a strong understanding of the design and a low understanding of materials science. This essential criterion ensured that the testing reflected the needs of designers while also ensuring that those with existing knowledge in material science didn't influence results.

What was core in the testing was to ensure all the designers involved were competent at design. Competence itself is linked to the ability to create output, while there is a lot of disagreement on how exactly competence is defined, it is intrinsically linked to the skills and knowledge of the individual. Most thinking on the subject argues that competence comes from applying skills consistently often supported by training, either before or during their work on the challenge. The criteria for competency are confused and there are many different models for ranking competence.

3.3.2 A Critical Review of the Science and Practice of Competency Modelling

It would be impossible to validate every designer's competency level, especially considering that competency modelling has no agreed upon or straightforward approach. As described in the introduction, the focus of this research is on the product and industrial design; this helps reduce the possible permutations of what design means as this can stretch widely (Potter 1980). Even refining to this limited view of design, the question of 'what is a competent designer' remains unclear. Instead of looking to academic research the researcher spoke to bodies of design practitioners, academics and students. The three groups agreed that the experience needed to meet this criterion was at least two years of graduate-level design education, or at least two years working in the industry. The logic behind this assessment came from the fact that by this point in their development of design skills, they had completed enough practical work to have used this skill repeatedly and have learnt from mistakes. This level of competence is not considered the final step in design learning but is merely the first step on a career in design.

Participating designers also had to be considered novices when it came to material science. A novice is an individual with a limited understanding of a topic or concept. The reasoning behind this is to ensure that those with a high functioning understanding of material science could not use that knowledge in place of the communications provided by the researchers. It is important to note that being a novice is the opposite of competence; individuals cannot have reached the stage of competence but still not be considered novices.

To be considered a novice, designers have to have nothing but the most introductory training in material science and to have not sought out their own knowledge of the materials being explored in the research. This will allow the designers to learn about the materials in question as a novice. In all tests, designers were asked to rank their knowledge, each participant filled a questionnaire that asked if they had any background in, or knowledge of, materials science and if so to specify this experience. In nearly all cases, this was answered as a no, but it occasionally caused some potential participants to be excluded from the results. They were screened out as they were not a 'Novice'. This made them inappropriate for these tests.

Participants were accessed through a number of methods primarily using the author's network but also through external networks as well. Participants were interviewed at the beginning of each test to ensure they fulfilled this core criterion. The resulting groups included professionals attending and senior students who had often completed a placement year. This guaranteed that no novices were included in the results.

3.3.3 Ethics and consent

All those involved in testing before any questions were asked had been offered consent forms that were designed to the standards set out by Brunel University's standards of ethics and consent. In addition, each test presented to participants was reviewed through BREO the Brunel Ethics Online portal and was cleared for being a reasonable, moral and fair test.

3.3.4 Selection of materials for research

As part of this research, it was necessary to use radically innovative materials in testing. To establish which materials were radically innovative and collect them for testing, a materials library company was contacted. The Materials Council are a group of independent materials consultants, who unlike some other materials libraries are not paid to promote specific materials and are able to share an unbiased knowledge of the materials landscape. This group was paid to collect a selection of radically innovative materials, all of which had to fulfil the criteria laid by the definition found in the introduction of this thesis.

They provided samples of over 80 radically innovative materials which were sourced from their knowledge of the materials industry. From this list, materials were chosen that allowed for a diverse array of different material types to be represented in the tests. With each material being considered as radically innovative by the members of this group and fulfilling the criteria for a radical innovation, the researchers could be confident that the materials being tested were accurately represented radially innovative materials and could be used as examples in the research.

The Materials Council was also able to source the material communicators information on each sample, ensuring the collection of information around each material was sourced in the same manner and to the same rigour. This is important for the workshops in descriptive study 1 and 2, which used this information to generate the communications around the materials.

3.3.5 Overview of the limitations of tests throughout the research

All the tests completed in this research have been crafted so that they can create an accurate view of the topics they are investigating. However, there are limitations to how the test can account for every possible variable, and in addition, compromises must be made on how the tests are run so as to enable them to work within the budget and rules of the institutions they call upon. Below is an assessment of these challenges.

The initial test was a fact-finding exploration to see in a limited group if there were problems surrounding radical innovations. The test was conducted in co-operation with another researcher who was looking to assess smart materials and used some of their resources. This led to this test being limited in scale, as it only pulled on a group of sixteen participants it could not be said to be fully representative of the whole population. However, this limitation was acknowledged and as a result, the goal of the main test was to direct future testing that could assess assumptions or insights gained at this early stage.

The second test allowed for short interviews with designers and design students. This test was on a larger scale and pulled on people from multiple backgrounds, so did not have the same limitations as the initial test. However, due to the need to be mobile in the space the selection of materials was minimal and in future tests, a spread of materials was always incorporated. There is potential for this to affect the results as without a range of choice, some lack of response may have been due to a lack of interest in the material. However, given the number of participants in this test this error is hopefully corrected for by the number or respondents contacted.

In the initial workshop, a review technique was selected that used audio recording of designer's discussions and then taking pictures of their design ideas. When arriving for some of the first tests in Italy, the researcher was informed that these techniques weren't allowed. As the tests represented approximately a third of all expected testing, a change needed to be made to ensure that the research could still be used. To enable the research to continue and to collect content the method of recording data switched to active notetaking. This system comes with limitations, most importantly that more content is lost compared to audio recordings. However, it can be useful and is a process that the researcher had used previously.

The second thematic review which looked at radical innovations in materials was mainly limited by the researcher's knowledge. It looked to pull in recognized radical innovations to help build up an understanding of the different 'types' of innovation. The innovations assessed were pulled from publications the researcher was able to locate. However, if there are other publications, in foreign languages or just not easily accessible, they would have been missed. There is the potential that this could've influenced the result of the review but over a hundred materials were included in the assessment which should contribute a significant amount of insight into the different radical innovations that exist.

Overall, nearly all the research in this thesis is of a qualitative nature with quantitative tests used to support. Qualitative data has its limitations as it relies on the interpretation of information, which allows for the introduction of bias. Where possible research systems have been used to help reduce this effect, the thematic review is one example. While being a qualitative system, it also is highly codified and aims to reduce the bias of those working on analysing the data.

3.4 Assessing Successful communication

In this thesis, effective communication is when the material has been communicated and that whoever is communicated to can then use that information to create ideas that are practically possible. This reflects that they have gained an understanding of the material. In these tests, this process is what is being tested to see if the communication is effective. In three tests, designers have materials communicated to them and are then challenged to use that knowledge. The nature of this challenge needs to be clearly defined, along with what is a success condition and a failure condition. To ensure academic rigour, several potential tests and scenarios for success were considered.

3.4.1 **Scenarios for success**

The assessment of this learning needed to be built of a clear understanding of 'successful' communication. This system needed to be rigorous and fit the cognition that designers were undertaking when thinking about these materials. This tool, therefore, needs to fulfil a specific list of criteria.

- Work with designers to create a mental model of the material's innovation – Designers are using these communications to build new designs, creating models of how the proposed design will utilize the material. This creation of a model is integral to the success of material communication as it is how designers understand the innovation. The ability to make a useful mental model rather than just repeating information creates a more complete understanding of the concept and better enable designers to create designs and for those designs to be effective, even if the model is incomplete (Christensen, B. T., Schunn 2009). This need for modelling is particularly important for smart materials, which by their nature are able to dynamically interact with the environment in a way that requires the ability to model the concept and have an underdeveloped language for traditional communication (Barati, Karana et al. 2017). As a result, the approach needed to be able to assess that a useful mental model had been developed.

- Support the development of scientific and design cognition – The goal of this research is to bring together material science and designers. While the goal is not for designers to understand the underlying material science, there is need to understand the physical properties of these materials and how they can be used. This places a focus on ensuring that the tools used to support this process should support scientific understanding of the concepts. The approach must provide space for intuitive design thinking to take place; this will help designers continue to use their reasoning as discussed in the literature review.

- Not to become overly concerned with the assessment of non-relevant information – The research aims to communicate the radically innovative material property through communication. It doesn't aim to explain every single aspect of the properties of the material. The focus of this approach needs to be upon the innovation and how that can be utilized, while other aspects are important to communicate, the tool shouldn't aim to communicate every detail holistically.

- Have a respected pedagogical background – The approach of this research is effectively education on a very limited topic. The successful communication and to enable the use of new knowledge is often seen as a pedagogical pursuit (Dymoke, Harrison 2008). So, the tool chosen should aim to support this assessment, should aim to have a strong connection to this area of research and be well-reviewed by academics in that industry.

Assessing various approaches out there that look to build mental models led to a focus on three possible approaches that could be built on to structure the challenge. All processes below have strong links to the pedagogical science and focus on the use of relevant information to solve distinct challenges rather than repetition of all information learned, meaning that each meets the last two criteria laid out above.

3.4.2 **Case based reasoning**

The first concept considered is Case Based Reasoning (CBR). This process involves asking individuals to solve a challenge using their knowledge based on their understanding of a case/scenario that challenges them to apply a mental model. CBR is very similar to problem-based learning (discussed below); both tools are used in teaching to help increase learner's knowledge by presenting ill-defined problems based in real-world challenges that demand realistic solutions (Leake 1996).

CBR could be an appropriate basis for this evaluation, as it has many similarities to the design process. Firstly, it expects the challenge to be ill-defined, a common attribute of design processes. Users are expected to resolve CBR by pulling on the knowledge they have gained about the topic and also their lifelong experiences as a designer and human being. This is an expected element of CBR which encourages the use of prior knowledge outside of specific facts. CBR also benefits from the fact its focuses on challenging and even encouraging the participants to look for comprehension not factual knowledge (Kolodner 1992). This is exceptionally important to the testing process of communication. If a test merely asked designers to recite factual knowledge, a test would be more representative of a memory test rather than the ability to comprehend the attributes of material and use that knowledge practically.

However, CBR has limitations that make it inappropriate for these tests. Currently, the act of conducting a CBR is considered the learning exercise, and testing comprehension of knowledge is not the specific goal. To assess a CBR additional frameworks are required to understand how the knowledge of the participants has shifted. In addition, CBR also has a limitation as the methodology that underpins it focuses on applying the learning in a specific scenario. This could prove a limitation as each scenario would need to be tested to see if it was useful for all designers and aided in building a model that was relevant outside of that scenario. Finally, the core challenge of CBR is that it puts emphasis on prior knowledge. Stated by Koldoner (1992) *'Case-based reasoning means using old experiences to understand and solve new problems. In case-based reasoning, a reasoner remembers a previous situation similar to the current one and uses that to solve the new problem.'* This need to use old information on new topics may be inappropriate for radical innovations which, as discussed in the literature review, often don't have strong relevance to pre-existing concepts. These concerns rule out the use of CBR based practices in this thesis.

3.4.3 **Problem-based learning**

Problem-based learning (PBL) focuses on stating challenges and asking those involved to apply their knowledge to these challenges in an attempt to solve them. These challenges often add specific barriers or issues to a known concept which requires those completing the reasoning to re-evaluate their approach to the challenge. The goal is that those undertaking problem-based reasoning cannot repeat memorised procedures but instead need to think on the model of how they understand the challenge to navigate around the issues (Boud, Feletti 2013).

The concept builds on stimulating thought around how a challenge can be resolved in a way that demonstrates an understanding of the issue, helping to strengthen the mental model and also illustrate comprehension of it. This approach offers benefits such as when issuing a specific challenge, correct solutions can be mapped out by the individual describing the challenge; this list can then be used to assess the ideas suggested by those undergoing the challenge. There is also the ability to offer space for creative problem solving that fits well with the design process as these problems can be ill-defined (De Graaf, Kolmos 2003). While there are many different approaches to PBL what limits the approach's potential in this research is that it focuses a great deal on the use of prior knowledge, expecting those involved to have previously solved challenges or at least applied the knowledge in theory before the problem is outlined. This is not appropriate for the research in this thesis which concerns itself with the application of new knowledge.

3.4.4 **Model based reasoning**

"Scientists and researchers in many disciplines frequently resort to modelling and model–based reasoning to concretize abstract ideas, to simplify and clarify complex phenomena, to predict trends, and to explain mechanisms and processes." (Raghavan, Glaser 1995)

Model Based Reasoning (MBR) aims to create an understanding of models by those who use the approach. The goal is to create an understanding of the function of a specific idea and to develop that knowledge into a comprehensive mental model of how the target works. It is also available to all, being a system that even small children can comprehend (Coso, Le Doux et al. 2014). This is relevant to this research as it concerns itself with aiding the understanding of a new concept. Model based reasoning also aims to build up the concept of the model without relying on specific challenges or scenarios like either of the approaches outlined above. This makes MBR highly appropriate for the research outlined in this thesis. By focusing entirely on the accuracy of the mental model that is created, the focus of the feasibility study does not need to concern itself with creating specific challenges that may not be appropriate for all designers. It also does not place an expectation of prior knowledge and actively helps to explain complex or counter-intuitive concepts (Vosniadou 2013).

The application of the model to a challenge is also a core tenant of the MBR. The expectation of creating a model is that it can be used effectively in a wide range of scenarios but more importantly, be used to creatively solve challenges in a way that effectively uses the model (Koning 1997). This makes it highly appropriate for this design research as it allows designers to prove their knowledge through the creative use of the model. This provides a method by which the understanding of the model can be demonstrated by allowing designers to use it a way that feels comfortable rather than setting a specific scenario or challenge that should be resolved which the other approaches demand.

Examples of research that has used modelling to enhance and assess learning include: Gobert describes how essential modelling is to understand new scientific concepts, arguing that the modelling helps create an understanding of the ‘system’ by which the concept being described functions and allowing for layers of understanding to be added to a system. She argues that this makes the MBR of incredible value to the teaching of new concepts and allows for those learning to higher use the knowledge (Gobert, Buckley 2000). To better enable consultants to learn and action that learning, a study by Lane worked to see if modelling could enhance the learning of the management teams. It found that those exposed to this methodology were better able to understand their clients and build a new methodology to fit those clients (Lane, Salk et al. 2001).

The strength of model-based reasoning and the applicability of it to design means that testing will revolve around allowing the designers to apply the model to the content they are interested in. Rather than focusing on setting a specific problem that must be resolved or a specific scenario to apply, designers will instead be given free rein to apply their model to create new ideas which will allow both the strengthening of the model and will facilitate the testing of the model's accuracy.

3.4.5 **Assessing the mental models**

The goal of this research is not to bring designers up to the same level of knowledge as material communicators, but instead to focus on raising their knowledge to a point where they can use it effectively in the design process. To evaluate if this goal has been successful, an assessment of factual understanding would be irrelevant. Instead, the focus will be on if the mental models that the designers create when learning about the materials can produce feasible solutions; this works in line with the process of MBR. Accurate mental models are a method with which humans understand concepts, creating a model that they believe describes how an item or system functions. These mental models are prone to a degree of inaccuracy, as they are often based off incomplete data but they can create accurate solutions despite this (Greca, Moreira 2000). This is another reason why assessing the outputs as an act of MBR is relevant as it takes processes that map directly to the nature of the communication and systems of design thinking.

This test will not explore each designer's exact mental model of the materials they learn about but instead focus on the output of the process. Assessing a complete mental model is a time-consuming task and would require extensive work with every group of designers involved in this research. The research on this topic is also not aligned, with no one method agreed upon to accurately assess the mental model (Moon, Moon 2018). This is compared to the ease of assessing each groups design outputs, which would expose if the mental model is fundamentally inaccurate while taking a fraction of the time and being a valid method to check if the mental model they have created can produce effective concepts which is the success state. Inaccurate designs are a clear indication that mental models have failed. Accurate designs do not mean they've succeeded though, the mental model may be flawed but allow for the creation of functional designs (Johnson-Laird 1983). As long as this model is accurate enough to produce consistently feasible designs then it serves as an effective resource for the designer. To what degree the concepts designers create corresponds to the materials actual functions and limitations will expose how accurate the mental model the designer has created is.

3.4.6 **System to assess feasibility**

To assess the output of the mental models, the first stage is to have an accurate model of the key attributes of the concept being modelled. So, for each material, a model has been created that pulls out the critical innovation of the material and its limitations. This information is pulled directly from extensive reading of communication materials available for each material, extending beyond that which is aimed at designers and also through consulting with material experts.

To create a model of each materials' overall qualities, the system Material Connexion used to describe its materials were copied. This system was picked as no specific academic model or tool exists to model materials for designers. While tools do exist for material science, these are not going to be useful to assess the mental models' designers create, as how designers and material scientists think is radically different. Other methods of creating models would necessitate forming a new type of model which hadn't previously been tested.

This system breaks down the material qualities into a few distinct groups: processing options, usage properties and physical properties. Processing options provides a list of manufacturing methods and states if they can be used or not. Usage properties and physical properties describe various attributes of the material. Either describing them in a one or two-word summary, for example, the surface finish might be described as 'glossy' or assessing the property on a simple three-point scale. This system is designed to enable designers to use the materials in their work and describes attributes using language designers will be familiar with.

While this system will enable the discussion of the material overall, it is not designed to describe radical innovations. While some may be able to fit into the system (for instance faraday film is both transparent and conductive which can both be represented in this model), those, especially smart materials, do not easily fit into this system. Current assessment tools for innovations are highly varied, and many tend to look at the innovation in terms of how it compares to other products on the market rather than focusing on its own characteristics. As the literature review found no appropriate established method to assess radical innovations in materials, the decision was made to assess the material by the key benefits listed by material suppliers and those limitations that are either listed or can be discerned by a cursory examination. These are taken directly from the communications provided by the material communicators and an assessment of physical samples of the material.

With a model of how the material is created complete, these models are then stored. When concepts are created, they are assessed in a similar manner. Those attributes that the creator listed in their description of their concept and those attributes that the concept would require to function are broken down into effects on the radical innovation and other material attributes. With each concept now paired with a list of necessary attributes to function, the original assessment of the capability of the material can then be referred to.

With this model in place, the concepts created by designers can then be assessed to see if they match up to these core attributes and limitations, a design that utilizes the attributes and respects the limitations shows the communication has been to a degree effective. Failure to meet some or all of these attributes and limitations shows that the mental model is flawed, and the communication has failed. Not all failures are the same though. Some mental models may be mostly accurate and create concepts that reflect this, respecting some attributes and limitations but not others. This shows that communication hasn't wholly failed but has not adequately communicated the nature of the material.

3.4.7 **The reasoning for not involving experts and reducing bias**

Perhaps the most effective method to review the feasibility of the concepts would be to have them assessed by experts. Instead, this research is using the above system. The choice to not use experts is due to a range of issues.

- **Range of materials used:** Each material would likely need its own expert assessor, as all the materials are vastly different from the others. Even those that share a similar category such as plastics are fundamentally different in the knowledge needed to understand the material. Finding experts for each material would be exceptionally time consuming, and there would also be issues of accuracy between them. Even those spoken to at material libraries only consider themselves experts in a limited window of materials.
- **Consistency:** If a large group of experts were assembled to assess all the concepts generated by this research, there would be another issue of consistency of assessment. With each expert having their own concerns about how to assess the materials, some may be more critical and others more accepting. This could shift the results significantly and reducing this bias effectively would require recruiting even more experts to be recruited to check the work of the first assessors. This exact issue was witnessed at the Light Touch Matters research consortium, which looked to bring designers and material scientists together. Designers created a number of concepts to use a new material that was being developed and there was often disagreement between the experts as to how feasible each concept was.
- **Issues with early design stage assessment:** This issue was surfaced when talking with Material Connexion and Materials Council as well as discussions with the Light Touch Matters research consortium. Those working in material science, likely to be part of this group of assessors, can be unwilling to state if a rough concept, as the ones in research will be, is feasible or not. With material scientists used to working with known challenges that have objective answers, early-stage design concepts can include many unknown factors for them to state if the idea is feasible or not. Scientists who were spoken to said that they were only comfortable weighing in on a concept's viability when it is more developed and the application of the material clearer. Those material scientists spoken to also said they were more likely to label an idea unfeasible than feasible when there are a large number of unknowns, as it could be damaging to their reputation to state an idea was possible falsely. Some feared that it could lead to an investment based on their recommendation and they preferred to be cautious because of this.

Considering these factors, the decision was made that the considerable logistical challenge of involving expert researchers was unlikely to create the quality of data necessary to justify the investment of time. This created a new challenge though. As this method relies on the researcher's assessment of the feasibility of the materials and this assessment is then used as a core part of the research, steps had to be taken to reduce possible bias.

- **Standardised test:** By creating a repeatable system for an assessment there is less space for biases to appear. While the system cannot be wholly objective, it breaks down the materials and concepts in the exact same way, helping to create a process that limits opportunities for differences of opinion to affect the results.
- **Splitting material assessment and concept assessment:** Bias was reduced through standardising the assessment process and splitting the assessment of the material away from the assessment of the concept. All the concepts were assessed first, with the requirements they placed upon the material listed. This collection once finalized, was then assessed against the abilities of the material. Describing the requirements of the concept without having the abilities of the material to hand was one step that aimed to reduce the researcher's ability to influence the results.
- **Reassessing all concepts: In the final workshops of this research:** Rather than just assessing all the concepts and comparing the results to the first workshops, all the concepts generated were reassessed as one. This created a limited blind to the researcher's ability to know which ideas were generated during the first workshops and the second. While it was possible for the researcher to be able to remember the concepts from the first workshops in limited detail, there were many similar concepts in the second workshops to confound this recollection. In addition to this, as the full assessment was gone through again, the initial assessment of the first workshop could be compared to the reassessed concepts to see if there were any notable discrepancies.

3.4.8 Description of the process

As the assessment of the ideas that the designers create will be assessed by the researcher, it is essential to create a system that eliminates bias and is as objective as possible. To do this, each concept needs to be assessed against the same criteria in a manner that is repeatable by independent researchers. To provide this, a simple system was devised.

Step 1: Material mapping: All materials have an accurate 'model' created of their innovation attributes and limitations. This is generated by looking at the content made available by material communicators and pulling out the attributes and limitations they highlight. Here is an example of a list of attributes and limitations for D3O, a dilatant plastic, derived from the materials accessible from material communicators.

Attributes	**Limitations**
• *D3O is a flexible plastic that can conform to movement with degradation.* • *D3O becomes harder when it experiences jerk forces.* • *Once exposed to impact, D3O will return to its original flexible state.* • *D3O is stable plastic that once formed, will retain its shape and capabilities until the plastic starts to break down.*	• D3O has a limit to how hard it can become before it shatters. • D3O cannot be melted down and reformed while retaining its' abilities.

Table 8: Example of material mapping

This model is only of the radical innovation and how the material functions due to this innovation; it does not include a model of the broader function of the material. Those capabilities that lie outside of the radically innovative properties were also noted down. The format used was taken from Material Connexion's communication tool. This system is applied to a large number of materials from many backgrounds and is flexible enough to cover most materials; it is also easy to use the various assessments due to their lack of objective detail which would not always be available.

In the below example, many categories are assessed as unknown; this is due to the assessment of the communication being focused on what has been covered in the communication or is evident through experimentation with the sample. Ideas that could be discounted due to features that are not covered by this will not be marked down as a failed communication. While the idea may be flawed, this is not due to a failure in the communication by the material communicators but instead by designers' own misconceptions.

An example of this may be that when working D3O, one idea presented by a design group was to use the material in replacement joints. This wouldn't work due to the way the plastic reacts with the body and also due to legal limitations placed upon medical equipment. Neither of these failure conditions is covered in the communication presented about the material and so it wouldn't be accurate to consider this a failing of the communication materials.

The model for each material will remain consistent for every test, ensuring that the same standards are applied to each idea that designers create.

Name: D3O	**Material type: Smart material, plastic**	**Material innovation: Dilatant material**
Processing	Usage properties	Physical properties
Injection moulding: No	Flame retardant: Low	Stiffness: Changeable
Extrusion: Yes	Usage temperature: Medium	Impact resistance: High
Cold pressing- Deep drawing: Unknown	Water resistance: High	Surface/texture: Rubbery
Blow moulding: Unknown	Wear resistance: High	Transparency: None
Thermoforming: Yes	Acoustics: Unknown	Surface Hardness: Low
Lamination: Unknown	Chemical resistance: Unknown	Additional properties
Printable: No	UV resistance: High	Gets harder when it gets hit (dilatant)
Stitchable: Yes	Scratch resistance: Low	
Weldable: No	Outdoor use: Yes	
Die Cut: Yes	Tear resistance: Unknown	
Wood Working tools: Unknown	Reflectivity: NA	
Die-cut: Yes	Stain resistance: High	
Metalworking tools: Unknown	Thermal conductivity: Low	
Castable: Unknown		

Table 9: Example of mapping non innovative material qualities

Step 2 Concept mapping: When the concepts were generated through the research, they were assessed by two criteria.

- Attribute use designers specified in their description: when the ideas were generated, designers often explained how the concept would use the attributes of the material. These statements are of the highest priority as they show the designer's mental model, accurately with no interpretation from the researcher.
- What material qualities the material would need to function: As part of the assessment, each concept was explored to see what material qualities were essential to its' functioning. With the concepts at an early stage, this was generally a minimal set of attributes. With most focusing on the material attributes needed to endure the uses outlined in the concept, while a few referred to manufacturing concerns.

Step 3: Comparison and assessment: Once the concepts that designers generate are collected, they will be assessed against the attributes and limitations of the material and sorted into different groups.

- Fundamentally flawed: Concepts that are sorted into this group will show signs of breaking limitations of the material while also failing to use the attributes of the material to add to the design. By both failing to create an understanding of what the material can achieve and explain the limitations of the material, the communication can be seen to have fundamentally failed.

An example of a fundamentally flawed D3O concept that appeared during testing is using it as a tyre that could stop punctures. This shows no use of the impact absorbing properties, or the materials ability to switch from being flexible to non-flexible while also ignoring concerns around the limitation of the material to handle cutting forces.

- Partially feasible: Concepts sorted into this category have successfully used attributes of the material but fails to respect the limitations set out and has created a design that exceeds those limitations. This provides evidence that the mental model is partially accurate in that the designer can picture the attributes of the material but has failed to understand the limitations of the material.

An example of a partially accurate D3O concept that appeared during testing is a bulletproof insert for clothes. This shows that the designer has understood that the material can absorb impacts and go from being flexible to being solid; however, it failed to consider the issue around the material shattering under high impacts.

- Fully feasible: This concept will respect the attributes of the material and work within the limitations of the material. Ideas in this category show no evidence that the mental model is flawed.

An example of a fully accurate D3O concept that appeared during testing is a comfortable lining for the hard hats that those on building sites wear. This shows that the designer has understood that the material can absorb impacts and go from being flexible to being solid while also not violating any of the limitations the material has.

- Unclear: Over the process of analysing the work, a few designs appeared that could not be sorted into any of the above groups as they didn't use any of the attributes or contradict any limitations. This minority group is noted but for the purposes of assessment is discarded as it is impossible to assess if the communication was accurate or not. With it being equally possible that the designers fully understood the information provided and chose not to use the attributes of the innovation, or it is possible that they have misunderstood the attributes but have accidentally remained in the bounds of what is permissible by the limitations.

An example of an unclear D3O concept that might be considered unclear (none were presented during testing) is a 'Drinks Coaster'. There is no evidence that the attributes are understood, but equally, the limitations haven't been ignored.

3.5 FOCUS GROUP METHODOLOGY

Focus group methodology was applied to several tests throughout this research. The most important being the broad set of workshops detailed in the prescriptive study. However, elements of the focus group methodology, especially the group size, was also applied to the workshop series in descriptive study 1 and descriptive study 2. These were applied as the considerations around group size is to facilitate discussion and allow all to be heard. This was important in the workshops which were meant to facilitate a similar environment.

3.5.1 The methodology of the focus groups

A focus group is a group interview that allows researchers to gain qualitative data from a small collection of relevant parties. The format is similar too regular interviews but encourages talks between the different participants to help expose information that may not have appeared in one on one interviews as well as exposing multiple viewpoints more effectively (Freeman 2006).

'Focus groups are unstructured interviews with small groups of people who interact with each other and the group leader. They have the advantage of making use of group dynamics to stimulate discussion, gain insights and generate ideas to pursue a topic in greater depth.' Hendry (Hendry 2003), p. 394)

Each group will be selected from junior to senior designers. Novice designers will not be selected as they will not have the skills or experience of communicating materials to complete design challenges. A junior designer will be a designer with at least two years of experience. The groups interviewed will need to be at least a specific size. This is to ensure the quality of the research. While thoughts on how big a focus group's size vary, with some recommending 6-10 and others 8-10 the goal will be for each group to have a minimum of 6 in each focus group and no more than 10 people to ensure that quality remains high (Krejcie, Morgan 1970).

In the first focus group, seven participants were involved, and for the focus groups completed in the prescriptive study, all consisted of between 6-9 participants, though one only had five this was considered an acceptable outcome as it still produced information consistent with the other workshops in both detail and amount of content. These group sizes were chosen as they allowed for meaningful discussion while also allowing for the data collection to be well managed by the researcher.

While who makes up the group is important; what also must be considered is how many focus groups should be completed (Freeman 2006). While very few groups will not generate useful or reliable data, too many groups will not produce significantly improved results. Current recommendations put the advised level between 4 to 5 focus groups. This has been shown to produce data of consistent quality.

While the first focus group was not part of a series this was deemed acceptable as its aim was to find an indication of what research might be needed. Its findings showed the need for further research that was explored in more detail by the interviews. The focus groups in the prescriptive study however needed to obtain far more detailed findings. As a result, a full five focus groups were conducted. This is the most significant number of focus groups usually considered useful, conducting any more focus groups would likely see repetition with limited new information gained.

The structure of the question is fundamental. Previous researchers have found that poor wording or limited question structure has had a potentially detrimental effect on the result they gain. To lessen this effect a guide for focus group formatting was researched.

After looking through multiple tools, the system laid out by Krueger was considered the most useful given the questions that needed asking. The questions were then generated using this template. In addition, following advice from numerous sources, all the wording was kept as generic and as easily understood as possible to ensure that participants understood the questions (Krueger 2014).

In the focus groups notation was used as the core tools to collect information. The notation is not the most reliable method to record data but allows researchers to be more flexible in the groups they work with (Sanjek 2019). While the audio and digital recording is a more exact method, it causes issues with data protection and intellectual property rights. In many organisations visited for this test recording was not allowed as they were protective of their worker's/student's IP.

3.6 Interview Methodology

The interview methodology has a wide-reaching application in the test completed in this thesis and can be applied to both the introductory interviews in descriptive study 1 and those complete with experts in descriptive study 2.

3.6.1 **Methodology of Interviews in descriptive study 1**

In this thesis, an interview has been deemed to be a conversation or verbal exchange where an interviewer attempts to gather information and understanding from another person, the interviewee (Turner III 2010). The goal of the interview is not just to gain qualitative data but to develop the information into a critical understanding of the information shared by the interviewee (Alvesson 2011). This includes the ability to understand what motivates and shapes interviewees answers (Seidman 2013).

Interviews are not all the same and, according to (Alvesson 2011), differ in the four core ways. Firstly structure**:** Interviews can vary in the level of structure they place on the interaction between the interviewer and interviewee. This functions on a scale from fully structured interviews to open interviews. There are different benefits based on the amount of structure imposed, ranging from the ease of data collection to altering what kind of content is collected. Next is the size of the interview, which is based on the number of interviewees. Is it a single person or group of people? Single person interviews require different strategies for interviewing groups of people. Third is in what context the interviewer conversation is conducted can have a profound effect on the outcome. They can also affect access to interviewees; for instance, in one scenario face to face meetings may be optimal for a given task. However, phone interviews will be used instead to gain access to specialists who would not usually be otherwise available. The final consideration is if an interviewee belongs to certain racial, vulnerable, or otherwise marginal group. It is believed to have a potential effect on the outcomes of an interview. This was a non-issue for this research project as no such group was targeted.

A semi-structured interview process is going to be used for the interviews in this thesis. Semi-structured interviews are described by (Drever 1995) as following these three main attributes.

> *The interviewer and respondents engage in a formal interview.*
>
> *The interviewer develops and uses an 'interview guide.' This is a list of questions and topics that need to be covered during the conversation, usually in a particular order.*
>
> *The interviewer follows the guide but is able to follow topical trajectories in the conversation that may stray from the guide when he or she feels this is appropriate.*

This was deemed most appropriate as the data collected needed to comparable from one interview to the next but allow participants the ability to explore topic the interviewer may not have deemed relevant.

During the interview, it was essential to observe the social cues of the participants. As the question revolved around their understanding of materials, it was important that their expressions and interactions reflected any claims of understanding concepts. The scenario in which the conversation takes place also must be controlled. With access to the internet, it would be exceptionally easy for a participant to look up the materials being tested, invalidating any research as they expose themselves to additional information. After referring to "Advantages and Disadvantages of Four Interview Techniques in Qualitative Research" (Opdenakker 2006) face to face interviews was preferred given the above constraints.

3.7 THEMATIC ANALYSIS METHODOLOGY

Thematic analysis was used at two stages in this research. It was used to assess responses from in an interview to generate different methods of communication, and it was used to assess the group of existing radically innovative materials. In both examples this coding and analysis was done by hand rather than using technology that might do this automatically. In the case of the first thematic review this was due to the poor quality of the interviews audio quality which necessitated an excessive period of transcription and review. To maximise the effectiveness of the time put into the process the thematic analysis was incorporated into this process.

In the second review the wide variety of sources of information had to be digested, the fact that these all used different formats, sometimes being images or print, made it difficult to collect the information so it could be assessed by an automatic system. The language used between materials was also not consistent, so the researcher collected the information and analysed it themselves. Both thematic analyses used the following methodology.

3.7.1 **The methodology of a thematic analysis**

A thematic overview is a robust tool that is designed to use qualitative data to provide useful information. The analysis works by codifying the qualitative data into small discrete chunks that are then assessed to find micro-themes and macro themes (Aronson 1995). The thematic overview has been chosen in this case because while there could be an assessment of all these materials by objective material qualities and assessing how they differ from each other, what makes innovation radical is seen as mostly subjective by innovators and designers.

The thematic analysis allows the innovations to be categorized in a formal manner ensuring the division is as unbiased as possible. Thematic analysis has often been poorly defined, so the system used in the thesis will use the more codified five steps laid out by Braun (Braun, Clarke 2006)

1. Collecting data: Technically not part of the review but essential to it, is the collection of data beforehand through interviews and testing.

2. Codifying the data: Once the data has been collected, it must be codified splitting it into useable chunks that can then be assessed as a collective whole. A core element of this is finding a model to codify the data usefully.

3. Identify themes: Once the data has been codified, it will then be refined into abstract themes. Themes in this sense mean repeating topics or commonalities between the data.

4. Review potential themes: Once these themes have been created, it is essential to refine their definition, so they are;
   a. Specific enough to ensure there is no overlap and avoid repetition.

   b. Broad enough to cover a set of ideas represented by the data they are describing.

5. Define and name themes: Once the themes have been listed, they need to be assessed to establish;
   a. What is unique and specific about each theme, each theme should be clearly defined.
   b. Define the larger groups of themes: Describe what these themes tell us and what the characteristics are of the group. This is now considered an 'organizing theme' providing a unifying description of all the features of the smaller themes in the group.

This is the process that will be followed to assess innovative materials in this review. The result will be a taxonomy of the innovations allowing for testing to focus on clear and verifiable aspects of radical innovation.

3.8 SUPPORTING QUESTIONNAIRE METHODOLOGY

Questionnaires were used in conjunction with both the workshops and focus groups completed throughout the project. Questionnaires are best used as a supporting tool for other research, and this was the role they played in this research. The first set of questionnaires were used to gain extra information from those involved in the initial workshop and provided immediately after the conclusion of the workshop.

The second questionnaire was open to designers of all backgrounds who did not have past involvements in this research. Data was collected and then used to help develop the discussion plan for the focus group.

3.8.1 **The methodology of questionnaires**

The questionnaires in this thesis are concise and targeted to specific issues, acting in a supporting role to other research methods. Surveys are also effective when they are used to help direct research or develop knowledge collected from other sources (Punch 2003).

While questionnaires can be both quantitative and qualitative, they were only used for quantitative data in this research. This was because all necessary qualitative data was being collected from the research tools that these questionnaires supported. To provide quantitative data, the questionnaires used two types of question format.

This questionnaire reached 195 designers. For surveys, it is essential to have a large number of participants to generate statistically relevant data. For most survey's the minimum number needed to have reliable data is based on the population. However once a population grows to a specific size there the number of respondents needed plateaus (Krejcie, Morgan 1970). Using the survey sample size calculators of Survey Monkey and Survey System, it was found that for a population of over a 100,000, the same number is statistically relevant. The two other considerations are the confidence interval and confidence level. The confidence interval is how likely the results of the survey are to differ from the population. For these surveys, the acceptable confidence interval ranges from 1%-10%. As these questionnaires would be supporting qualitative research and not standing as proof of a hypothesis, it was deemed that a confidence interval of 10% was acceptable. The confidence level of most surveys is 95% meaning this is the likelihood that findings are accurate. This level was maintained for this survey. Using the survey calculators, it was found that 96 participants would be needed for this research to be considered statistically significant. However, as there were two variations of the questionnaire it was considered best to have 96 respondents for both each. This led to the target for the questionnaires being 192.

3.8.2 **Questionnaire tools**

Likert scales are one of the most used question formats in research. The format allows participants to select a number that represents where they feel on a scale set by the tester (Bertram 2007). The scale can be any bipolar pair of positive and negative options. Likert scales are useful as they are both versatile and straightforward. The respondent's answers can be easily tallied and then averaged to give an indication of the group's overall feeling, allowing for a robust quantitative value for an abstract concept like 'understanding' to be generated.

Like other forms of testing though Likert scales have their disadvantages and a key one for this testing is 'social desirability bias'. This bias happens when respondents answer in a way that they feel makes them look better, rather than answering honestly (Johns 2010). This bias is not unique to Likert scales, but as the scale is quite small, even a one-point shift can have a substantial effect on the outcome. This is in part why the questionnaire remains a supporting research tool rather than a core one.

Another tool used was multiple-choice questions. Multiple choice questions allow those tested to select the best answer to the question from a list of possible choices. With multiple-choice questions, it is essential to frame the answers so they are not leading (Punch 2003). The limitations of a multiple-choice question though are the fact that with only a limited number of options the real thoughts of the respondent may not be reflected. This can be addressed by offering an 'Other answers' field that allows respondents to write out their own response.

The final tool used in the questionnaires allows respondents to rank various options from most effective to least effective. Unlike multiple-choice answers ranking allows respondents to rate a variety of options by comparing them to each other. This helps collect a better average of opinion by ensuring that each option rather than just the most preferred choice is factored into the data (Punch 2003).

3.9 WORKSHOP METHODOLOGY

The methodology outlined here applies to workshops covered in descriptive study 1 and descriptive study 2. These significant workshops are an extension of the same test and needed to be held to identical standards. They also need to be some of the most robust testing in the thesis as much of the conclusion will be drawn from them.

3.9.1 **Participant Recruitment**

To recruit participants, designers need to be contacted and engaged with. This could be done by contacting groups individually, but there may be a high chance that without some benefit to themselves, the designers will not be interested in taking part-time consuming event. To get the necessary number of participants, the test will be offered in the form of a workshop that will offer to explain new materials which are ready for mass distribution. The idea is to provide the workshop as a tool that can add value to the designer's work and that can be used to inform the research.

The workshop will be assembled in a way that resembles a business venture that the designers will receive as 'free' if they agree to engage and complete the test that will be a part of the thesis. In fact, the whole of the workshop will be tailored to provide information to the thesis however only a portion of it will require the designers to participate in an actual test. The rest will take the form of an observational study. The process for this is to produce promotional material for the workshop and distribute it to design agencies and designers based around London and the surrounding area. The industrial designers that are of particular interest are those that work with a variety of materials and technologies; however, their sphere of interest is irrelevant (medical, consumer products, automotive). The goal is to get a minimum of ten different designers/design agencies involved to gain a meaningful understanding of the different groups; the desired group is to be at least 20 different design groups.

Figure 25: Workshop layout for workshop at Institute of making

Figure 26: Workshop layout for workshop at Institute of making

In these tests, the selection of participants was critical. They had to be designers relevant to the research, those aimed at creating physical products, primarily product and industrial designers and they had to fulfil the criteria laid out in the methodology. Also, large enough groups had to be contacted to ensure that the workshops generated a significant number of concepts and each group within the workshops were large enough to enable discussion of the materials in accordance with the focus group methodology.

These participants were sourced from numerous universities and professional design consultancies. Each group had a minimum of two years of undergraduate or equivalent training, ensuring that they had advanced beyond being novice designers and were at the same standards maintained throughout the research in this thesis.

The courses the students were on were all product design or industrial design focused, and their studies were focused on the creation of physical products rather than digital resources. The professional designer's companies were all focused on the production of physical designs and considered themselves to be product or industrial designers.

3.9.2 Data collection in the workshop series

The essential data in this test is that which shows how designers interact with information about the design process and how this interaction is affected by the inclusion of new media. To gain this insight the testing is split into two main parts. Observations of group interactions and issuing short questions for the participants to answer. These methods are both excellent at gaining understandings of the nuances in the culture and providing information on the complex interactions that are being studied (Marshall, Rossman 2014).

The observation will be note based, relying on the researchers to transcribe the notes from those in the workshops. The goal is to collect verbalization of the design decisions, which is considered an essential part of understanding how designers think (Cross, Dorst et al. 1996). The main goal is to capture how the information interacts with the design process, especially those novel design decisions which are the unique decisions which define a design. While some observation will be passive, the designers will also be asked to verbalise their thoughts and produce sketches to illustrate their design.

This is supported by the note takers taking a tally based on the occurrences of the communication tools outlined in the interviews and thematic review and being, Comparison, Contextual, Objective and Subjective.

When note-taking the researcher and research assistants will be built with consideration to the guidelines set out by Emerson et al. in the Handbook of Ethnography (Emerson Robert, Fretz Rachel et al. 2001). This focuses on collecting data at critical points and working towards a complete overview. Note taking was chosen as the was no consistency in testing environment. Some locations had facilities to record other like those showing in figure 15 and 16 found the workshops spread out over a large area where multiple recorders would've been needed and the volume of the location was very high making it unlikely that the recording would've been have good quality. This was only one of the challenging locations visited. There were also challenges from legal point of view when considering recording the workshops for example multiple universities visited prohibited filming their students even with those student's permission to protect their ideas. Some professional designers didn't want their ideas recorded as they considered it a violation of their intellectual property. When it came to record the concepts generated by the designers this was done by asking the designers to write down a description of their concept which could then be taken by the designer. This allowed for minimal loss of data.

3.9.3 Controlling bias in workshops

The workshops outlined here rely the researcher to introduce materials in an unbiased and consistent manner. Changing the presentation of the materials from one workshop to another could have an impact on designers understanding and interest in the materials. To limit the affect the researcher took three actions. Firstly, the researcher repeatedly practiced the introduction of the materials until they could consistently deliver the same quality of presentation each time, using volunteers to assess if the presentations were consistent.

The researcher also assessed the results from each workshop, once all workshops in that series were concluded. This assessment looked to see if any workshop had outlier results, that being a notably higher or lower overall understanding of materials. This assessment resulted in the removal of one workshop in the second workshop series where every concept created was feasible and the group created a larger number of concepts than the average group by a factor of two. This workshop was also notable for only including four members, making it the smallest workshop completed and the only one were a group only focused on one material, a hydrophobic textile. As the workshop was a collection of designers who frequently worked with textiles as part of their design work it was deemed that due to the outlying nature of the results, test conditions and expertise of the group that these results should be discarded as not in keeping with the focus of the other tests.

Finally, the researcher used written text to support all the communication, this meant that while the spoken element of the workshop could change there was still a backbone of text that was consistent across all workshops. This resource was used consistently by designers in all workshops ensuring that they had access to something not influenced by the researcher's language or tone.

3.10 SUMMARY OF THE CHAPTER

In this chapter, the methodology that this research will follow was made manifest; Design research methodology was the chosen form of the research process for this thesis. This came after other systems were considered. These were discarded because they were either too design specific or too generic for the process and design research was seemed to be a medium between the two opposites.

The system laid out outlines the path of future research, following the clarification of the research, a descriptive to study the current situation of the area being researched. A prescriptive study that examines this understanding and explores where improvements could be made. A final descriptive study then works to establish if the new, improved system, developed in perspective is effective and looks to also improve upon it further.

Other key factors were set out, including what the definition of knowledgeable designers and material science novices which allowed for recruitment of participants. The selection of participants was of paramount importance to ensuring this research is relevant and useful.

Finally, the methodology for individuals' tests was set out. Each test in this thesis has now been described in the section, as to why it has been chosen. The design of the tests is backed up by the existing research that establishes that the tests will be rigorous and provide valid research.

In addition, it highlights how the comparative study system is going to allow the comparison of workshops in descriptive study one, and descriptive study two. This comparison will be used to establish a change in communication effectiveness. This will be used as evidence of the validity of the research conducted here.

The next chapter covers the first descriptive study and explores how radical innovation in materials can be communicated to designers using the established methods of communication found in material libraries and other resources. The goal of this next chapter is to resolve how greatly affected designers are by poor communication and how this may differ from the communication of incremental innovation.

It also explores how designers discuss and talk amongst themselves with about radically innovative properties, which is a core element to understanding what tools may be useful to improve the communication of radical innovation.

4 DESCRIPTIVE STUDY 1

4.1 INTRODUCTION AND POSITION IN LARGER RESEARCH

In descriptive study one, the goal was to answer **research question 2** 'Assess how effective communication materials aimed specifically at sharing radically innovative materials with designers are at enabling them to create concepts that are feasible and use that knowledge accurately.'

This was enabled by a series of tests that would evaluate how the communication of radical innovative materials was distinct from incrementally innovative materials. At the same time, it also assessed how designers used language to describe materials, and the effectiveness of current communication techniques for radically innovative materials.

This methodology to also helped start to answer **research question 3** 'What text-based communication techniques enable designers to understand radically innovative materials better', by looking into what language designers used while communicating about the materials.

The first test was a small focus group study that asked a group of designers and specialists to assess a number of new radically innovative materials, as well as some incrementally innovative smart materials which have been on the market for many years and fulfilled the criteria for being incremental innovations. The goal of this test was to establish at a fundamental level if there was a difference in how designers understand the two innovation types.

The second test was a series of short interviews that asked designers to both discuss incremental and radically innovative materials. The goal behind this was to establish if there was a distinct difference between how people communicated the two different forms of innovation, both incremental and radical, as well as establishing what linguistic tools designers preferred through a thematic analysis of all the descriptors that designers used when discussing all the innovative materials. This test would help answer **research question 3**. It also fuelled the ability of the researchers to assess the final test in this descriptive study in more detail to further add insight to this question.

The last exercise was a large workshop series that asked designers to use radically innovative materials which were communicated with the descriptions available from suppliers or material libraries — assessing how effective the communications were by challenging designers to use the materials in practical applications. Success meaning the communication had been successful and failure showing the communication had failed. The performance of this communication in this test would form the core answer to **research question 2**. In addition, this test gathered more information as to how designers discuss radically innovative materials amongst themselves allowing for a greater understanding of what tools should be used to communicate to them, this was enabled by the insights gained from the above test and added further insight to **research question 2**.

The performance in this workshop also allowed for the assessment of **research question 5** 'Does this new communication system function notably better than the tools currently used by material communicators?'. Creating an understanding of current communication techniques performance that could then be used to assess against.

4.2 INITIAL FOCUS GROUP STUDY

The initial study was targeted to see if the distinctly new nature of radical materials influenced their ability to be used in design. The goal was to compare the use of radically innovative materials that designers had not seen before to materials that designers were more likely to recognize and be aware of due to their long-term presence and dissemination in the market. Challenging them to use the material in a design exercise.

The explanations provided were pulled from the official communications around the materials, available through the manufacturers or retailers though these communications were supported by information provided by the researchers to help designers understand the materials, as the workshop was focusing on the nature of the material not the nature of the communication tools.

4.2.1 Limitations of the initial focus group

This initial test is a fact-finding exploration to see in a limited group if there were problems surrounding radical innovations. The test was conducted in co-operation with another researcher who was looking to assess smart materials in particular and used some of their resources. This led to this test being limited in scale, as it only pulled on a group of nine participants it could not be said to be fully representative of the whole population. However, this limitation was acknowledged and as a result, the test's main goal was to direct future testing that could assess assumptions or insights gained at this early stage.

There were also limitations in regard to data collection. The data collection focused on notetaking by the researchers. Two researchers recorded the discussions had by those involved. This method only provides a limited fidelity of information. However, having two researchers allowed for a more considerable amount of information to be collected and allowed the notes to be compared to ensure that the information collected was accurate.

4.2.2 Participants in the initial focus group

In this activity, participants needed to fulfil the criteria laid out in the methodology. To ensure the validity of the research, the focus group included nine members; this was enough to be considered viable by the focus group methodology. A breakdown of the participants is shown below,

Type of design experience	**Number involved**
Three years of academic knowledge of material science with at least one-year professional experience.	2
Three years of academic knowledge in design with at least one-year professional experience.	7

Table 10: Summary of participants for the initial focus group

This group was chosen from a selection of designers involved in the design program at Brunel University, choosing selection of designers who had already completed their undergraduate degrees and had spent some time working in the relevant industries.

4.2.3 Process of initial focus group study

Session	Description	Supporting Materials	Desired Outcome
First Session: Gaining material knowledge	All participants had the opportunity to manipulate the materials ask questions and are instructed as to their functions.	Material samples, a poster with materials properties, videos of materials	Improved understanding of materials
Second Session: Understanding interaction potential.	The participants were all asked to brainstorm the potential ways that interactions could influence people's reactions or mood.	Brainstorming map	Develop an understanding of groups perception of materials
Third Session: Idea creation	The groups were asked to imagine potential applications of the materials that might improve the lives of the elderly and describe them.	Material samples	Creation of a wide range of ideas showing an impact on the ability to ideate

Table 11: Summary of the process of the initial study

4.2.4 Results

4.2.4.1 *First Session: Gaining material knowledge*

In the first session, the materials were shared with designers; the goal is to integrate the materials into designer's knowledge fully. All the materials were shared alongside information provided by suppliers and information available through material libraries to help communicate those materials. Designers were also free to ask questions of the researchers to clarify that knowledge and understanding of the materials. This was to ensure that they had the maximum amount of knowledge that they felt they needed to understand the material and were not limited by the printed communications.

As the materials were discussed, designers showed distinct preferences for materials. When questioned on this by the researchers, they identified that they found the materials that can be described as 'unfamiliar', as the most interesting, and those materials that they found 'familiar' were the least interesting. A breakdown of how the group labelled the familiarity and unfamiliarity of the material are listed below.

Unfamiliar materials	Familiar materials
Rheological Property Changing Materials, Shape-Changing Materials	Light Emitting Materials, Electricity Generating Materials, Colour Changing Materials

Table 12: What materials were seen as unfamiliar and which were seen as familiar

This corresponded directly to the materials that were radically innovative and were expected to be new to the designers and those that would have been familiar to the designers due to their long-time presence in the market.

4.2.4.2 ***Second Session: Understanding interaction potential.***

In the second session, the consistent trend was that the rheological changing, shape-changing were the most interesting to the groups. The participants cited a combination of attributes to it, stating the material made them feel "surprise, interested, attentive, reactive and odd." When asked why they all replied with variations upon the phrase "new and different" stating that the newness and distinct difference of the interaction was what drew them to it, those who worked with the elderly highlighted that the reaction to these materials would probably be 'very good amongst the elderly' which helped continue the discussion. The electricity-generating materials were also discussed but only briefly; the group saw them as a form of button or sensor. A known factor.

This misunderstanding indicates an incomplete understanding or distinct disinterest with the potential of generating electricity. The least talked about the material was the light-emitting material which was only talked about when the supervisor asked the group to discuss the subject. In these discussions, the light-emitting material was treated as an already known quantity with one participant stating that "but it is just like a regular light right?" which reflected the attitudes of the rest of the group who wanted to move back to the discussion of other materials.

Most interesting materials	Moderately interesting materials	Least interesting materials
Rheological Property Changing Materials, Shape-Changing Materials	Electricity Generating Materials, Colour Changing Materials	Light Emitting Materials

Table 13: Summary of how interesting designers saw materials

Participants were asked to rank the materials into groups; the above is an average of those rankings.

4.2.4.3 ***Third session: creating ideas based on the material***

The third session participants created ideas that they felt used smart materials to improve the lives of users. The ideas were generated quickly and through the support of personas which intended to give examples of tasks or situations that needed improvement. Each idea was then assessed for feasibility.

In the table below the materials are shown in order of uses. It is interesting that the uses are precisely the opposite of how interesting the materials were seen as in the second session. The materials that were consistently used by the designers were those that were identified as having 'familiar' functions. It is also worth noting that the designers during the ideation session expressed great interest in using the Rheological Property Changing Materials and Shape-Changing Materials but could not create ideas for using them.

4-5 Uses	2 Uses	1 Use
Colour Changing Materials, Light Emitting Materials	Electricity Generating Materials	Rheological Property Changing Materials, Shape-Changing Materials

Table 14: Summary of materials use to create concepts

4.2.5 **Assessing Feasibility in this workshop**

During the exercise, the designers were encouraged to create ideas that the materials could achieve. The feasibility of the designs was assessed according to the criteria in the section above. Each material was presented and saw designers attempt to create solutions and the results of the assessment of feasibility for each idea is listed below.

Material	**Light Emitting**	**Colour Changing**	**Electricity generating**	**Rheological Property Changing**	**Shape-Changing**
Feasibility assessment for each idea	**Fully Feasible:** Light up collar for a dog that glows steadily brighter as time without walk passes **Fully Feasible:** Light up tableware especially the plate. (Illuminate food) **Fully Feasible:** Light up bookmark **Fully Feasible:** Replacement of audio alerts such as bells with lighting. (Aid those with specific hearing disabilities) **Fully Feasible:** Glowing post-it notes to make notes more visually available	**Fully Feasible:** Thermochromic stickers that can be applied and are tuned to certain heat ranges. (Meant to make things like ovens or water pipes that are sometimes hot more visible to carers or those with memory problems) **Fully Feasible:** Colour changing broom to show heat built up from friction, to show how much work is completed. (Intended to make cleaning more fun) **Partially feasible:** The carpet shows footprints with the photochromic or thermochromic colour change. (Intended to help motivate those who sit still for extended periods of time see how long since they moved) **Partially feasible:** A thin glove that gives the temperature in an objective manner about food from the fridge and other surfaces. (For safety and confidence)	**Fully Feasible:** Physical address book with embedded piezo's allowing for one-touch calling (intended to simplify the use of mobile phone by pairing it with physical object) **Partially Feasible:** Reactive room, piezos sense location in room and activate common electrical appliances that may be required	None submitted	**Fully Feasible:** Handle that uses memory foam for added communication (Exact goal unknown)

Table 15: Assessment of feasibility for concepts created

4.2.6 Key findings

The first issue that the workshop revealed was that the designers showed a distinct preference for using materials with 'familiar' functionality. The functionality of both the light-emitting materials and the colour changing materials was seen by the designers as 'familiar'; these were the most popular materials used to create ideas. In addition, the groups understood that the energy generating materials could be used as sensors, another feature that they identified as familiar in the second session and used only that feature in their designs. Materials which were seen as 'unfamiliar' were used the least, only present in one idea out of twelve. This shows that designers (1) could more easily create ideas using familiar functionality (2) had significant trouble using new materials properties to create ideas.

The challenge in designing with could be down to a number of factors; the interest of the designers in the materials was lacking, the explanation of the materials was inadequate or incomplete and lastly the nature of the brief favouring the use of certain materials. A lack of interest from the designers in Rheological Property Changing Materials, Shape-Changing Materials that was ruled out by the designer's interest and focus upon those materials in the second session showing that designers were thinking about the possible applications of those materials. As for the incomplete explanation of materials, all were explained with the exact same method with no one material being given undue preference. The materials feasibility was checked, and no material produced only unfeasible ideas showing that the communication of the materials had been at least partially successful. The brief is also unlikely to have interfered with the results as it was engineered to be broad and no challenge would be unlikely to prefer solutions that utilized one material over others.

The factors that affect this are likely connected with how the design process is affected by the nature of the innovations in materials. As materials which designers deemed 'new' were used least, so we can see that designers must struggle with incorporating the properties, they see as new into their design process. This may be a result of two factors (1) The design process cannot use radically new materials as effectively as incrementally new materials (2) That radically new materials need to have a different method of explanation than incremental innovations to be incorporated into the design process. Either way, radically new materials require some additional support to be used effectively in the design process.

4.3 INITIAL INTERVIEWS

4.3.1 Goal of interviews and limitations

A series of short interviews aimed to understand the language designers used when talking about the materials amongst other designers. The goal was to extract the language tools that the designers used and see if there were any themes in what they said. Once this was established the goal was to see if the was a different language used when describing radical innovations compared to talking about incremental innovations. Knowing how designers preferred to communicate about radical innovations would give further information on what tools the research should explore the use of, to communicate and what tools are most suitable for designers.

The interviews were intentionally short and gave the designers a limited time to familiarise themselves with the material. The goal of this short window was to ensure that designers did not have the time to produce a sophisticated understanding of the material and to stimulate them to talk about it with their instinctive responses. This method was chosen as it made designers communicate in the way that came most naturally to them rather than how they may perceive the interviewer expects the material to be explained. The interview also knowingly stripped the designers of potentially their favourite tool for communication, sketching (Ullman, Wood et al. 1990). Removing sketching was intentional as it is already a proven method of communication and gives no insight into the language a designer uses.

Once the interview was complete, it could then be transcribed. The goal of this transcription was to help build up a list of all the different ways that designers communicate and then use that to generate an understanding of what language was used most. It is essential to understand that the goal of this work was not to assess if the explanation was accurate but instead, what communication tools were used.

The process for this is called thematic analysis and is described in the methodology chapter.

In these interviews, designers were asked a list of questions each provided below with a description of why the question was asked and what information was hoped to be gained from the answer.

- How would you describe your familiarity with material science?
  This question was designed to surface those who may be familiar with materials science. The answer given would allow the testing to continue if they identified

themselves as a novice, those who showed expertise would have the interview terminated.

- Do you recognize either of these materials and are you familiar with the materials called (insert material brand names)?
  This question aimed to ensure that people familiar with the specific materials being tested would not bias results. Participants answers to this question would show if they were familiar with the material. If they were familiar, the interview would be terminated.
- I'd like you to imagine you are describing this material to a designer, how would you describe it?
  Designers would be presented with the material; this would be the self-annealing plastic or Hybrix steel. The goal of this question would be to establish how the designer discussed the material. The answer would reveal the language they used.
- Now, this material is different. I'd like you to imagine you are describing this new material to a different designer, how would you describe it?
  Designers would be presented with the remaining, just like the question before the goal of this question would be to establish how the designer discussed the material.

This set of interviews was on a larger scale and pulled on people from multiple backgrounds, so did not have the same limitations as the initial tests limited view. However, due to the need to be mobile in the space, the selection of materials was minimal leaving only four materials tested. By only testing one radical material and one incrementally innovative material, the tests would be affected by the nuances of those materials in a way that couldn't be assessed against other results. Future tests always worked to include a spread of materials to ensure the results were accurate. There is also potential that the responses in this test to be negatively affected by designers' lack of interest in the material. However, given the number of participants in this test, this error is hopefully corrected for.

4.3.2 **Participants in the initial interviews**

In this activity, participants needed to fulfil the criteria laid out in the methodology. To ensure a large selection of this group, designers were recruited at the Made in Brunel graduate design show. This was a mix of students who had completed a three-year course with the majority completing a year in industry as well as design professionals and design students from other institutions. At a minimum, those canvassed had three years of design experience, academic or professional with most having a mix of academic and practical design experience. A breakdown of the participants is shown below.

Type of design experience	Number contacted	Proportion of those canvased
Three years academic knowledge no professional experience.	8	19%
Three years academic knowledge with one-year professional experience.	19	45%
Three years academic knowledge with more than one-year professional experience	12	29%
More than three years professional experience with no academic knowledge.	3	7%

Table 16: Summary of participants in the interviews

This group was chosen as it provided an effective way to canvas a large number of competent designers and it also ensured that those canvassed were seeing the material for the first time when it was shown to them. Their participation in the graduate show also showed that they were engaged with the design practice and were invested in their design thinking processes.

4.4 THEMATIC ANALYSIS

The interviews were transcribed and the various methods that the designers used to communicate were broken down into groups based upon what language tool was used. These tools were divided into broad categories that were based upon the descriptions of both the incremental innovation sample and radical innovation sample. This grouping was essential as understanding how designers communicate material properties is essential, whether those properties are familiar or unfamiliar as radical properties may be accompanied by more familiar incremental improvements.

The process followed the six steps laid out in the thematic review section of the methodology chapter. All coding and identification were conducted manually as the transcriptions of the interviews that generated this work were of poor quality, and the output was not suitable for being entered into software that would do this automatically. Instead the interviews were listened to by the author.

4.4.1 Thematic analysis process

1. Collecting data: Completed through the interviews.

2. Codifying the data: To fully codify the data, each communication was assessed to establish what tools were used at each moment. This involved a lengthy analysis of how each statement of the interview established different tools. An overview of this codifying is shown below.

Identifiers used in the coding of the interviews. These were generated through an inductive process which is an established method by which the coder assesses the data without a pre-existing framework (Miles, Huberman et al. 2014). This approach was chosen as the existing literature on descriptive tools used for materials doesn't focus on the language used but rather what aspect is being described so would not have aided a deductive approach.

Examples of level 1 codes
Cloudy; cool; elastic; elastomer; Feels like the material would be useful; feels like wax; flimsy Perspex; geckos foot; good for waterproof clothing; grippy; had excellent shearing strength; hard to unstick; hardy; hassle free; I can't describe it; I don't know; I have no idea; I think this would be good for tape that doesn't leave residue; Interesting; it wouldn't be good as clothes though it would stick to itself; It is like a polythene bag that can stick to itself; It is a cool material; It is like built in glue; like a toy rubber dolphin; like bamboo; like cling film; like frosted glass; like rubber; Like vinyl; like your skin healing; plastic; plasticky (making a comparison to plastic); pliable; quick to recover; Reminds me of Velcro; resilient; Rubbery; self-adhesive; so it is chemical bonds are connecting?; somewhere between a jelly and a polymer; springy; stretchy; supple; tacky feeling; This is like an alternative to duct tape; This would be good in repair industries; Tough; twists and bends easily; very stretchy; weird; You could make self-sealing pouches of this stuff;

Table 17: Examples of coding from the thematic review

3. Identify themes: With the data codified, the themes could be identified. This stage highlighted several linguistic tools that designers consistently used throughout their descriptions of the materials. This was grouped into six overarching themes which showed repeated patterns of use and conventional methods of communication.

4. Reviewing themes: This was further explored through the fourth step of a thematic analysis, Reviewing themes. Where each of these themes was then applied to the data to see if they provide a convincing and comprehensive overview of the information provided.

Level 2 and Level 3 coding

Comparison			
Similarity of whole material to another material	Similarity of a specific material quality to that quality in another material.	Difference of a specific material quality to that quality in another material.	Similarity of material quality to a complex concept
Subjective description			
Opinion of material quality	opinion of a visual aspect	Opinion of a tactile aspect	Opinion of material overall
Contextual			
Described organisations who would benefit from using the material.	Stated intent of how they would use material	Example of how it could be processed	Questioned if an application was a poor application for the material
Objective description		Do not know	
Used scientific terminology to assess material		Explained they didn't know how the material worked,	

Figure 18: How the final groups were coded

5: Defining and naming themes: Now that the themes have been identified for the overall system, each of these themes is then further explored to ensure they have a valid name and title. These themes are shown in the following table. The nature of these themes and how they fit into existing literature was also explored in the literature review.

Communication method	Examples of communication method
Subjective	Described using a simile. Opinion of material quality. Use of adverbs to emphasise opinion of material quality. Used emotional language. Explored physical sensations as encountered. Opinion of material overall. Made hand gestures or physical movements for emphasis.
Objective	Used a factual statement. Used scientific terminology to assess. Use of empirical measurement.
Comparison	Similarity of whole material to another material. Similarity of a specific material quality to that quality in another material to another material. Difference of a specific material quality to that quality in another material. Similarity of material quality to a complex concept. Describe a correspondence to a complex concept.
Contextual	Stated intent of how they would use material Imagined material creators goal Example of a possible application Questioned if an application was a poor application for the material. Explained circumstance when they might use material Described organisations who would benefit from using the material.
Don't know	Explained they didn't know how the material worked. Explained they could not communicate a certain aspect. Asked how a material works

Figure 19: Summary of the communication tools used by designers

4.4.1.1 ***Objective statement***

> "The (self-annealing) plastic is transparent." Interviewee #8
>
> "This (Hybrix steel) is conductive right?" Interviewee #17

The designers also communicated using objective statements. These, however, were universally shallow, often explaining a material property in a binary manner. Such as 'This is conductive." This statement is an objective phrase but hasn't got any additional information beyond the presence of the attribute.

4.4.1.2 ***Comparison***

> "It (self-annealing plastic) reminds me of Velcro." Interviewee #3
>
> "This (Hybrix steel) is like metal cardboard." Interviewee #25
>
> "It is (self-annealing plastic) like a rubber band that can fix itself." Interviewee #32

Designers frequently compared the materials to other materials that they identify as being literally similar. This literal similarity would compare the two materials, saying they shared this same material property or attribute. The other use was to compare the materials and state that one material differed in the material property. Both expected the user to understand the material the designer was comparing the sample to. Interestingly when looking at the objective realities of these comparisons they were frequently incorrect. The designer would state for instance that the material 'was as light as aluminium' but the comparison of their weights shows that aluminium has a significantly different density to the sample.

In addition, they used an analogy to compare the material to other materials and systems; differing from literal similarity which described attributes, it describes the material as sharing specific system or function with the system or function of the comparison. An example of the comparison of systems was like saying the self-healing plastic stuck together like Velcro. The comparison exists but does not intend the listener to imagine the two as literally similar but to imagine the system of two pieces of material being brought together and sticking under their own power.

4.4.1.3 ***Context***

> "This (self-annealing plastic) would be good to seal you in a waterproof just hold it together." Interviewee #3
>
> "I think it (Hybrix steel) would make a good suitcase." Interviewee #18
>
> "I can see this (Hybrix steel) going in aeroplanes and boats" Interviewee #37

The designers also put the material into a context of use saying it would be appropriate for use in this manner. This application was a part suggestion but also helped frame how the designer understood the properties of the material, illustrating the use of critical properties.

4.4.1.4 ***Do not Know***

> "I don't know how I'd explain. (self-annealing plastic)" Interviewee #12
>
> "It is odd I'm not sure what to say (self-annealing plastic)" Interviewee #31

This is not a category in how designers can explain but one marking that they can't. It appeared in the language of many participants who could either not explain the material or who used a variation on the phrase 'I don't know' even after partially describing the material. This is important as it shows that designers felt they did not have sufficient language to express the properties of the material and is a theme in its own right.

4.4.2 **Difference between radical and incremental descriptions**

When comparing how these tools were used to describe the radical sample compared to the incremental sample, it is possible to see that the two different innovations types prompted designers to change the language tools used to communicate the material properties.

The data collected for the thematic review was assessed again, comparing the uses of each theme in each interview. Each time a language tool was used in an interview, that interviewee was marked as having used that tool and at the end the overall interviews featuring the tool was divided by the number of interviews. This allowed for a view of how prevalent the use of each tool was.

Innovation Type	**Subjective description**	**Comparison**	**Context**	**Objective**	**Don't Know**
Incremental	92.5%	60%	32.5%	37.5%	2.5%
Radical	72.5%	75%	25%	25%	30%

Table 20: Use of language tools in the interviews

Overall, there were essential differences between the two communication methods. Subjective descriptions fell from having nearly all designers using them, to having only 77.5% of designers use the tool when exposed to radical innovation. Comparison also shifted seeing incremental innovation show considerably less use of the tool. Context also changed in usage, though not as significantly as with the other tools. Perhaps, showing that there isn't a pronounced difference in how this tool is used in regard to innovation type. Don't know reactions also increased to 30% with radical innovations, where incremental had 2.5%.

This assessment shows that there is a distinctly different approach to describing the radically innovative material compared to the incrementally innovative material. This is, however, a preference. It does not mean that the communication is effective; only designers find it most appropriate method to communicate. Many designers did not use correct comparisons when explaining how the material functions, using systems which did not accurately relate to how the radical material functioned.

4.5 Workshop Series 1 - Introduction and Overview

Having gathered information on what tools are used to communicate material properties between designers, it is essential to understand what's the most important form of communication. The following test was looking to find what the most popular forms of communication are and how effective they are at communicating materials radical innovations.

To do this, focus groups were put together under the umbrella term 'workshops. Each group would be exposed to many radically innovative materials. From that list, they would then choose to examine one in more detail and would finally be tasked with creating design concepts using this material. From observing the workshops and providing a short survey to allow for feedback, the overall understanding of the materials could be gauged alongside the designer's preferred method of discussion.

4.5.1 **Goal of workshops**

Once it was established through initial testing that the main tools used by designers to converse about new materials are limited to a few groups, this new test was designed. The workshop had two primary goals.

Understand what the most popular forms of communication are.

The fundamental goal of this work was to establish thoroughly what the preferred forms of communication are between designers. This information would be gained through observation of focus groups. exploring how designers used Subjective, Objective, Comparisons and Contextual descriptions in a wider variety of materials through extended interaction with them.

Evaluate how effective current forms of communication are in explaining radical innovation.

The other goal was to provide a benchmark for future tests. During the workshop, designers would be challenged to create ideas using the materials shown. These ideas could then be assessed to see how many were feasible and how many were completely unfeasible. See the feasibility section of the methodology chapter for more information on how this is assessed.

4.5.2 **The methodology and limitations of the first workshop series**

The methodology of the workshops combined actively testing the knowledge of recipients with small focus groups. These groups would be presented with material explained using current tools and from their responses, generating an understanding of the effectiveness. The groups were presented with materials as well as the communication, as evidence was found in the literature review that working without physical samples could reduce the effectiveness of the communication (Wilkes, Wongsriruksa et al. 2016).

Firstly, the material was given a short introduction, the goal being to expose the participants to all the material explaining their radical properties. The method of explanation used a combination of Subjective, Objective Comparison and Contextual tools to communicate these details fully. How the four tools were used was dictated by the available communication resources for each material. As the test aimed to explore how effective current communication techniques were, each material description was sourced from existing sources, they were either being pulled from material libraries or direct from marketing communication produced by suppliers. The goal was not to have identical communications for each material but instead to represent accurately what information is currently made available to designers.

Once participants had been exposed to this information, they would then be separated into small groups, each functioning like a focus group. Each group then talked about the materials and were challenged to discuss their potential and features amongst themselves. In this period, they could learn more about the material using the communication tools provided or discuss amongst themselves. Their communication was recorded in a tally system that identified when they used one of the essential four communication tools of designers identified by the thematic review in descriptive study 1.

After completing this session, they were challenged to create potential ideas for how the material could be applied in real-world scenarios. Each ideation exposed how the designers understood the material. As the designers were in groups, it also helped to reduce outliers, while one designer might misunderstand a design and create a number of designs that did not function (or vice versa), a group was more likely to discuss ideas and put forth concepts that used the combined knowledge of the group.

These ideas were then assessed for feasibility using the previously established system. Those ideas that proved to be feasible showed it was likely designers had understood the application of the material while ideas that were unfeasible showed that the communication had to some degree failed.

In the initial workshop, a review technique was selected that used audio recording of designers' discussions and then taking pictures of their design ideas to work. When arriving for some of the first tests in Italy, the researcher was informed that these techniques weren't allowed. As the tests represented approximately a third of all expected testing, a change needed to be made to ensure that the research could still be used. To enable the research to continue and to collect content the method of recording data switched to active notetaking as described earlier. This system comes with limitations, most importantly that more content is lost, compared to audio recordings. However, it can be useful and is a process that the researcher had used previously.

4.5.3 **Participants of the first workshop series**

Type of design experience	Number contacted	Proportion of those canvased
At least two years academic design knowledge.	54	43%
At least two years academic design knowledge and some professional experience	32	25%
Professional designer with at least two years professional experience.	41	32%

Table 21: Participants in the first workshop series

These participants were met at their places of business or at their universities under the supervision of their teachers.

For the purposes of reporting, all groups are treated as one, 'designers. This is in part to simplify the data presentation but also because when analysing the results it was found that designers professional experience did not create a significant change in their ability to understand the communication, with each group getting very similar results when feasibility of their ideas was assessed. This was consistent for both this test and the second workshop series detailed in descriptive study 2. The only notable difference between the groups was that designers with professional experience were able to create more ideas. A group of design students with no experience contributed an average of 0.45 ideas per designer, while design students with experience contributed 0.5 ideas per designer, and professional designers contributed 0.56 ideas per designer. This may reflect their greater practice in the design field.

4.5.4 **Material selection**

For the research to be valuable, the learnings must apply to all materials, making a diverse range of materials necessary for two key reasons.

1. A wide selection of materials ensured that the results of the testing would reflect materials rather than a particular material or material type.
2. A wide range of materials ensures that whatever designers' personal interest in materials might be, they can find something of interest. If designers cannot find a material that interests them, their disinterest could bias the results.

To allow for a full range of materials, 20 were selected. This was because three of the reviewed libraries break materials down into eight-ten categories. These are the material groups considered important for designers. To accurately represent a wide range of categories, representatives were chosen for those that appeared in most of the existing libraries. The remaining materials were chosen from smart materials that currently don't have a slot on material libraries but are essential to the study of radical materials and are increasingly present in society and as covered in the literature review need to be treated as their own material type for the purposes of communication.

Categories	Category appears in	Materials chosen
Natural	Material Connexion, GRANTA, Institute of Making, Chris Lefteri	LifoCork, Bright green
Polymers/Plastics	Material Connexion, GRANTA, Institute of Making, Chris Lefteri	UPM Formi, Microsuction tape, D3O, Fibre-optic fabric, Shape Memory Polymer
Metal	Material Connexion, GRANTA, Institute of Making, Chris Lefteri	Cellular metal, Nitinol wire
Glass	Material Connexion, Institute of Making, Chris Lefteri	Gorilla Glass
Composite	Material Connexion, GRANTA, Institute of Making	Fiberline, EL Panel, Dry Inside
Ceramic	Material Connexion, GRANTA, Institute of Making, Chris Lefteri	Piezo ceramic
Smart		Bare Conductive, Intumescent foam, Ferro-fluid, Phase change, Nitinol wire Photochromic pigments, D3O, Thermochromic sheet, Fibre-optic fabric, Shape Memory Polymer, Dry Inside

Table 22: Material categorisation

4.5.5 Workshop design

Session	Description	Supporting Materials	Desired Outcome
First Session: Materials introduction	20 materials were introduced to the designers with a discussion using objective, subjective, comparison and contextual phrases	Material samples, information cards on the materials	Improved understanding of materials
Second Session: In-depth discussion on the chosen material	The participants were asked to select a single material to learn about in more depth	Material samples and cards	Listen to how participants describe materials
Third Session: Idea creation	The groups were asked to imagine potential applications of the materials	Material samples and brainstorming	Creation of a wide range of ideas to see if materials are understood

Table 23: Process of the workshops

The goal of the workshop was to assess three main factors; use of communication tools previously identified, what aspects of the material did the designers have the most interest in and finally to set a baseline for understanding when using all three communication tools to explain each material's properties. To achieve this, the workshop was split into three sections; the first was a short introduction to 20 different materials listed in appendix A.

4.5.6 Process of the first workshop series

4.5.6.1 *Communication of the materials*

Each of the materials was described to the participants using the language made available by suppliers or through online resources. Each material's innovative property was also physically demonstrated if possible, using the sample to help illustrate the properties of the material.

4.5.6.2 *Deeper exploration*

After this explanation, the participants were asked in smaller groups to select materials that interested them from the twenty materials listed above. This freedom of choice ensured that those involved would be able to work with a material that interested them, ensuring a more engaged group. Due to many participants, it was not essential to force them to select materials across the spectrum, as the variety of workshops ensured a wide range of materials being selected. In this session, the material was explored more in-depth, and the participants were also asked to describe the materials they had to each other, as if the other knew nothing about the material. This behaviour was observed, and notation was taken in real-time of each occurrence of one of the four communication tools established in the thematic review. The goal was to see how in a more in-depth scenario what communication tools designers would use and if it would alter between materials.

Beyond variety, it was essential that the materials the designers described were of interest to the participants. Generating information on how people communicate about materials should focus on communication that is animated and powered by an interest in the material rather than a forced observation of the material.

During this session, the participants were permitted to talk amongst themselves for some time about the material to allow the group to explore their understanding of the material. These explanations generated a lot of discussions and each time in the discussion, a participant used one of the four communication tools it was noted down along with small notes if the description was significantly different.

4.5.6.3 *Idea generation*

In the final session of the workshop, the participants were asked to create a quick brainstorm about how they could apply they had selected to learn more about. The creation of ideas challenged designers to create the first iterations of concepts they believed used the material effectively. The sessions were brief but gave some insight into how the participants believed the materials could function. In addition, the ideas generated in this session were copied down and assessed for viability to see if there had been a lack of communication of the materials function.

4.5.7 Use of communication tools

The use of communication tools was one of the most important elements of the test. Seeing how designers used these tools when given access to a more extensive selection of materials with a wide variety of properties enabled the generation of more insightful data. To gain this information several elements needed to be catered for, most important were the selection of materials.

Below are the results of that summary. It is important to note that objective descriptions were seen as distinct from the other tools in both their content and their length. Most objective descriptions were short statements such as 'it is conductive' or 'Ferrofluid is a liquid'. In many ways, objective descriptions are similar to some subjective descriptions that occurred such as 'it is highly conductive'. The difference being that highly introduced ambiguity and opinion were as objective statements tended to be binary and absolute. Other phrases varied far more greatly, with subjective, comparisons and context all being varied in their use.

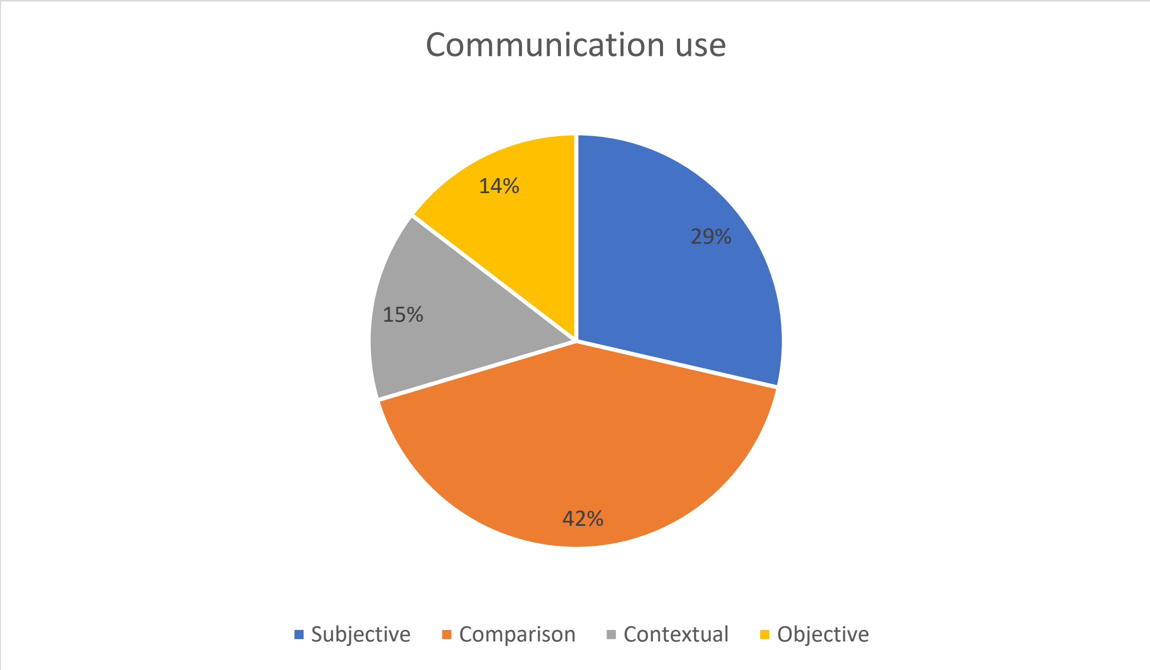


Figure 27: Use of communication tools in first workshop series

This test showed that the use of comparison was high compared to other tools. The notes from the session's, found that analogy was rarely used, most often in a very narrow spectrum to explain smart materials primarily. Most of the communication was not generated as a cohesive description, where each detail was then incorporated into the next descriptive tool. Most descriptions were a standalone phrase that needs no support from other phrases to be whole. This allowed the research to see precisely how designers construct their descriptions.

This study continues to support the value of comparison as a useful communication tool. The next stage is to see what communication can do for explanations of materials in the future. Currently, it is impossible to see if a comparison can work effectively without the support of the other tools. The need for further testing that delves into this will be an essential next step.

4.5.8 **Feasibility Study**

Just stating an increase in knowledge does not necessarily demonstrate that knowledge in use. To see this factor, the designers did short brainstorms of potential applications in the final session. The ideas they generated were then assessed for their feasibility (using the system outlined in the methodology,) to try and understand if the concept would function effectively.

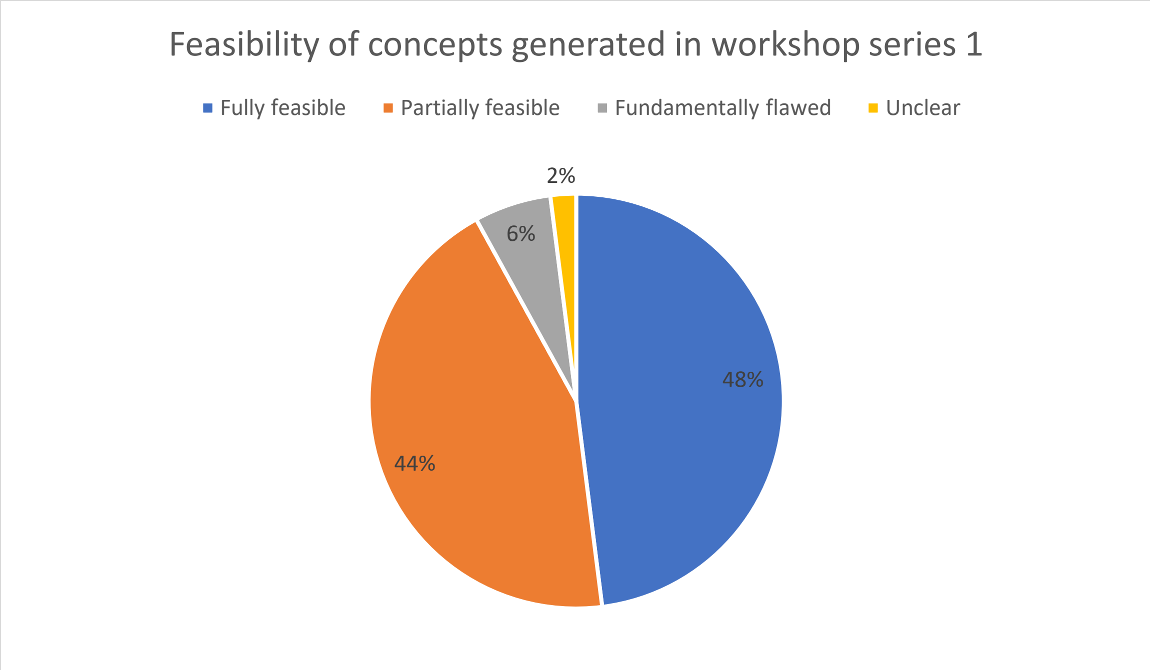


Figure 28: Feasibility of the concept created in the first workshop series

In these workshops' designers generated 51 concepts. Most participants managed to generate in their group an idea that was fully feasible, with 48% of concepts generated in that bracket, 44% were partially feasible, 6% were fundamentally flawed, and for 2%, it was unclear how the communication had impacted their concepts.

The small percentage of concepts which are fundamentally flawed showed it was rare for participants to completely misunderstand the materials after exposure to the combined communication tools. As only 6% of concepts would not have functioned, it indicates that the core function of the material was appreciated. However, the significantly higher chance of the participants misunderstanding the material, leading them to produce only a partially feasible concept showed there is a significant way to go. This was indicated, as over 4 in 10 concepts showed a flawed mental model of the material.

Fully feasible concepts are the largest group, and that shows that the communication is working for nearly half of all the ideas created. An assessment of the fully feasible ideas revealed a trend that didn't appear in any other category. Several fully feasible ideas appeared multiple times across different design groups. In one case the same application (Helmets liners/padding for motorbike helmets) for D30 was suggested by almost every group who looked at the material. While these commercial applications didn't appear in the communication materials supplied to the designer's, ideas similar to them did. For instance, in the case of the D30, the communication materials included examples of the material being used in ski helmets and military helmets. It is possible that designers were using this context to generate the idea of using it in a motorbike helmet.

It is possible that while still representing a significant understanding of the communication, the results are biased to some degree by the inclusion of those concepts that are variations upon the examples provided by the communication. It would not take a full understanding of the material to apply a material that works in one scenario and apply it to an analogous scenario. However, as it can't be stated for sure what the logic of the designers was in generating these ideas, it wouldn't be accurate to exclude these results. The future workshops must instead remain vigilant of this potential bias.

4.5.9 **Key findings.**

The workshop established that of the communication tools available to them, designers chose to use comparison and subjective most commonly when talking about radical materials amongst themselves. They also only used objective terms as binary statements of a material's ability, rather than looking at specific terminology. Context did play a role in the conversations as well as a descriptive tool of the capability of the material.

These insights allow for the continued development of the communication research, highlighting those tools that are most frequently used by designers and recording the methods with which they use those tools. In particular, the notes found that when communicating materials, comparison and metaphors were often combined and used together or part of a larger descriptive message.

The outcome of this research was the evidence that current systems of communication were failing designers, with over half of all ideas for how to apply the radical materials showing that designers had not understood the briefing. Not only that but 6% of all ideas generated showed a complete lack of understanding of the material. All the miscommunication has the potential to impact the use of the materials by designers, as they struggle to find possible uses for the material.

This lack of understanding of these materials is especially troubling as the communication methods used in these workshops was taken directly from sources specifically attempting to engage designers. This shows that there is not a lack of interest in engaging designers, but the very systems used may be flawed.

This research now looks to find ways to improve communication. The effectiveness of this research will be evaluated against the outcomes of this workshop, especially trying to improve on the current 48% effectiveness of communication.

4.6 Summary of the chapter and next steps

4.6.1 **Initial focus group**

Primarily, the initial focus group has established that there is likely a distinct issue amongst designers with using radically innovative materials. When presented material options to use, those which were incrementally innovative and were familiar to designers, and those which were radically innovative and unfamiliar to designers, designers showed a distinct interest in unfamiliar materials.

Despite finding these far more engaging than the familiar concepts when it came time to use those materials to create designs, the unfamiliar concepts were far more popular to create ideas from. In addition, when unfamiliar materials were used to generate designs, they were less feasible than the designs created using familiar materials. This overall illustrated that despite an increased interest, and a thorough explanation of both material types, radically innovative materials challenged designers more than incrementally innovative materials.

This helped with the understanding of **research question 2**, the assessment found that radically innovative materials appeared to be harder to effect solutions with than incremental innovations even when equipped with the same communications. This showed the distinct challenge of radical innovations in design.

4.6.2 **Thematic analysis**

The thematic analysis also helped establish an understanding of what language designers prefer to use when describing materials. This helps in part resolve the **research question 3** in several different ways. The analysis of descriptions about both incremental and radical innovations showed that design used four distinct tools to enable comparison. These are subjective, objective, comparison and contextual. These four distinct methods allowed designers to create an overall picture of the material. However, it should be emphasised that this did not necessarily prove that those tools would be effective at communicating the material as it only illustrated that designers prefer to use these tools.

With the understanding of the communication tools used for materials established the interviews were then assessed to understand if there was a difference between how designers talked about radical and incremental innovations in materials. This analysis found there was a distinct difference in how designers used the communication tools. When describing incremental innovations, subjective was the most popular tool but when describing radical innovations, comparison became more important.

This underlines a potential flaw in the current system of communication about materials. Currently material libraries and other resources do not change how they communicate materials based on the type of innovation present. This identifies a potential weakness in their ability to accurately communicate radical innovations.

4.6.3 **First workshop**

The first workshop series established how effective current communication examples are through exposing designers to existing information around radically innovative materials, and then challenging them to use the materials explored to create ideas. An analysis of the concepts created showed that over half the time, designers failed to create fully feasible ideas, demonstrating that the information provided had failed to create a meaningful understanding of material.

It also established that overall, the use of the four communication tools outlined in the thematic analysis were used consistently, though when allowed to discuss the material amongst themselves, designers showed a preference for using the comparison communication tool. Again, this does not establish that this tool is necessarily an effective method of communication but does show how prevalent it is in communication among designers.

The other result of this process was developing a baseline through which research can aim to improve upon with this. When this test is repeated using different explanations generated through the next steps of the research, a marked improvement in understanding would show that the communication has improved.

Overall, the first workshop thoroughly explored **research question 2**. The ideas that were created by the designers showed that there was a limited understanding of the materials with only 49% of all ideas being fully feasible and using the material's innovation. Of the remaining ideas 43% were partially feasible and 6% were not at all feasible. The remaining 2% were feasible but didn't use the materials innovative property. These results show that there is a significant problem in communicating radically innovative materials to designers, as half of the time they are failing to make full use of the material.

The other issue that was highlighted was that a significant proportion of the functional designs created were similar to those concepts that were provided as examples (for instance if a material was listed as suitable for a motorcycle helmet in the explanation, designers would recommend using in a bicycle helmet). The fact that these designs occurred often could show some evidence that designers are not applying themselves to design new applications but are instead limiting themselves to re-imagining the known applications. This would indicate that there was a significant effect on the process of design thinking.

This also connected with the work in the initial focus group, and in the semantic analysis, established designers use distinctly different methods of communication for incremental and radically innovative materials when challenged to explain the materials. The fact that half of concepts failed to create a feasible idea also established a target for a new system developed for **research question 4** to meet, and that could be used to answer **research question 5**.

4.6.4 How do these findings compare to the literature?

When assessing the language designers used about materials, they preferred clear and exact language, staying away from ambiguous figurative language and being very direct in their descriptions. This focus on clear language matches to the work highlighted by innovation journalists in the literature review. In particular, this matched the recommendations of Mast (2005) about how radical communications should use simple, relevant language when being communicated. The language used was also consistently language that may be considered designerly, some of the phrases used correlate directly with those found in the research that Karana and Pedgley (2013) have completed into assessing how material aspects should be communicated. Given this active use of these terms, the designerly language therefore should be used by any future tool.

There was a high use of comparison tools. These tools were used to draw comparisons to materials had a greater understanding of. The interest in making comparisons to known concepts shows that the is a desire to make the concept more relevant to them, matching the work of Karana and Hekkert et al. (2009) and Mast (2005). This interest also indicates that designers might be trying to fit the communications more into the process of design thinking which prefers to use processes that fit with past experiences (Cross 2007). The fact that designers so consistently looked to use comparison to tie the material to known concepts, matches how in the early stages of the design process, designers look to understand a problem by finding analogous problems they have previously encountered. Any future work in the area will look to ensure that this interest in applying prior knowledge is fully explored and worked into the new system that is to be developed.

The failure of half of the designers to accurately make use of the material shows that radical innovations may be hard to understand, or the communication is struggling. The initial focus group showed that the ideas which used incremental innovations were more likely to be feasible and that designers preferred to use these more familiar materials. This matches the innovation theory of Abernathy & Clark (1985) who explored that radical innovations are harder to absorb and build into new practices. While research in the literature review did explore that the communication of new concepts from one industry to another can struggle due to the differences in understanding between the groups,(Cohen, Levinthal 2000) it is hoped that this factor was reduced by picking content from material libraries specifically aimed at designers. However, given the poor results it is possible that there is still an issue of cognitive distance between the material communicators and their design audience.

4.6.5 Next steps of the research

The next step of this research is to assess how comparison, contextual, objective and subjective tools can be used to improve understanding of radically innovative materials by designers. It aims to expand on the research question 4 to which looks to find effective means of communication.

And there is also the goal to explore comparison, which is currently the most popular tool, more thoroughly. As designers' value so much in discussing radical innovation, it may be integral to improving communication. The goal is to explore how comparison can be used and what current theories enable complex comparisons to be produced effectively.

The next chapter will focus on exploring the nuances of comparison, aiming to understand the different types of comparison that might be used to communicate these radical materials. In addition, it will focus on reviewing the language that designers use to identify better comparison techniques leveraged by designers. It will do this through a literature review and an analysis of past data from the first set of interviews.

5 PRESCRIPTIVE STUDY

5.1 INTRODUCTION

In prescriptive study 1, the goal was to gain a better understanding of what communication tools best served what forms of communication. Building on the understanding of descriptive study 1's identification of four distinct communication tools and chapter 5's discussion comparison and metaphor. This study looked to gain designers insights on why specific forms of communication were used and how best to use them. This would bring a final answer to **research question 3** and help build the foundations of a system that would be able to contribute to **research question 4**.

Before this goal of building a complete understanding could be achieved, the research aimed to identify if there are distinct categories of radical innovation in materials. If there were distinct forms of radical innovation in materials strategies could be created that served the category helping make any systems to communicate them more tailored and potentially more effective, helping to develop an understanding that could enable a system to communicate these materials that is repeatable — offering the solution for **research question 4**.

Once the radical innovations were assessed, the next test was to use the different communication tools identified in descriptive study 1 to communicate them and test which tools were the most effective at communicating the material to designers. A questionnaire was built that asked designers to rate which communication tools were most effective and gave them the opportunity to explore why they felt that tools were helpful to them. This would provide insight that would identify which tools were most effective, helping answer **research question 3.**

Finally using the insights from all prior testing, designers were contacted to create focus groups that explored those communication tools that appeared to be most popular amongst designers. They were tasked with exploring why these tools were essential to designers when discussing materials and they were asked how they would use these tools to explain the materials reliably. This provided the last insights needed to complete research on **research question 3** and provide the basis through which a system might be built to communicate materials to designers better to satisfy **research question 4**.

5.2 GROUPING USING THEMATIC REVIEW

The goal of this activity is to develop an understanding of the types of radical innovation that currently exist. To do this, a wide range of radically innovative materials will be assessed to discover overarching themes. The tool used will be a thematic review which is designed to assess qualitative data for repeating patterns. Once these themes have been established, they can be used to help develop analytical tools.

The second thematic review which looked at radical innovations in materials was mainly limited by the researcher's knowledge. It looked to pull in recognized radical innovations to help build up an understanding of the different 'types' of innovation. The innovations assessed were pulled from publications; the researcher was able to locate. However, if the are other publications, in foreign languages or just not easily accessible, they would've been missed. There is the potential that this could have influenced the result of the review but over a hundred materials were included in the assessment which should contribute a significant amount of insight into the different radical innovations that exist.

5.2.1 **Creation of list**

There exists no comprehensive list of radically innovative materials, not do any of the material libraries categorise materials by the innovation type, finding radical material is, therefore, a challenge. Claiming your material is radically innovative is often used in marketing speech without due consideration to the qualities of the material. The loose use of radical innovation as a descriptor and the lack of any form of aggregation meant that to study radically innovative materials a dedicated exploration of materials properly was required.

Once the list was created a thematic review was used to establish the most critical elements. In this review, the data collected was on radical innovations in the materials sector. To ensure these innovations were truly radical, they had to fulfil one of two criteria.

1. Be listed as an innovation by a materials expert. The materials experts were generally other materials researchers or those operating a material library.
2. The innovation also had to fulfil the criteria of radical innovation. This was to ensure that only radical innovations were assessed.

Overall, five different sources were used to select these innovative materials.

1. Materials Council radical innovation library
2. Chris Lefteri's 'Materials for inspirational design' book (Lefteri 2007).
3. Inmatteria online – this is an online resource that collates news about materials that is aimed at designers. It also breaks down and assess these concepts to understand their potential.
4. Material sample shop's radical material selection – this shop offers samples of materials for educational purposes. Along with its samples it provides a small amount of documentation that explores the material.
5. Material Revolution by Sascha Peters – This book contains a list of innovative materials that are available to designers. The author collected a wide range of materials that are innovative and are changing what can be done.

5.2.2 **Codifying data and identifying themes**

Breaking the data about the innovations was simple. Each innovation was based on how the material's properties compared to other properties on the market. This meant the text could be broken down by material property and how it was an improvement. The most crucial element of this is how innovation is an improvement because it is innovations in materials, not materials that need assessment here. The property being innovated is only there to help provide context and potentially inform comparison to other properties later. This process generated 144 distinct innovative properties. The properties were then assessed, and themes were constructed. This process went through a number of iterations described in the diagrams below. There were also some core learnings about how materials innovate.

Through the process of grouping the materials it became clear that those materials designated as smart materials in most publications could not be considered a single innovation type and were split into three distinct groups based on their ability to react to stimulus. These became the separate parts of the Reaction Innovations category. Innovations cannot be easily grouped by what they can achieve, with materials as complex as conductive fabrics that can change resistance under strain just trying to group. Innovations tend to impact at a certain point in a materials life cycle. Innovations in the production stage have the ability to provide a new option with the materials possible form, origin and lifecycle. These changes impact the decisions and options of material ever sees a consumer. There are also innovations in the use of the material. These may stem from production processes but will stretch the lifetime of the product and be of use to the consumer themselves. Finally, the is the group of innovations that allow the material to dynamically react to a stimulus after it has finished production and entered the hands of the consumer. These are referred to as

Reaction Innovations. Of the properties, it was found that they could be described in one of nine distinct themes.

1. Allowed the product to be manufactured in an innovative form.
2. Allowed the material to be made from a new base element
3. Reduced the creation of a negative by-product
4. It improved on the existing attributes of the material
5. Removed an unwanted attribute from the material
6. Added a new passive property to the material
7. A property was added or created that allowed it to affect the external world without changing its composition
8. Could react to the outside stimulus in a way that altered it permanently
9. Could directly change its properties in reaction to an outside stimulus in a repeatable manner which didn't cause permanent change.

5.2.3 Construct network

These themes were then found to follow more substantial groups. They were grouped into these distinct areas based on two factors. The first being when in the lifetime of the product, the innovation could be applied and secondly if this innovation allowed the material to react to stimuli dynamically.

Many networks were mapped, showing relations between the different themes. This was found to be the most robust as it enabled the themes to be easily grouped in a consistent manner. There were other potential relations between the groups, such as two key groupings which focused on themes which added features and themes that removed negative features. These, while important was abandoned as many themes (mainly those in the reaction innovations group), did not fit well into this framework.

Group name	**Description**	**Connected themes**
Production innovations	These innovations are beneficial in the production of a finished item. Allowing new shapes, reducing negative issues and potentially reduce the need for expensive materials in the production.	Allowed the product to be manufactured in an innovative form.
		Allowed the material to be made from a new base element
		Reduced the creation of a negative by-product
Use innovations	These innovations allow the user to gain benefits from the materials while using them but without these materials responding to the external stimulus.	It improved on the existing attributes of the material
		Removed an unwanted attribute from the material
		Added a new passive property to the material
Reaction innovations	Reaction innovations allow the material to react to specific stimulus in a way that affects it or the environment.	A property was added or created that allowed it to affect the external world without changing its composition
		Could react to the outside stimulus in a way that altered it permanently
		Could directly change its properties in reaction to an outside stimulus in a repeatable manner which didn't cause permanent change.

Table 24: Different themes generated by the assessment

5.2.4 **Mapping the components**

The image below explores how a material communicator can categorise their radical innovation. By starting in the top left-hand corner, a communicator can then answer the questions to asked in each box to understand what category the innovative material property belongs to. This helps the communicator understand the material better and may also allow them to generate a better communication.

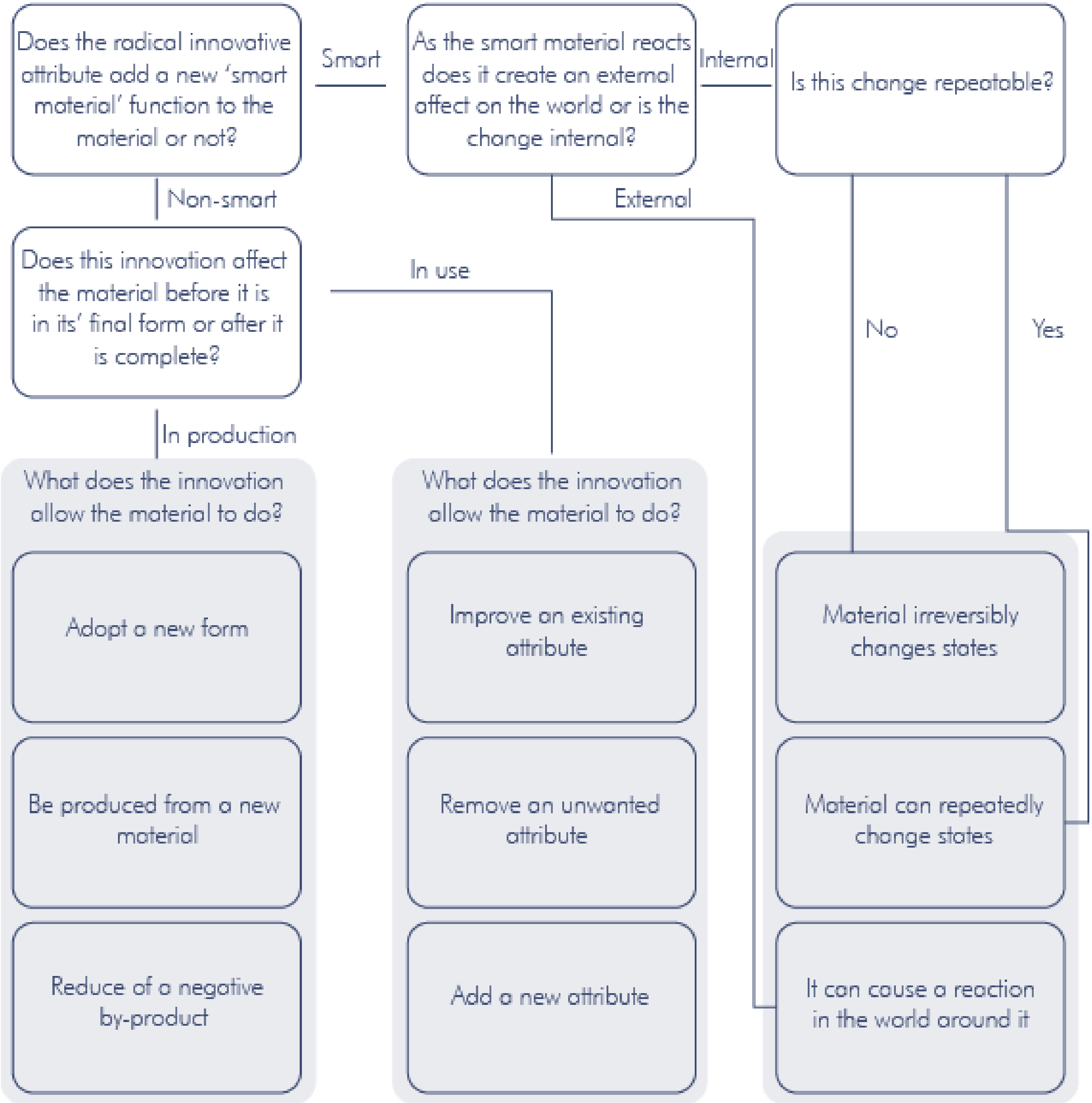


Figure 29: Different categories of radical material innovation

5.3 Questionnaire

The goal of the questionnaire was to gain a large amount of quantitative data on what designers saw as the most useful method to communicate different radical innovations. By offering them four different tools to communicate and asking them to select the most useful, it would give an indication as to which tools are preferred. The results could then guide more in-depth focus groups that would probe why designers preferred these tools for each innovation.

5.3.1 **Screening of participants in the questionnaire**

In the initial question of the survey, members were asked to describe their background and their familiarity with materials. This was to ensure that undesirable members were screened out. The goal was to collect information from designers who were material novices and no other group. To get this selection, two questions were introduced.

The first question asked for a background with years of experience in the industry. Complete design novices were not desired. Examples of this group are; first-year design students and designers who only recently picked up the design as a hobby. In addition, this screened out non-designers who had mistakenly accessed the survey.

The second question asked what the respondent's familiarity was with material science. Respondents were given a scale of 1-5 to select from. This question allowed quick identification of those who had too high familiarity with material science and did not classify as a novice. Novices were categorised as anywhere between 1-3. This was in line with some initial testing with known material novices in the first workshop who consistently saw themselves in this bracket.

5.3.2 **Question Design**

The design of the survey focused on the different categories of radical innovation. These nine categories allowed a closer focus on the potentially different ways that radical innovation might need to be described.

Each category needed to be examined to check whether metaphor and comparison was the best tool to use to explain it fully. This comes from the fact that while comparison was the most popular method of communication, it was not the only method. To establish how effective the methods of communication were for each specific category, participants were exposed to the innovation of that category explained through the four-different analytical techniques. Participants were then asked to evaluate which of those four they found most helpful.

The analysis could then be made of the proportion of participants who selected each method. High proportions selecting a method showed that that method was preferred and low proportions showing that these methods were not suited to explaining that category. It also allowed for innovations categories which suited more than one explanation tool to be identified, if two methods were equally favoured.

5.3.3 **Reducing Bias in the questionnaire**

As was stressed in the literature review, innovation is a tricky subject to discuss as innovations are not always equal in complexity. An immediate concern was when explaining these innovations that the specific wording or nature of the innovation would bias the results. This would mean that the results reflected the specific innovation rather than the category.

To reduce the possibility of these errors occurring, additional controls needed to be added. A second parallel set of questions was also run. These questions followed an identical format to the first set of questions but provided different innovation examples and explanations for each category. The goal of running this second set of questions was to provide a tool to analyse the results more accurately.

If both questionnaires showed similar answers by category, it would provide stronger evidence that the selection was correct, as well as showing that the category had a distinct preference. If there was a disparity, it would expose that the examples or explanations used were heavily influencing the responses.

The decision was made not just to extend the survey to include the additional questions. This was to ensure that the answers were not influenced by prior answers as well as keeping the test concise.

5.3.4 **Limitations of the questionnaire**

All the tests completed in this research have been crafted so that they can create an accurate view of the topics they are investigating. However, there are limitations to how the test can account for every possible variable and in addition, compromises must be made on how the tests are run so as to enable them to work within the budget and rules of the institutions they call upon. Below is an assessment of these challenges.

5.3.5 **Survey results**

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Subjective	2.9	2.6	2.8	2.5	2.8	2.7	3.1	3.1	2.8
Contextual	3.4	1.2	2.5	3.1	2.6	2.5	1.9	2.0	2.6
Objective	1.4	3.5	1.1	1.3	1.2	1.4	1.4	1.3	1.0
Comparison	2.4	3.5	3.5	3.1	3.4	3.4	3.6	3.5	3.6

Table 25: Results of the survey

The results rise on a scale of 1-4, with 1 indicating a perception that the communication was least effective at communicating the material property, and 4 indicating that the communication was ranked most effective. This is based on the where each choice was placed in the ranking and how many times it was placed there by respondents. Looking at the results, it is possible to see a preference for the comparison tool. However, there were differences in the preferences shown in each response; the exact results of each innovation category fall into one of three groups.

- **The overwhelming support of comparison**
  In these answers comparison scored over 3.4, which represents a high proportion of respondents rating it highly as a preferred method of communication.
- Use of comparison with support
  Participants showed that comparison was the most popular method of communication, but it competed with another tool for this role.
- Use of another tool
  The comparison was not popular in this scenario and a different tool was seen as far more effective at communicating the material property.

5.3.6 **The consistent support of comparison**

For most innovations' comparison was the most highly ranked method of communication. It was evident that designers like using examples, what other tools were selected varied, but no one tool stood out. When asked what made the best selection members reported that they picked these because they provided superior information over selections. Participants liked that they gained an immediate understanding of what that added value of the innovation was which was not accessible with the other methods of explanation without prior knowledge of the market.

5.3.7 **Use of comparison with support**

Participants, in some cases, didn't show an overwhelming preference for one tool or another. While comparison remained the most popular another tool also chose by a significant portion of the respondents. This dual selection happened with both the innovation category: Improving an existing attribute and all three innovation categories centred round features.

In the case of the Improving, an existing attribute category, both surveys showed that participants also looked to the context for information. When looking at the responses as to why there was this preference, participants responded that context was a reliable way to see the material in a new light, allowing them to compare it to their existing knowledge of the material that was being innovated.

For all three innovation categories related to the function, comparison was shown to be the most effective tool at communicating the innovation. However, for each example, subjective was also popular. In all six examples (three innovation categories on both surveys), there was consistent feedback about the subjective being 'short and compelling'. The comparison answer in these examples was all longer than the other options due to the fact they were explaining more complex concepts. In addition, members found subjective solutions more straightforward to understand as they were in a simpler language than the other options. Non-comparison tool was the most popular

For innovation categories: new material and new form, the comparison was not seen as the best tool for communication. In both these categories, participants showed a clear preference for another tool.

In the new material innovation category: the subjective tool was considered the best option for communication. This selection was explained by participants in the survey as they felt the subjective description contained all the information needed. This showed that the participants understood the original composition of the material and could see the value of the new material base.

In the new form innovation category: the context tool was considered the best option for communication. The reason that context was the most popular tool in this category appeared to be because members prefer an idea of what they can shape the material into rather than an understanding of the process involved. Participants reported that the context was much clearer than the alternative methods which focused on the process rather than the output. This does raise the question that if the comparison was reworded to focus on the output rather than the process, that it would show an improvement. This is something to be explored in future tests.

5.3.8 **Key findings**

The survey was a useful tool to explore initial reactions to the communication tools. Their answers showed, most importantly, that comparison is the most preferred tool but not in every situation. The preference for comparison was clear but what was equally important to the research was through the ranking system; it became clear that many of the other tools were equally favoured. This shows each tool has a role to play in communicating innovation.

The comparison was also not the most effective solution for some innovation types. The fact that in some innovation's comparison came a clear, shows that it isn't totally effective though there is some potential to look at whether the comparison wording used in these scenarios was flawed.

The ongoing effect is that comparisons will remain the focus of the research but that other tools need to be embraced, both in those categories where the comparison was not seen as the best tool and those categories where other tools were equally viable.

The below flow chart allows a material communicator to explore what type of radical innovation category their radically innovative material property belongs to; it also provides advice on which communication tools are best suited to support the communication.

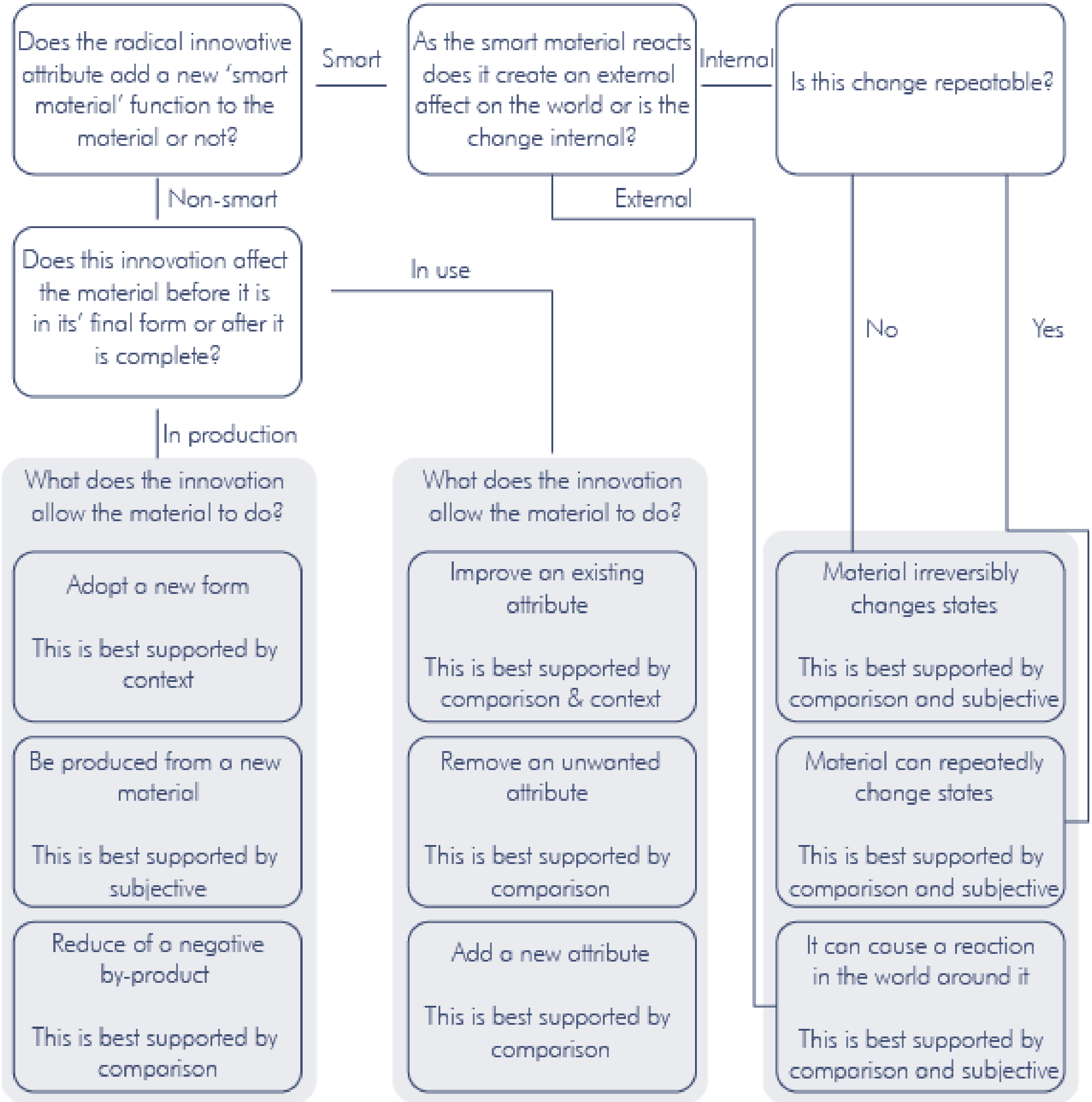


Figure 30: Updated innovation categories with preferred communication tools

5.4 FOCUS GROUPS

The goal of the focus groups was to establish exactly how the communication tools identified in earlier testing could be most effectively utilised. This focused on the fact that while comparison had been identified as a key tool in explaining materials, there are multiple ways to compare any two objects. The focus groups described in this test looked to find concrete examples of the most useful comparisons by category. It also explored more fully the innovation types that weren't best suited to communication through comparison.

5.4.1 Participants and methodology in the focus groups

These tests involved six focus groups that were sourced from designers at universities and professional design companies. The selection of these participants aimed to ensure they continued to fulfil the standards for design expertise set out in the methodology. These participants were met at their places of business or at their universities. A breakdown of the focus groups is described below;

Focus group	Participants expertise	Number of participants
1	Professional designer with at least two years professional experience.	5
2	At least two years design academic knowledge	6
3	At least two years academic design knowledge and some professional experience	5
4	At least two years academic design knowledge and some professional experience	7
5	At least two years design academic knowledge	6

Table 26: Participants of focus groups

5.4.2 Limitations of the focus groups

All the tests completed in this research have been crafted so that they can create an accurate view of the topics they are investigating. However, there are limitations to how the test can account for every possible variable, and in addition, compromises must be made on how the tests are run so as to enable them to work within the budget and rules of the institutions they call upon. Most tests were done in whatever available space was offered. Such an example is shown in Figure 26 which shows the setup of one such focus group.

Figure 31: Participants reviewing the materials

5.4.3 **Detailed findings of the focus groups**

This full review separated by question covers the critical points raised by the participants. The opening and first questions aren't included, as their principal goal was to get participants into the right mindset for these focus groups and not to gather data. The final question collected thoughts on the process as a whole and is reflected here.

5.4.3.1 ***What do you think is important to cover when explaining this material to other designers?***

This question caused some confusion which is to be expected as the previous testing has shown that people don't anticipate explaining materials. It was noticeable that in some groups people were quite nervous and it had to be made clear that the question wasn't asking them to explain the material but rather to cover how they would go about it.

I would want to cover what makes it special first.

> "It is important to know what we're talking about, there's a lot of information out there and I don't have time to read it all."
>
> "I mean to me it is just a piece of plastic (Fiberline) I want to know what's special straight away otherwise it is a bit boring."

Many participants centred on what made the materials special as the primary goal of their explanations. They immediately decided that the innovations should be the focus of their attention. When asked to elaborate, they felt that explaining the innovation would help highlight the benefit and make it more prominent in the designer's mind.

There was another issue around attention span. One designer summarised many others thinking by saying "What you say first is what I'm most likely to remember. I'm also more likely to pay attention then to the rest if I think it is cool." The designers admitted that they had a short attention span and while some were very engaged others felt that they would more likely want to pay attention only if they knew 'it was worth it'. Clearly highlighting what was interesting about the material first gave the maximum chance that they would pay attention.

We need to explain what type of material it is.

> "I want to know if it is (Dry Inside) synthetic fabric, a natural one or if it is just some treatment, I can apply so I can work out how I'd use it."
>
> "So, the EL light, is it a plastic or something more complicated? I'd want to know because otherwise I'm scared, I'm going to break it."

The other core topic among participants was to frame the material into a group. The reasoning behind this was so that the designers could apply knowledge from those material groups to the new material. One designer when talking about D30 highlighted its plastic nature was incredibly important to the description, as it gave them ideas for applications, *"The second I know it is just a special plastic I can think of so many ways to apply it."*

Members explained that identifying the material was the core to as it allowed them to think of the material within the context of all other materials in that category. Putting it in a category they understood was important though one designer said: *"I don't care if it is (Fiberline) pultruded plastic, that means nothing to me, when she (referring to another participant) said it is GRP (glass reinforced plastic) that made sense."* This shows the categories need to pull on information designers will recognize to make meaningful communications.

Having this information also allows the designers to understand more easily what makes the material innovative. By having a clear frame of reference as to what the material was, the designers could then see how the innovation stood out compared to others in the category. With one designer saying, *"I didn't get why the eco-plastic was special (UPM Formi) until I tried to think of alternatives to silicone. You should really focus on that to make it clear."*

I wouldn't want to explain it & I don't know how to.

> "It is not something I can see myself doing well."
>
> "Hell, if I know."

Members repeatedly shared that they felt intimidated by the idea of explaining the materials. One designer summarised this by saying, *"What I want from materials and what others want is really different. I'm not sure I could explain it well to someone else."* This sentiment was repeated in multiple focus groups. The main concern was that their insights would not result in effective communications for everyone.

5.4.3.2 ***What would be the best way to explain the innovative material properties to you?***

This question was met with a lot more openness than the first question put to designers. Participants were quick to pick out the tools that they felt would be most effective in communicating the materials to them.

Comparison - 'I want to know how it compares to X'

> "It is important to understand if D3O is as flexible as let's say rubber."
>
> "How is this (Fibre-optic fabric) like normal fabric and how is it different?"

In most focus groups, the tool that participants choose to use first was comparison. In each case, they wanted to compare it to other materials that they knew. They also had specific materials in mind, wanting to compare to a chosen material that they saw as similar to the innovative material. A quote that summed up the reasoning behind this was provided by a designer *"I see the material and I'm immediately comparing it to something in my head, there's just a lot I can't work out unless you tell me."* Designers are defaulting to comparison. When they see the material, they pick another material whose aesthetics or material type are the same, which they then start to evaluate the new material against.

'Is there some information I can read?', 'Is there a video I can watch?' And 'Do you have a datasheet to go with it?'

> "I like to learn through something I can repeat, I like YouTube videos or blog posts that I can refer back to."
>
> "I'm most happy with a datasheet, even if I don't understand everything on it, I can always take it to someone else who does."

Participants wanted information that they could consume at their leisure and refer back to. Most of this information would've been something they could find online, and members highlighted YouTube channels such as Smarter every day, VSauce and Veritasium were listed as being examples of what they were interested in.

Out of all those surveyed, only three mentioned that they wanted to see data sheets, information packs that cover relevant material attributes in an objective assessment, which covered the properties of the material in an accurate and objective fashion. These participants explained that they could then compare the materials themselves through their own understanding and speak with their colleagues. However, they felt that this was not the only method to comprehend the material and was supplementary to other techniques. With one designer saying, *"I love a data sheet, but it is only a bit of the story. I'd prefer to have a real play with a material before looking at its datasheet."*

Context

'I'd like to know what I could use it for' and 'What's it being used for currently?

> "I want to know how a material is being used, and how it makes that idea work."
>
> "Examples of products using it already would be helpful, as long as it plays a key role"

The other tool designers wanted to be explained early on was how the material is currently used, known as 'context' in this study. This may in part be due to the fact that all the materials introduced were explained as being commercially available. Participants knew they were in use and felt that they could quickly gain some idea of potential uses from placing it in a work context. One designer said *"It (Nitinol) must already be being used, so how? Some examples would really help me understand what it can do."*

For this tool to be useful, the examples had to have the material feature prominently in the example and the example had to be something the designers recognized. One designer, said, "It doesn't help telling me ferrofluid was used in the aviation industry for years, it is not like I design planes or know enough about them to figure out how this works." He went to explain that whilst the explanation did go onto specify that the material was used in a specific way, because the context led with an example, he wasn't familiar with, he started to feel lost. He was indicative of many other designers.

Context as proof of application - "If you explain something, and then tell me how it is used I'll know I understood it if I agree with how they use it."

Members explained how context helped them work out if they had understood the material. They felt if the application was one, they could imagine the material being applied to, considering what they'd just learnt about it, then they knew they'd understood the material. One quote that summed this up was *"It is all kinds of complicated. I'd prefer to see an example and see it working before I could say I understood."*

> "This (referring to a material communication) says it gets harder under stress (D3O). Once you've told me that I'm intrigued, but I'm not sure how hard. If you give examples of it in use, I would have a better idea of exactly how it works."
>
> "I like the memory wire (nitinol) and I kind of get the explanation but I'd want to know how it is used so I can check I've understood. "

Subjective

"I need to know if it is strong/hard/tough/bendy/stretchy"

> "It is the basic stuff that's really important, like is flexible and is it strong or weak. I don't need to know the exact numbers, but I do want to know how it feels and acts in clear language."
>
> "I just would like a summary, is it light or heavy, soft or hard, or somewhere in-between?"

Participants wanted subjective descriptions of material properties. They were happy to have little detail in these descriptions, preferring the text to highlight in a simple manner the properties of the material. Designers wanted the subjective descriptions to accompany complex descriptions like comparisons, with one designer saying *"I don't expect this to tell me everything, just to kind of frame the material so I know the basics, then I can turn to other things to improve what I know."* From their requests, it seems that designers use subjective terms to help build a more complete picture of the materials non-innovative properties and to understand what stands out about the innovation. An example from one designer was *"If you let me see that paint and tell me it is black, dries quickly and can paint on different surfaces that's great. If you also say you can run a current through it then I get why it is special."*

If you were comparing the material to another, how would you describe it?

Participants were asked how they might describe materials from the different innovation categories found through the review. This gave valuable insight into what forms of the language they felt were most useful.

5.4.3.3 ***Designers wanted comparison introduced by a subjective description***

> "Tell me what's important then compare it, like tell me it is tough and then say it is as tough as titanium, otherwise you say something is like titanium and I'm just wondering if you mean it is good in submarines."
>
> "You should guide us in, tell us it is (Micro-suction tape) sticky and then says it is like a million tiny suction cups. "

An insight that was shared by respondents is that they felt comparison should begin with an introduction. Some explicitly stated this as an idea and many others, when giving an example began it with a subjective description of the material and then followed on with the comparison. One designer explained, *"When we start talking about two materials, there's so much we could be talking about, anything from do they both floats, to is it the same colour. It helps to nail down this bit is what I'm talking about"*. Not only did it help them frame the concept in their mind but with most examples, the combination was used to draw attention to the property that the comparison was communicating. This idea appeared independently in all but one workshop and as such should be seen as an essential tool.

It was also used consistently to help frame analogies with designers. It was applied in the same way as with the other comparisons, using a subjective description to ensure people didn't get 'lost'. One designer described this as, *"I want to say the nitinol wire can work like a muscle…but that can mean a lot, so you should say 'when this wire gets hot it changes shape, allowing it to pull like a muscle.' That's way clearer."* Designers felt that adding the subjective angle was necessary when using analogies as it gave more clarity and made it very clear what aspect was being discussed.

5.4.3.4 ***Designers use of analogies***

> "The fibre optic fabric is like water spilling out of hoses, except it is light not water."
>
> "The nitinol wire isn't like any other material, so I'd compare it to muscles or something else you can change the shape of, if you want to see it change."

The use of analogies by participants showed they are open to the concept but creating analogies for materials they had never seen before was not easy for them. Some examples were offered using materials outside of the test, to reduce potential biases on how participants talked about the tested materials. When participants did come up with metaphors, they tended to be inaccurate.

Despite the challenge generating analogies, the designers were more than happy to refine the work of others. When discussing the self-annealing plastic, which was described by the manufacturer as 'plastic that can heal itself', designers remarked, *"I'd prefer if it was more* *accurate, say something like 'Can heal from a cut and be stronger than before."* They felt that with any analogy it should be apparent where the similarities end between the material and system the analogy used ended. Referring back to the self-annealing plastic one designer commented, *"It annoys me as heals can mean anything, if you're going to give me an example don't make it unclear. Otherwise you might as well not bother."* Designers felt that exactly where the similarities started and ended was crucial for avoiding confusion.

Designers also suggested that any analogy should be tangible and related to practical systems. One of the least popular examples was comparing smart magnets (a programmable magnet material) to computer programming. This was singled out as causing a disconnect between the physical and digital world, and while participants understood the comparison, they felt it didn't enable being used practically. A designer summed this up by saying *"I get that you can program them to do things in certain positions, but programming a computer is so different, they're completely different systems. I just end up with more questions."*

5.4.3.5 ***Designers use of direct comparison***

'It is like X'

> "Keep it simple, the plastic is basically silicone. (UPM Formi)"
>
> "I think it easiest if you can choose something that exists and say it is like that, tell me it is like steel or something"

Some participants used direct comparison where the only two elements are the new item and original item it was compared to. This is the most basic form of comparison and the easiest to understand due to its simple nature. Participants used this often but as part of a longer explanation of the material. It never formed the whole explanation. Often, its main goal seemed to be to categorise the material in the context of other known materials.

5.4.3.6 ***Designer's use of direct comparison with property qualifier***

"It has the qualities of X but with Y property improved/removed/added."

> "You should focus on what it does better, this conductive paint is just that, like paint but conductive. (Bare conductive)"
>
> "Tell me what's improved, with the Fiberline, tell me it is GRP but then say, 'but it is as strong as steel.' That makes it clear."

Very similar to comparing to a material type, this technique compared the materials a specific material or category while emphasising what attribute made it stand out. This was one of the most popular forms of comparison appearing consistently in all focus groups. Its popularity was due to the fact it made clear exactly what property the designers considered important while also establishing many other properties at the same time. Designers saw this as combining their desire to see the material grouped with other materials they recognized, a need designers described as part of the first question of the focus group, and a need to find out more. One designer said, *"I know the basics of most materials but if you then tell me what it does differently, that change is what I'm interested in."*

5.4.3.7 ***Designers use of direct comparison with numerical qualifier***

"This has the qualities of X but with half/quadruple/33% less/100% more (using any amount) of property Y"

> "I like the plastic (UPM Formi) and 60% less CO_2 compared to regular plastics makes the benefit clear."
>
> "I keep trying to think how I'd explain how light that cellular metal is. If I just say light, I don't think people will get it, but if I say it is a tenth of the weight of the same metal block, then it starts to sink in."

This form of comparison was used by designers less often and seemed to be picked up from the explanations of the properties of the material provided as part of the communications. Participants would listen to a description of materials innovation and hold onto easily understood numerical explanations of the properties of the material. A designer summarised this. *"It makes the benefit clear, if it is that plastic is a quarter of the weight of steel and almost as strong, then I can see what appeals about it."*

The comparisons focused on describing a single easily understandable factor such as weight or CO_2 emissions compared to a material they already knew. It is worth noting that they preferred phrases such as 'fifth', 'half'/'double', a 'third' or a 'quarter'. These terms are favoured as they were simple and easy to communicate, though percentages were also used as well. They, however, dropped numerical representations when they struggled to picture the property itself. A designer summarised this with *"I don't really get what being more viscous looks like adding a statement like 'it doubles in viscosity' will just make me switch off."*

5.4.3.8 ***Designer's use of stacked comparisons***

"It is got the property of X, but it is also like Y"

> "This plastic(self-annealing) is like a rubber band that can also heal itself from cuts."
>
> "Cellular metal is light like polystyrene but strong like honeycomb."

This comparison technique came up in multiple conversations. Participants rarely wanted to use just one comparison to explain the complex materials, preferring to 'stack' multiple comparisons together. *"I'm happy to add things together, as long as it is clear what I'm talking about in each one,"* one designer revealed. When adding interpretations together, designers aimed to make it clear what properties were important when mentioning each comparison and what material they were drawing a comparison to. In these exercises, designers often drew comparisons to specific materials when using this technique rather than general groups. They felt this made it clearer what they were aiming to communicate.

5.4.3.9 ***Asking, 'why did you pick this method of comparison over other ways to explain yourself'?***

Designers chose analogy because:

> "Analogies do the job when there is nothing real to compare it against."
>
> "Analogies should be really exact. I'm still not sure I'm getting mine right."

When talking about analogies designers stated that they only used them when other tools wouldn't work. When they did use the analogies, they preferred a very clearly defined analogy, participants were clear that it was because they wanted to be able fully to understand it. When analogies were used, they made designers more uncomfortable than direct comparisons as they felt the explanation was more likely to be unclear. This sentiment was summarized by one designer saying, *"I don't like using analogies as they can be tricky, but sometimes there's no other way to describe something."* Designers felt it was apparent where the limits of the direct comparison began and ended which made them more reliable, *"I don't like analogies. If you can do it simpler, simple explanations are always better and more likely to work for me,"* one designer said.

Designers chose direct comparisons because:

> "They are simple and let me understand the basics without any fluff."
>
> "If I want to know what a material is like I'd prefer to know what's out there that it has the most in common with, as long as I'd hear about that one too."

Participants were motivated to use direct comparison as it was the 'easiest' form of comparison. It was often the first thing that came to mind. In many cases, they also felt that when using direct comparisons, they would minimize any chance of being misunderstood. A big part of the simplistic, direct comparisons was also the context of the material they were discussing. For instance, if designers saw something that was clearly plastic and were able to point at it and say, 'that has the strength of steel' it would be evident to other designers why that was an innovation. *"Once I know what it is like, working out what's special is easier,"* summarised one designer.

The other purpose was to ensure that the material was put into a category or grouping. Once it was in that grouping, they felt they knew a lot more about the material than when other comparison tools were used. What was important though was that this example is something they understood. If the example wasn't known to them, it provided no value.

Designers chose direct comparisons with qualifiers because:

> "This is really useful for when the improvement is clear cut, saying exactly what's better immediately."
>
> "It works when you can make it clear what is standing out."

Participants felt that explaining materials using a qualifier allowed them to quickly explain a material's features and point out the innovation. The simplicity meant that the communication had clarity, and they felt others would understand the explanation and be immediately aware of the importance of the innovation. It was also the easiest way to explain a material, as they only needed to understand two things; what the material most closely resembles, and what additional feature needs to be explained.

Designers were quick to admit that it wasn't the most accurate method as it wasn't as clear as other tools and some participants pointed out that they initially used 'Direct Comparison with Qualifiers' till they could find a suitable 'stacked comparison which would add extra information about the material property. *"I prefer comparing to a few things. Then you can* *get the benefit of each one, saying it is like this but not quite, feels less elegant,"* a designer said.

Designers chose direct comparisons with numerical qualifiers because

> "The exact nature is a big benefit; I think I'd remember it more."
> Interviewee #3
>
> "I prefer this when there's only a single or simple difference that I can put a number to."

Using tangible amounts made participants feel like they were accurately describing the material. Designers felt it let them use a potentially limited pool of materials, understanding more freely while still being precise. By connecting to a known factor and then changing it with the number, they were able to keep their comprehension of the property while also changing the property's quality by a significant margin. "Putting a number to it means that you are sure of what you're saying, and others can also work it out."

Designers did mention that saying something such as 'twice as strong as steel' was hard to picture as to exactly how strong that might be. This applied to other measurements as well. But the explaining that the material had a specific change meant they could apply their knowledge of how the material was currently used, imaging what how they could change the design with the innovative material's new abilities. A designer described it as, *"When I say it is twice as strong as steel, I'm not really sure how strong steel is but I can imagine what it would be like to be able to use half the amount of steel to get the same strength, so I can see really skinny bridges or low weight cars."*

Designers chose stacked comparisons because:

> "I like how you can add up different ideas to get an overall view of what the material looks like."
>
> "When you compare it to different materials it is like you filling in bits of a puzzle, each comparison gives me more pieces."

Stacked comparisons were very popular with participants as they felt they could explain multiple details of material reliably. Participants noted that the radical materials were very hard to compare to just one other material, to communicate the innovation properly. Stacking the comparisons allowed them to hold on to what they saw as a reliable form of communication while building in the complexity they needed to make the explanation useful.

Participants noted that they felt stacked comparisons were the same as direct comparisons with qualifiers but were easier to produce. They liked to use stacked comparisons more than direct comparisons with qualifiers but were often challenged to think of a suitable comparison. This meant that when they couldn't find a comparison to 'stack', they defaulted to using the direct comparison with a qualifier. When probed designers said, *"I find it easier to talk about attributes the material shares with others. It is easier and more obvious what you're talking about, better than trying to work out how it is different to other things."* This indicates that their reason is that they preferred the comparison over the qualifier because it was more evident to them and they felt would understand more effectively as it gave more information.

Other topics that came up

Outside of the question, some topics came up reliably, and these require a special mention as they do not fit into the question answers explored above. Due to their prevalence, appearing in most if not all focus groups, they need to be recognized as core topics.

Designers said "I would use all of the tools"

> "I don't think there is any one perfect explanation. I'd prefer lots of different ones so I can compare them to get the best idea."
>
> "As long as they are all right there's no reason to not explain in every way."

The overall response of many people in the focus groups was to state that they wanted to use every tool to describe the materials. When either the moderator or other members focused on communicating with one tool, participants would often mention how it would be easier to use other tools. It was also reflected in the examples they gave to the question 'What would be the best way to explain the innovative material properties to you?' and, 'If you were comparing the material to another how would you describe it?'

Both questions often had members of the focus group providing examples, which used subjective, comparison and contextual. Often specifically in that order. This was of such note that the moderator started to question this process.

Designers use of subjective, comparison and context

> "The moss is really natural, but basically a plastic…I'd like to see it on buildings or behind glass."
>
> "I like how light the metal balls material is (cellular metal). They're kind of like metal polystyrene, I'm sure you could make some really tough stuff out of this."

When challenged as to why, when providing examples, participants used the repeating pattern of subjective, comparison and context, designers replied that it helped them understand the idea. When this was further discussed, the group seemed to believe that the reason this was both popular, and in their impression, effective was that it made it very clear what was being discussed. The subjective description was bringing attention to critical aspects, the comparison was explaining them, and the context was giving clarity on whether their understanding of the last two communication tools was correct.

For the participants, the reasoning as to why this system works is complex. Firstly, it helps them direct their thinking. One designer said, "*I like knowing what's important first, otherwise I'm just going to pay attention to what I care about.*" This was her reasoning around having an intro, as it brought immediate attention to what they felt was necessary. While this intro statement was mostly subjective, occasionally designers used binary objective statements instead. An example of this occurred when designers discussed Faraday Film, a clear conductive coating for glass and plastic. One designer described it as *"It is a conductive spray, like spray on wires."* This use shows that there are potential ways to use an objective description as long as it clearly communicates what is important.

The core explanation, which was nearly always a comparison, was key to their understanding. For many, the reasoning behind this was that it allowed them to 'fit' the knowledge in their minds. One designer said, "*If I'm going to be able to use it, I have to work out how it'll fit in my designs. Easiest way to do that is see if it is like anything else, I've used.*" He felt it was essential to understand what the material was like. This matches the general focus on comparison but shows that this central communication should allow the designers to apply their prior knowledge to the concept.

The contextual tool provided a system for the designers to check if they had understood the material description and gain additional knowledge around the material. Designers liked knowing how others had used the material, as one designer explained: *"How's it been used already is important. If it is already working, then it is not too hard to work out what I could do with it."* Knowing the application let them understand what a proper application for the material might be. The ability to check that their understanding was accurate provided a method for designers to check themselves when the contextual was used as part of a description one designer said, *"That's when I knew I'd got it wrong, I couldn't see how you could make it work (the example was photochromic pigment as a UV sensor on suntan lotion bottles). I thought it would just stay the same colour permanently."* The designer was able to see they'd made a mistake when another designer talked about an example of a material being used. They could then go back and examine the information more clearly.

5.4.3.10 *Key findings and next steps*

One of the focus groups' primary outcomes was the vital discovery that designers prefer to use multiple tools to communicate materials. This collection provides a more holistic overview of the materials property. While the core methods of comparison picked in the questionnaire remained valid designers preferred to use subjective, comparison and context in every explanation but using them in different ways. Designers used the different tools consistently to create a communication consisting of three elements, an introduction, the core explanation and a summary. This led to explanations such as…

> "It is a weirdly cold sheet, kind of like it is been in the fridge, I'm sure it be great for clothes in hot countries"

In these examples, a subjective statement marks the intro, establishing what material property is essential. The comparison works as the core explanation, communicating the exact nature of the materials property. Finally, the contextual tool is used to summarise, showing a potential use and clarifying with an example.

In multiple groups, this same system arose naturally through discussion and when challenged to improve the system of communication. The effectiveness was apparent to the designers and it aligned closely to the system laid out by the questionnaire with comparison tools mostly being preferred as the core explanation tool. Whilst using more tools to communicate is not necessarily efficient, if each description is accurate, the additional pieces do not add any confusion to the explanation. In addition, it seems from feedback that the designer believes that adding context onto the end of the description helps the listener/readers evaluate whether their initial understanding was correct. This could be a valuable tool to increase understanding, as it would enable those who misunderstand the subjective or comparative description to realise their mistake, prompting them to re-read and reassess the communication.

Going forward, the design of the communication will aim to use the structure laid out by the designers in this test. While testing previously investigated the tools as separate instruments to enable communication, now the focus will be on combining the tools.

When using a comparison, designers liked to add extra details to their comparisons. This even included using multiple comparisons together. These strategies are detailed below.

Direct comparison with property qualifier

"It has the qualities of X but with Y property improved/removed/added."

> "(UPM Formi) …is like silicone but doesn't need any oil to make it."

This form of comparison was prevalent. It allowed designers to use materials they were familiar with whilst exempting properties that did not fit the comparison. It could also be used to emphasise the benefit of the material.

Direct comparison with the numerical qualifier

"This has the qualities of X but with half/quadruple/33% less/100% more (using any amount) of property Y"

> "This stuff (Fiberline) is as strong as steel but is a fifth of the weight."

Participants explained that this comparison tool made it very easy to explain the benefits of a material when describing a single, easily understandable factor.

Stacked comparisons

"It is got the property of X, but it is also got the same property as Y"

> "The moss (Bright green) looks like real moss but lasts like plastic."

When explaining complex innovations, participants wanted to use just one comparison to explain the materials property, preferring to 'stack' multiple comparisons together. When doing this they made it clear what properties were involved or exempt when adding the comparison.

5.5 SUMMARY OF CHAPTER

5.5.1 Analysis of radical material innovation categories

In the assessment of radical material innovation categories exercise, a large number of different materials were assessed, and it was found that there are distinct similarities between some forms of innovation. These come in at three distinct periods of in a material's life. That is innovations that take effect before production, during production and use, and as a reaction to use. In these distinct categories, there are a further three variations, making nine distinct categories.

With these nine different categories identified, the research could then focus in on how the categories could be communicated. This has helped answer **research question 3**. By exploring the different types of innovation out there the understanding of how to communicate each type can be explored in more detail. By building an understanding of radical material innovation types, the tools identified in descriptive study 1 could be assessed against each category rather than being assessed against radical innovation as a whole. As radical innovation is so varied dividing by categories not only makes any assessment more stringent but also ensure that tools which may work on some forms of radical innovation are not misapplied to very different radical innovations which would not benefit.

5.5.2 Questionnaire.

In the questionnaire, two pieces of learning from the descriptive and prescriptive studies were applied to generate the questions. Firstly, the understanding of the nine different forms of radical innovation categories was used to divide up a number of materials and use them to understand if there were distinct differences between how designers communicated each category. To see what tools would be useful the four communication tools that were identified in descriptive study 1 generated potential explanations for a variety of materials grouped using the categories.

The responses overall showed that comparison was seen as the most useful tool to communicate the materials by designers. Whilst this applied overall comparison was not uniformly the most popular tool for all material types, with material types. For other materials, comparison was the most popular but was closely followed by another form of communication.

These insights not only helped to increase the knowledge of which tools help communicate radical innovation, helping answer **research question 3**, but also helps inform the design of a future system, which will enable **research question 4** to be answered.

5.5.3 Focus groups

The focus groups conducted in this study helped to build on the understanding from both descriptive study 1 and prescriptive study 1. Those in the groups recommended using comparison, and other tools to better communicate radically innovative materials. They highlighted that to use these tools effectively for designers, the communications needed to choose if they used a direct comparison or a metaphor. Preferring to use direct comparison in a variety of ways to get the most information out of them. With a focus on building numerical constraints, combining multiple comparisons and using additional qualifiers to clarify what the comparison is trying to convey. This helped build tools that enable a unique understanding of what it is to communicate radical materials to designers, bringing answers to **research question 3**.

In addition, it also highlighted that these tools should not be used in isolation. Designers repeatedly mentioned that the different tools were part of a system to communicate materials. In particular, one system that came up organically in multiple focus groups appeared to be more effective than others. The system used a subjective description, then a comparison, then a contextual description to communicate materials more effectively. Considering the system appeared multiple times organically and was seen as very useful by designers when discussed, it is likely essential to building a system for communicating radical material innovations. This will be essential to answering **research question 4** and ensuring it is more effective than previous tools.

5.5.4 How does this compare to the literature prescriptive?

The aim of the review of the innovation types helps to build a clear understanding of what must be communicated. This not only helps make the communication more specific but also ensures that the system converts the tacit knowledge around innovations to an explicitly definable knowledge base as recommended by Nonaka (1994). This will help ensure the communications are more focused and the boundaries and limits of how any future system functions is precise.

When conducting the questionnaire and focus groups, the focus on the use of comparison as a tool to aid comprehension was consistent. While supported by other tools, designers did see it as core to their understanding, the reasoning being that it helped them understand, and apply their prior understanding to the new challenge. This focus on using prior knowledge is something that also may be connected with the popularity of the contextual communication tool and its ability to apply the material in a scenario that is familiar to designers. This need to link to known factors shows a lot of similarity to the process of design thinking, where designers are looking to enable their understanding of new challenges through applying older knowledge (Cross 2007). This desire to use familiar and helpful language fits the recommendations laid out by multiple authors covered in the literature review. In the realms of communicating radical innovations, Mast (2005) recommends that the language be relevant and clear to the audience matching their ways of thinking. In particular, Mast recommends using scenarios that are relevant to the audience; this adds further support to the use of contextual communication for the final framework.

5.5.5 **Next steps**

The next step of the research aims to take the understanding gained from this prescriptive study to build the first iteration of a system that can be used to create more effective communications of radically innovative materials to designers. This upcoming chapter will focus on distilling the findings from the research so far, into a single useable system that can be applied to the materials and tested in later chapters.

6 DEVELOPMENT OF THE COMMUNICATION FRAMEWORK

This chapter looks to address how a new system could be created that would allow for the communication of radical materials to be more effective, looking to answer **research question 4**. This investigation will pull on the learnings from each chapter beforehand, using those methods that have proved effective to guide the development.

The goal is to at the end of this chapter, have fully described a new system that will allow for radically innovative materials to be communicated to designers in a way that improves upon the existing methods provided by material communicators. This will allow testing of the new system, which will answer **research question 5**.

6.1 THE NEW SYSTEM, A TOOL OR A FRAMEWORK?

The development of this new system involved taking a choice as to if the end result would be a tool or a framework. Both options were assessed to see, which would be the most practical to offer.

6.1.1 What is a toolkit?

A toolkit is something that helps you complete an activity, a physical or digital object or prescriptive set of rules that aids you in completing a task. The benefit of a toolkit is that it offers something that material communicators can interact with to create a solution. This may be a set of physical cards that help shape their thinking or guide them to communication or it could be an online resource that generates potential communications.

There are many different communication toolkits that exist which aim to help communicate materials; the material libraries highlighted in literature review could be seen as a communication toolkit.

6.1.2 What is a Framework

A framework is a system of ideas, information, and principles that form the structure of an organization or plan (Collins 2020). The concepts detailed in a framework enable those following them to create resolutions that follow the same principles as other solutions generated by the framework while giving each solution space to work creatively within that framework. Frameworks are common in communication theory. Being used for both cultural and scientific communication, though is not explicitly tied to communication radical innovations or materials (Trench 2008).

6.1.3 Choosing between a framework and a tool.

While both approaches could work for creating a new system to answer research question 4, the system will be developed as a framework due to a number of considerations all of which are informed by the work of Ravitch and Riggan (2016).

- Frameworks can account for all the new materials: Frameworks may be more fluid than tools.
- Difficult to build a tool that can account for all the different types of innovation.
- A tool could soon be outdated as new materials and new comparisons/contexts become relevant.
- A model can flex to accommodate new information, instead of enabling a process.

6.1.4 Purpose of the framework

The radical innovation communication framework (RICF) can be used to help explain radical innovations in material science to designers. The goal of creating the RICF is to have a framework that allows materials producers to have a set of rules that they can follow to create useful descriptions for designers.

The tool will allow any material producer who knows what makes their material radically innovative to approach designers with a structured explanation of the material's value, using techniques that have been shown in workshops to be more effective than current techniques. As it becomes easier to understand these materials, designers will be more able to use them which will increase their chances of being used in commercial products.

6.1.5 **How prior testing will influence the framework**

Over the last six chapters, a number of key learnings have been gained, these are listed below with a description of how the research in this chapter aims to use those learnings to produce a better system for communication.

In particular, three key learnings have been identified that will form the basis of the new communication framework.

Key learning one: What communication methods designers use, and which they prefer.

In descriptive study 1, a thematic review found that designers used four distinct forms of communication. These are comparison, subjective, contextual and objective. These describe how designers discuss materials amongst themselves. Further testing in the first workshop series found that of these tools, comparison was the most popular for communicating materials.

Key learning two: Different innovation categories, are best communicated using different communication methods.

In the review of materials in the prescriptive study, nine distinct innovation categories were described. Each category established different ways a radical innovation could affect a material. When tested against the communication tools found in key learning one, it was found that while comparison was used most consistently, there were differences in which tool designers felt best enabled them to understand radical innovation.

Key learning three: Designers prefer to use a combination of tools to communicate radical innovations.

In the focus groups in the prescriptive study, designers described how they preferred to communicate — expressing a preference for combining two or more communication tools to create the most effective communication. In particular, the group identified a system of using Subjective, comparison and objective statements together to create a single explanation that was more effective than less detailed communications.

Research	How it contributed to the framework
Literature review	The literature review's discussion on what tools and suggestions that current material innovators use (mainly innovation journalists) was key to building this framework. In addition the learnings on how designers think and the current approaches to communicating materials was also incorporated.
Interviews & thematic reivew	The interviews and the thematic review of the feedback provided insight on what language should be used in the communication. By knowing how designers speak the communication could be built with confidence that it would be relevant to designers.
Workshops	The workshops showed that the current communication tools were not completely ineffective but they needed support. In addition the feedback from designers about the challenges they faced also helped shape the communication.
Innovation catergorisation	The catergorisation of the innovations into different groups shaped the communication. The different types of innovation helped to break up radical innovations into maneable groups, each of which could be targetted in specific ways.
Questionnaire	The questionnaire allowed for the innovation catergorisation to be expanded upon, highlighting which catergories were most effectivley supported by which elements of language that designers preferred to use. This helped to make sure the framework would be robust as possible.
Focus groups	The focus groups allowed for the discussion on how to apply the designers language to bet enable communication. This research developed the key tools that the framework relies upon. It also helped to further understand how designers use comparison which was by far the most used tool for communication.

Table 27: How research contributed to the framework

6.2 Developing the Framework

To build a framework that can accurately communicate product innovations, the first step is to identify what must be communicated. In the literature review, radical innovations were defined as having a set list of characteristics. This definition is important as it allows the user of this framework to choose what about a new material must be communicated. Focusing specifically on the aspects of it that allow it to do something more than the rest of the industry. The framework does assume that its user would be aware of what about their material is a radical innovation, and if indeed, that is one distinct innovation that needs communication or multiple innovations each needing communication.

The other material attributes are important, but the communication of those aspects is not the focus of this research. The reasoning behind this focus on innovation comes from the fact that the research has highlighted that radical innovations are seen as distinctly different to incremental innovations or material attributes in general. The literature review identified that radical innovations are a distinct form of innovation and that the innovation is due to the fact that they aren't easily reconcilable with prior knowledge may be a poor fit for design thinking.

In practical testing, designers couldn't use incremental and radical innovations as quickly, showing that there was a problem understanding the communications around the materials. In the interviews, designers showed a preference for discussing the radically innovative material in a different manner to the incrementally innovative material. Overall, the research indicated that the radical innovations were a unique challenge and as a result, needed a tailored approach that should be different from the systems that material communicators use currently. This insight was given additional support in the first workshop series which established that these systems only work for designers half the time when communicating radical innovations.

All these elements and more helped to build the framework, table 26 summarises how each step has contributed to the framework.

6.2.1 **How the literature shaped the framework**

The literature review that supports this thesis covers some of the tools that already exist to help improve the communication of radical innovations and the communication of materials to designers. This existing research offers advice and recommendations which will shape this framework. The first elements that will shape the review comes from researchers who were looking to improve cross-industry communication. As stated previously, Nonaka (1994) recommends generating a useful tool for communicating across industries. The system must deal with a definable knowledge base and set clear boundaries of what must be communicated. Secondly, this tool must be reliable in its communication to be respected by those who wish to use it. An observation laid out by Brown and Duguid (2000). These recommendations have shaped the development of the framework. With the focus being on creating a clear definition of what is to be communicated, how it is to be communicated and that a certain reliability must be inherent in the process.

The second topic that will shape the framework is the recommendations from academic literature on communicating radical innovations, covered in the literature review. This pulled together multiple recommendations from those in the area of communicating radical innovations. An observation of these tools found that three main recommendations were consistent across each piece of research.

- Clarity – The audience expects the communication to be clear and direct, aiming to be as efficient in how the topic is communicated as possible, where possible the communication should avoid topics which are not significant or clear.
- Relevance – What is being communicated must use language that is relevant to the audience and use examples or scenarios that make sense to them to be effective and interesting. Where possible boring or irrelevant content should be cut to keep the audience engaged (Zerfass, Huck 2007).
- Strategy – The communication must have a strategy to ensure the communication is as effective as possible and reaches the audience effectively (Zaltman, Duncan et al. 1973).

Each of these challenges has been woven into the development of the framework, with each communication following a clear strategy. The need for clarity and relevance is something that is already of top priority for all the comparisons and contextual communications generated. As explored in the literature review, the need for these tools to be relevant and transparent is essential to their success. Especially for comparison the need for clarity is one of the core concerns laid out by Genter (1983). The final framework aims to produce communications that fully embrace these goals and in doing so, maximise their likelihood of being understood.

In addition, to focus on making the language clear and relevant, there is a need to keep the communications grounded in design language. This in part served by the focus on the comparison and contextual communication, which by their intuitive nature fit with the processes of design thinking (Cross 2007). However, there is the need to bring focus on the other primary tool used in the communication, subjective reasoning. The subjective language used benefits from the fact that it is of a designerly nature. Karana used subjective tools to communicate new materials to designers. The goal is that by using language they were more connected to the communication could be more emotive. This is reflected in focus on subjective communication over objective communication as well as the list of potential subjective communications suggested by the framework.

Overall, the past academic research has already significantly shaped the testing and research of this thesis and so is reflected in the results that will form the framework.

6.2.2 The four communication tools used in this framework

To create a useful framework the needs to be structure. As one of the key questions of this framework is how the material is communicated. It is essential to define what communication methods can be applied by those using the framework. Over the course of this research communication tools have been grouped into four distinct categories. Subjective, Comparison, Contextual and Objective, these groups were defined by the analysis of language used in the interviews. These communication methods are commonly used by designers looking to communicate materials.

It is essential that the communication methods designers are familiar with are identified and used to structure the communication in this framework, as each industry may have a different approach to communication (Rogers, Shoemaker 1971). By identifying the communication methods that designers prefer to use this framework can ensure that its outputs are as relevant as possible to designers and fit with design thinking. The communication methods and their nature are described in more detail in the following sections.

With this crucial question answered the next step will look at defining the leading theory that forms the core of the framework.

6.3 THE CORE INSIGHT OF THE FRAMEWORK: THREE-STEP COMMUNICATION.

This section assesses the core insight of the framework, the use of three distinct communication tools to allow for accurate communication of a radically innovative material attribute. This three-stage communication appeared through the focus groups of the prescriptive study. Designers reported that this method was their preferred way to communicate materials, their insight also aligned with learnings from other focus groups.

The three-stage method uses three of the communication tools mentioned in the section above, subjective, comparison and contextual to create a single cohesive description of a radically innovative material attribute. The subjective description should clearly establish what attributes of the innovation are being communicated. The comparative description comes next and can be relied on to help relate it to materials or processes that the user recognizes. Finally, the contextual example helps establish how the material might work when applied to a product that requires specific attributes to function. Combining all three brings the designers attention to the relevant material properties, communicates with a relatable example of the properties limits and then provides a method through which they can check their understanding of the material.

This three-step communication is featured so prominently in this framework due to the strong response in the fieldwork but also due to the fact that using multiple methods to communicate is recognized as a valuable tool in communications research (Beck, Bennett et al. 2013). The ability to bring multiple communications which essentially communicate the same item allows for the learning to be compounded, a method shown to improve understanding. In addition, the use of contextual examples at the end of the communication allows for validation of learning. Allowing learners to validate their learning provides them with the ability to assess if they have correctly understood the communication.

As part of the framework, this learning allows for the communication of the material to follow a clear structure, one that fits design thinking and uses communication tools that designers prefer. The three-part communication also benefits from the fact that each section can help support a designer's understanding of the other sections. This not only improves the learning but also reduces the impact of one element of the communication being poorly constructed. This helps alleviate the need to have every element of the communication be perfect, as the collected communication can help absorb small flaws in the distinct elements.

6.3.1 **Understanding the role of subjective communication**

The first step in this three-part communication is in most cases subjective. The subjective communication is expected to both share knowledge and signpost what is important about the innovation, better enabling designers to understand the next step of the communication.

Focusing on the communication aspect of this communication stage, the value of subjective communication comes from the ease with which it is understood and the emotive quality of the communication. As a subjective communication is by definition a based on or influenced by personal feelings, tastes, or opinions, (Collins 2020) how it is interpreted will also be shaped by those same influences. Subjective communication is generally short; some wording that designers have used is listed below.

> "It is (Cellular metal) very light, but I can see it is strong."
>
> "This gets harder as it is hit."

In most cases, these subjective statements aim to bring attention to what aspects of the radically innovative material attribute are different from what might be expected of the material. The language used is straightforward and generally follows the structures laid out below.

Looking at the communication as a signpost, a subjective statement is useful as it can clearly state what is exceptional about the material without also setting an absolute understanding of the material. In all the research conducted, there is no evidence that designers considered subjective statements to correspond to an objective understanding of the material. For instance, the statement of 'this material is very strong' was never used to create an assumption of specific tensile strength or another objective measure. This is useful for the purpose of signposting as it leaves the designer open to gain more information to add to the limited understanding they gained from the subjective description.

6.3.2 **Understanding if this should be subjective, objective or both?**

While subjective descriptions are based entirely in personal opinion, objective descriptions are factual. In past tests, designers did use objective statements, but it was the least popular communication tool in both the interviews and workshop series 1. When used, it tended to be as a binary statement, stating a material had a distinct property, an example is stating a material was 'conductive'. While only used occasionally objective statements are still a valuable communication tool if used in simple terms.

Objective statements can clearly state if a material has a specific property. This can either aid a subjective summary of a material or, if the radical innovation is defined by having a specific property, can form a method to signpost that this property is essential, in the same way, a subjective property might. To be effective in this role, the objective statements must remain simple. Some examples of 'simple' communications that designers used or mentioned explicitly that they felt were effective are listed below.

> "Bare conductive is a conductive paint."
>
> "The (Faraday) film is a transparent conductive material."
>
> "The D3O is a non-Newtonian material."

All these communications are statements that focus on material attribute. It is crucial when considering how to structure an objective communication, designers have specifically called out they cannot easily apply objective measurements to increase their understanding. This inability to use measurements means that if an objective statement is needed it should either remain as a declaration that the material has that attribute, or it can be modified by making it a subjective statement like those listed below.

> "This plastic (Faraday film) is very conductive."

6.3.3 **Understanding the role of the comparison communication**

Comparison was the most popular communication tool to communicate radical innovations. In the first workshop series it was used the most to discuss radical innovations and, in the questionnaire, it was seen as the most effective method to communicate most types of innovation. The fact that comparison has proven to be the most popular tool in multiple tests, indicates the tool is likely to play a key role in the communication. This hypothesis was tested in the focus groups where designers explained that comparison helped them apply past learnings to new ideas, which they felt was one of the most effective ways to learn about radically innovative material attributes.

In comparisons, the expectation is to take information from a familiar material, **the base**, and apply it to a less-known material, **the target**. It is essential that the base be familiar to the designer for this to be effective (Gentner, Markman 1997). This ability to apply prior knowledge to new ideas is essential for designers as it connects with how designers think. In the literature review research around design, thinking highlighted that intuition is an essential part of how designers create new ideas. Intuition relies on the ability to use prior knowledge to make decisions (Bechara, Damasio et al. 1997). The comparison communication tool supports this need and allows designers to transpose their knowledge of an old system on a new idea, supporting both simple concepts as well as complex analogies.

6.3.4 **Considerations when choosing a comparison; relevance, richness and clarity.**

When picking a base material to compare to a target material there are a number of considerations to consider ensuring the comparison is as effective as possible.

6.3.4.1 *Relevance*

The material used as the base must be known and understood by designers to be considered relevant. Without being relevant, the base could be as unknown as the target material. This gives no opportunity for the designers to apply prior knowledge and is likely to confuse them more than if nothing was said.

Picking a material that is known by designers is its' own challenge. Designers knowledge is not identical between different institutions let alone individual designers. Without a unified knowledge base, picking a material that designers are likely to know limits the options to highly ubiquitous materials or very generic terms. While this may seem vague, when looking at the terms that designers have used in their interviews, workshops and focus groups, this simplistic terminology is very close to how designers discuss materials amongst themselves.

Examples of material categories that designers use to create comparisons during testing.

Material used	Example of comparison designers used
Plastic	"So, it is a like a plastic moss" (Bright green)
Steel/polystyrene	"So, it is a steel polystyrene" (Cellular metal)
Rubber	"The D3O is like an intelligent rubber ball" (D3O)
Glass	"It is glass but also conductive?" (Faraday film)
Silicone	"I like how it is basically just silicone but more eco-friendly) (UPM Formi)
Polyester	"It is no different to a polyester sheet with fibreoptic cables" (Fibreoptic fabric)
Sponge	"Feels and acts like a sponge" (Intumescent foam)

Table 28: Examples of the different material categories described by designers

This focus on simplistic comparisons by designers is not due to a lack of material knowledge but maybe more a reflection on the fact that they wish to understand the base. Earlier in this research, it was highlighted how important it is for designers to be able to put materials they are learning about into a category. This focus on categorization was very general and didn't require that the designer know the exact specific family a material belonged to but more that they understood the general category so that they might understand what the material properties might be like. For designers, their comparisons seem to take a similar role; they use them to illustrate connections to either general concepts they understand and occasionally specific material types they are familiar with and understand. Going beyond material types (like polystyrene, or high carbon steel,) doesn't help this understanding as there is an increased chance that the designer won't necessarily know what is being discussed.

6.3.4.2 *Richness and Clarity*

When the research was conducted to look at how to create useful analogies, the importance of richness and clarity was highlighted. While originally created to be tools to assess analogies, the insights are relevant to the assessment of comparisons in general. Richness and clarity concern themselves with assessing how much of comparison is valid and how much of a comparison between the base and target is outside the realm of the comparison (Gentner 1983). It is argued that better analogies are made when the base and target are as similar as possible. For comparisons, the ability to map as much knowledge from the base to the target is important. The more information that can be applied the more significant the application of prior learning. It also helps reduce the likelihood that incorrect assumptions will be taken from the base to the target if there is less that is incorrect.

When creating rich and clear comparisons, the goal is to choose comparisons that are the most consistent. While the focus on the radically innovative material attribute might mean that multiple comparisons are possible. For instance, if a targets materials tensile strength is its radical innovation this attribute might have the same strength as steel or carbon fibres. The material that should be chosen to be the base is the material that has the most in common with the target. So, if the material with the high tensile strength was a composite, it would be better to pick the carbon fibre comparison as this is also a composite.

Assessing the best way to produce richness and clarity is not the target of this research and would be its own area of research entirely. So, while some decisions may be simple others will not be as clear. The goal of thinking about richness and clarity is to check which materials have been picked and to assess if other options may be better to produce a reliable comparison. This line of thinking will also allow incorrect comparisons to be spotted, which remains a significant concern. While ensuring the comparison is accurate is just as important as ensuring that the material chosen is relevant. Just as it would be no use having a rich and clear comparison to material designers have no knowledge of, it would be equally useless to have an inaccurate comparison to a well-known material.

6.3.4.3 ***Building a comparison***

As discussed in the literature review and as part of the review of material types, there is an ever-expanding range of radically innovative materials. Creating a system that gives a comprehensive guide on how to create comparisons for each type of innovation is not possible. Instead, this framework will focus on listing a number of comparison types that can be used to create meaningful and useful communication. In testing, comparison was the most diverse communication method. The focus groups identified many ways to use comparison to improve communication. Those methods are described below along with the advantages and disadvantages of using that specific method of creating a comparison.

6.3.4.4 ***Direct comparison***

'Feature X is the same as Y' In direct comparisons, the base and target share the same material qualities.

> "The UPM formi is the same as silicone"

Advantages: Using a direct comparison to another material with an almost identical quality is one of the best ways to communicate a material property or an overall similarity to a material type. Importantly this connection doesn't have to be objectively exact, designers explained in the focus groups that they saw comparisons as stating this form of connection meant that they were very similar, enough so that the difference was negligible for the creation of early design iterations. They did not expect them to be entirely identical.

> "I get when we say something is the same as something else there are limits to it, otherwise they'd be the same thing. What I do want to know is that those differences are small enough to ignore at this stage."

Disadvantages: The limitation of direct comparison is that the material must be directly comparable, if there is no old material that offers an exact match to the material, then this option will not be viable.

6.3.4.5 ***Direct comparison with property qualifier.***

"It has the qualities of X but with Y property improved/removed/added." In direct comparison with property qualifier, the base and target are the same, but a specific property is different.

> "It is basically like taking glass or plastic and adding a conductive ability to one side?"

Advantages: This method is useful to communicate innovations in materials the designers already know. The system is also useful when new materials are created which are almost identical to an old material but with added properties.

Disadvantages: The issue with this form of comparison is that there must be a relevant material for designers to use as the base. In addition, if there are other significant differences between the base and target other than those highlighted in this comparison, then this method risks confusing the designers and hiding those changes.

6.3.4.6 ***Direct comparison with numerical qualifier.***

"This has the qualities of X but with half/quadruple/33% less/100% more (Using any amount) of Y" A direct comparison with numerical qualifier allows the difference between a specific attribute in a base and target to be quantified to explain the innovation.

> "So, this cork plastic (LifoCork) produces like half the carbon of the same amount of Polyurethane? Or is it less?"

Advantages: Using a property with a numerical qualifier is useful in many situations. It is best used when an existing material is innovated, but it can also be used for new materials that have strong similarities to existing materials but are not similar enough to use direct comparison.

Disadvantages: The focus on numerical change requires an objective understanding of both the target and bases material property. With *direct comparison* the similarity can merely be very close as the comparison is not meant to be taken as literal truth. However, when numbers become involved designers mention that their expectation is this statement is based on an objective assessment.

> "If you tell me the that some plastic is 25% stronger than carbon fibre, I expect that be a fact. But if you were just to say it is a bit stronger it is not as helpful, but I won't be annoyed if it turns out to only be 20% stronger."

6.3.4.7 ***Stacked comparisons***

"It is got the property of X, but it is also like Y" Stacked comparisons are not one single type of comparison but instead are a system where multiple comparisons are used together to communicate the properties of a material. A stacked comparison will use multiple methods from the above list of tools, and each method may use a different base.

> "The cellular metal is normal steel, but it is all puffed up like little bubbles?"

Advantages: Stacked comparisons allow for complex differences between materials to be communicated to designers. By highlighting the different ways materials differ, a broader picture of the material can be created.

Disadvantages: Building stacked comparisons risks confusion, especially if various base materials are used, it is possible for designers to become confused as to how to apply the material attributes.

6.3.4.8 *Creating analogies*

Comparisons are not all the same; the focus groups in the prescriptive study highlighted designers see different methods with which comparisons are created. In the research, designers tended to use the comparisons listed above as well as analogous statement. Analogies offer the ability to make a comparison that focuses on the similarities between concepts which are not totally similar. They are distinct from metaphors, another form of comparison that analogy is often confused for, which are not literally true, while analogies, despite being between disparate concepts have literal similarities (Holyoak 2012).

In some cases, the radically innovative material attribute may not be as easy to describe as increasing a single attribute or chain of attributes. When assessing materials, smart materials in particular often required analogies to be fully understood. In focus groups, designers preferred to use the comparison tools listed above over creating analogies, describing analogies as "confusing" and "challenging to create".

> "These less obvious comparisons work but when I'm trying to come up with them, I'm worried I won't get it right, compared to just saying it is the same as some other thing."

However, when challenged to describe smart materials radical innovations in particular, many designers had to resort to analogies to accurately describe the material. This implies that in designers minds there is no other way to create comparisons for these attributes.

The role of analogies in teaching is a distinct area of study, with some considerable work published on the matter (Aubusson, Harrison et al. 2006). It is possible to find a number of guides on how to create useful and practical analogies between two systems. An investigation of these systems was explored in the literature review. The reason that Genter's analogy framework is most applicable is that it allows for the creation of analogies by building a method to ensure that the base and targets systems are similar while allowing aesthetic attributes to be excluded. The framework is discussed fully in literature review and can offer a comprehensive guide for those trying to create analogies to communicate materials.

6.3.5 **Understanding the role of context**

Context was one of the four tools identified as commonly used by designers to communicate materials. Contextual communication illustrates a scenario where the material being communicated is used in an application where it would excel. In particular, this scenario focuses on applications that utilize the radically innovative material attribute that is being communicated.

An example of a contextual communication is saying that 'D3O would work well as part of motorcycle safety clothing. This statement allows the designers to see how the materials radical innovation could be used in a practical example, as D3O is a dilatant material it can respond to impacts, so it has the benefit of being flexible and then hardening when struck. This attribute is important for motorcycle jackets allowing them to be flexible garments that can still protect users in a collision.

This contextual communication plays a vital role in the three-step communication system as it both continues to inform designers about material properties but also allows designers to check their understanding of the communication as a whole. In focus groups, this system of having a physical application was considered invaluable because designers could then see if their understanding of the properties of the material aligned with the proposed use.

> "When you give an example, I can play out the idea in my head, if what I thought doesn't line up, I know it is not right. When it is right though I get to tick it off as understood."

Outside of its' role in helping designers assess if they've understood the communication, contextual communication also aids comprehension. By illustrating how the material can be applied it allows designers to see where the strengths of the material lie and how the innovation can be used. Doing so is reported to help designers' picture other uses for the material, aiding them to create new designs that accurately use the material.

> "The cellular metal being used in sports cars made something click. I imagined on boats, in planes, all sorts of places where something light and strong would be perfect."

When using this framework to create a contextual communication, users will need to be aware that the context chosen needs to fulfil specific criteria to be effective.

Contextual communications need to choose applications that use the radically innovative material property. The application of the context needs to ensure that the scenario makes significant and obvious use of the property the communication focuses on. In an ideal situation, the context is one where without the property, the material would not allow the scenario to function effectively. By having an application where the material *needs* the attribute being communicated, it showcases to the designer how the attribute enables that design. This helps them comprehend the nature of the material. Designers flagged this issue in focus groups.

> "Why does it talk about D3O in helmets. Helmets are already hard and soft stuff layered, why does it matter that you've got a material that does both if in the example you've still got a hard shell on the outside. You don't need the D3O, just need better padding."

Contextual communications must be relevant to designers. As with comparisons, the context must be relevant, being both known and understood by the designer to function. If it does not have these attributes, it will not enable the communication effectively as designers will not recognize what attributes are necessary to function effectively in the scenario.

6.3.6 **Communicating limitations**

When analysing the results of the first workshop series the partially feasible concepts created were not fully feasible because the designers overestimated what the materials could achieve. For smart materials in particular these overestimations showed that while designers had understood the potential application, the limitations were not understood. For materials which are not smart communicating limitations is best achieved by ensuring the description of the material is accurate and thorough. If materials are communicated well with their attributes labelled clearly then designers can use that knowledge to build their own understanding of the materials limitations. However, for smart materials this is not a viable approach. Smart materials have an ability to dynamically react to their environment, but exactly how they react can be limited. For instance, D3O has the ability to get harder when struck but there is a limit to how rigid the material can get before it shatters, equally this hardening affect isn't as good against sharp piercing damage. This limitation must be communicated in the description and there are two potential methods to do this.

Clarify within existing communication: When either the subjective or comparison tools are being written the limitation must be explicitly added to the communication. This may involve naming the specific limitation of the material as part of that communication. An example of this type of clarification is below. Photochromic ink has the ability to change colour when exposed to sunlight. It gradually shifts from one colour to another. It cannot change between more than these two colours.

An example of a three-point communication without clarity.

Photochromic ink changes colour when exposed to the UV light, acting like skin becoming sunburnt, it works well in anti-counterfeiting applications by hiding UV sensitive data.

An example of a three-point communication with clarity.

Photochromic ink changes **from one colour to another** when exposed to the UV light, acting like skin becoming sunburnt, **before rapidly returning to its original colour,** it works well in anti-counterfeiting applications by hiding UV sensitive data.

Add extra details to the comparison

The other approach to communicating limitations is in adding additional information to the comparison component of the communication. Adding extra details should build on the comparison or analogy being used rather than adding a separate step to the communication. This can be enabled for smart material by expanding and carefully considering the analogy being used. An example of this extra detail is below.

D30 becomes more rigid when exposed to jerk forces but can become brittle and shatter or break when exposed to extreme forces. If this force is from a piercing strike the material also has limited ability to react as the material cannot spread the force.

An example of a three-point communication without added detail.

D3O is a rubbery plastic that gets more rigid the harder it gets hit. The reaction is like falling into water at low speeds the water moves around you but at high speeds the water feels more solid. D3O works well in making flexible and protective clothing for sports like snowboarding.

An example of a three-point communication with an added detail.

D3O is a rubbery plastic that gets more rigid the harder it gets hit. The reaction is like falling into water at low speeds the water moves around you but at high speeds the water feels more solid**, like water this resistance can be overcome by either, moving so fast the water is blasted out of the way or by diving, allowing you to cut through the water**. D3O works well in making flexible and protective clothing for sports like snowboarding.

6.3.7 **Using innovation categories to improve the communication for radical innovations**

In the prescriptive study an assessment of radical innovations in materials was carried out. This assessment found that there were nine distinct types of radical material innovation by attribute. Further testing was conducted to see if there was a difference in which tool designers preferred to use when discussing the material. This questionnaire found that there was a preference by material type for specific forms of communication.

In this assessment, it is possible to see that comparison is in most cases the preferred method to communicate the material. This aligns with testing showing it is the most popular form of communication. Some other categories do prefer different communication methods. The fundamental way this knowledge can be applied to the three-part communication tool is to highlight which of the three parts should have the most significant focus in the overall communication. It also highlights that the preferred element needs to be as accurate as possible as designers will most likely base their communication of that tool over other tools. In some cases, there is a preferred tool and one that was also considered particularly effective. In these scenarios, both the primary communication tool and the secondary communication tool require particular focus to produce better communication.

6.4 SUPPORTING THE THREE-PART COMMUNICATION FRAMEWORK WITH ADDITIONAL INFORMATION

While the three-part communication framework focuses on communicating the radical innovation, there are other aspects of the material that must be communicated. While some of these aspects fall outside of helping to communicate the radical innovation, one aspect that does aid the communication of the radical innovation and is in high demand by designers is explaining what material category the radically innovative material belongs to.

> "Which kind of material we are talking about is always front of mind, if you're still trying to work out if it is a plastic or composite or whatever halfway through the explanation I'm going to be really confused."

Communicating the category, the material belongs to helps designers picture the material and enables them to help understand what its physical properties might be like. This is considered invaluable to designers, some of whom expect it to be the first thing communicated about the material as it shapes their understanding from that point onwards.

> "I need to know what we're talking about first. I just want to understand what kind of family it belongs to so I can get what we're talking about."
>
> "When you tell me it is a plastic, from there I can work out a whole load of things about how it might be shaped, where it will work where it won't, lots of stuff. It also means I'm more likely to get why it is special."

The material category is the same form of generalized categories used by material libraries. Examples of these material categories, mentioned by designers, are…

- Metals
- Plastics
- Ceramics
- Composites
- Woods
- Fabrics
- Natural materials
- Smart materials

These categories are not exhaustive though and there is also potential overlap between material categories (plastic-based fabrics are typical). These categories are not specific and on their own do little to help communicate the qualities of the material but designers feel they play a vital role in the understanding of the material similar to the subjective description, the information helps signpost what is important or different about the material.

6.4.1 Communicating the non-radically innovative material qualities

While this research has worked to explore how to communicate radically innovative material qualities, it is essential to note that there is no evidence that current communication techniques used by material libraries are not valid at communicating non-radically innovative material qualities. The current systems that are used by different organisations are still relevant to communication and there is no reason not to use those methods to communicate the other material properties. In fact, the assessment conducted in the literature review found that there are a number of similarities around how the libraries communicate materials. This consistency may show that this is a practical approach as so many have made use of the system.

When communicating the material, designers will be interested in finding out more about the attributes the material has outside its radical innovation. This can best be served by using reasonable means of communication formalised by the material libraries. Examples of how this can be completed can be seen in the literature review. This can be provided after the three-part communication.

6.5 Framework process summary

- **Identify what category the material belongs to:** identify what kind of material category or categories the radically innovative material belongs to so it can lead the communication.
- **Identify the materials radical innovation:** it is up to the user to identify the materials radically innovative material attribute. If in doubt they should assess the material to see what aspects of its nature can be described by definition or radically innovative provided in the introduction.
- **Identify where it sits in the radical innovation categories:** Use the radical innovation category map, to identify which innovation category the radical innovation attribute fits into. This also gives insight into what aspects of communication should be focused on.
- **Construct a three-part communication:** Look to construct the three-part communication giving special consideration to the communication tools highlighted by the radical innovation category.
- **Build your subjective description:** Establish the language that best describes the innovation and will be understandable by designers.
- **Build your comparison:** Create a comparison that allows designers to take their knowledge of existing materials and apply them to a new material. Choosing from the different communication techniques to ensure the communication accurately describes the innovation. The comparison must also be relevant and offer a rich and clear comparison between the materials.
- **Build your contextual description:** Create a contextual scenario that shows off the materials radically innovative ability in an application that designers will recognize and understand why the attribute is relevant.
- **Ensure other aspects of the material:** Look to material libraries for inspiration on how to communicate non-radically innovative material attributes.

6.6 Summary of the chapter

In this chapter **research question, 4** has been thoroughly explored. The form of the communication system would best serve to be a framework. The system needed to be adaptable to the emergence of new materials and allow the user to have greater latitude in how they explored their options. While creating a tool-based system was considered, it was seen as too likely to be limited and be unable to adapt to the very diverse and ever-increasing range of radical material innovations. The majority of the chapter focuses on bringing together the research from the literature review, descriptive study 1 and the prescriptive study to create an understanding of how the framework should function. This chapter brought together these topics and combined those consistent themes or those which featured highly in any of the distinct pieces of research. The end result of the chapter was the production of a prototype framework which would allow material communicators to process their understanding of the material and create a communication suitable for designers. This process was repeatable and while giving a great deal of freedom to the creator of the communication, it also prescribed some detailed suggestions as to how best to achieve each specific goal.

There is now a distinct framework that should enable material communicators to communicate radically innovative materials. The system is based on the learnings of the last seven chapters. With this system now in place, it can start to be tested allowing the exploration of **research question 5**.

The next chapter will look to explore how useful the framework is through a series of workshops. This workshop series will allow the designers to explore the communications created by the framework developed in this chapter. The results will be compared to those of the workshops from the first descriptive study. The comparison of the two should provide insights to answer **research question 5**.

7 DESCRIPTIVE STUDY 2 AND VALIDATION

7.1 INTRODUCTION

In descriptive study 2, the goal of work is to assess if the system created in chapter 6 is effective at communicating radical material innovations to designers. In addition, to answer **research question 5**, the effectiveness of this communication will be assessed against the results of descriptive study 1's workshops. As the test is identical in most ways to the first workshops. The core difference would be how the materials are explained.

While the old workshops used the tools and methods that are currently popular, this new test used communications based on the new understanding developed over the course of the research presented in this thesis and developed to answer **research question 4.** While the rest of the test remain identical, this change allows for a comparison of the two techniques. By comparing the results from each test, it can be established how effective new communication is compared to old communication. This 'effectiveness' is established wholly by how the ideas generated at the end of the test.

In the first test, it was established that of the ideas generated by members, over half of them were not feasible. This meant that in most cases, the communication provided by manufactures and supported with information from current material libraries failed to communicate the content effectively. The goal of the new workshop is to increase the percentage of feasible ideas and completely eradicate 'impossible' idea creation. If this can be shown to take place, then it can be argued that the outcomes generated through the research in this thesis have resulted in improving the communication of radical materials. This insight provides an answer to **research question 5**.

7.1.1 Participants for the second series of workshops

In these tests, the selection of participants aimed to be as close to participants of the first workshop series. As with the earlier tests, these participants were sourced from numerous universities and professional design consultancies. Each group had a minimum of two years of undergraduate or equivalent training.

The courses the students were on were all product design or industrial design focused. The professional designers' companies were all focused on the production of physical designs and considered themselves to be product or industrial designers.

A breakdown of the participants is shown below,

Type of design experience	**Number contacted**	**Proportion of those canvased**
At least two years academic design knowledge.	49	40%
At least two years academic design knowledge and some professional experience	34	28%
Professional designer with at least two years professional experience.	39	32%

Table 29: Participants for the second workshop series

These participants were met at their places of business or at their universities under the supervision of their teachers.

7.1.2 Testing concerns and limitations for the second workshop series

This, however, cannot be a perfect test by the terms of the scientific method. In most perfect tests, only one element changes. The most crucial change was altering the communication technique, due to the design of the test, another change had to be made (Cohen 2011). In the original workshop participants were introduced to 20 new materials they had never encountered before. The challenge was to educate them on those materials then. In this new workshop, the same people could not be introduced to the same materials, so a choice had to be made between introducing new materials or new people.

It was decided it was better to introduce new people rather than new materials. As each radical innovation can be completely different, it would be challenging to select similar parallels for each material. However, new participants could be selected who closely resembled the original groups. This was done by selecting from similar courses and companies to the first workshops.

In addition, the materials chosen could be a factor in influencing the test. While the selection of the material remained the same, the spread of materials chosen would also be monitored. If the selection of materials was radically different to that of the first workshop, there was the potential that some materials may be inherently 'simpler' to understand and as such, account for a change in the results.

Table 26 below shows the materials picked in the first and second workshop. As can be seen, the overall difference is minimal with the same materials being preferred. Thankfully there was no need to account for a radical shift in materials selected.

7.2 APPLYING LEARNINGS TO GENERATE CONTENT FOR MATERIALS

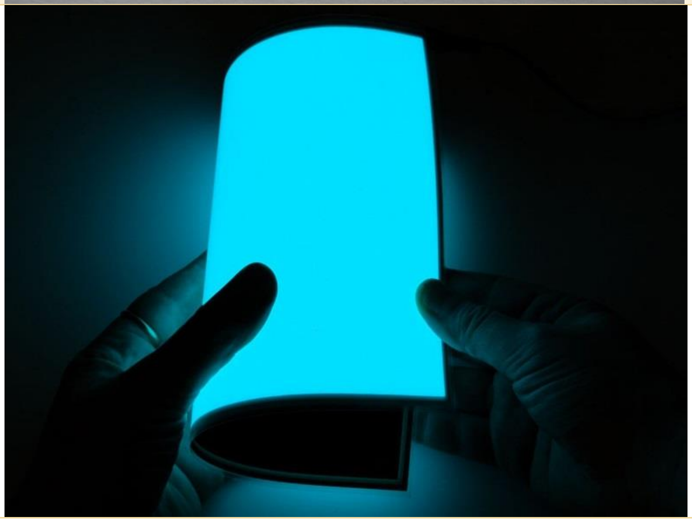
Each material from the first workshop series had to be converted into the communication method based on the research outlined throughout this thesis. There are three main stages to this process.

7.2.1 **Breaking down features**

In the first stage, each material needs to be broken down to its critical innovative features. The list below reflects the features of each material that are part of its' radically innovative nature. There is no precise way to break down each material and this feature list is taken from the material's own marketing information. Claims that are not connected to the radical innovation have been excluded.

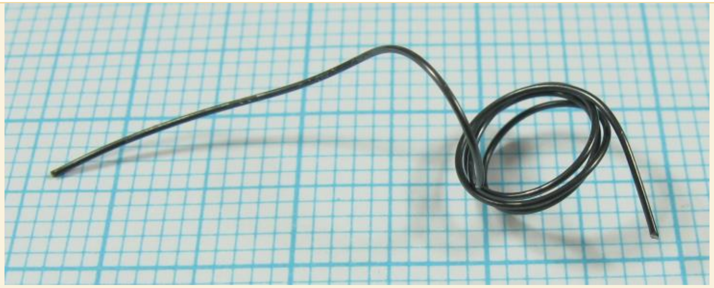
Material	Short summary of the material	Images of material	Innovative features
Fibre-optic fabric	Fabric impregnated with fibre optic strands, appears like a normal fabric but lights up when led is shone into the fibres. This fabric looks like a grey shiny synthetic and has a rough scratchy texture with the pattern of the fibre optic cables both visible and easy to feel. However, when a light is shone through it lights up in an organic manner.		Conducts light across the surface, is flexible, is a fabric
Bare Conductive Paint	Electronically conductive ink. Functions like a wiring when dry and can be painted on flat surfaces for quick results. Bare conductive was a recent start up that has gone from strength to strength. The has been a recent wave of conductive inks/paints and bare is one of the better solutions. In its dried form the paint can cold solder, draw circuit diagrams and be a touch interface. It's quite cool but often sees little use outside of home electronics kits and art projects. It looks like a normal black paint. Dries with a matte finish that's pleasant to touch.		Paint, Conductive when dry

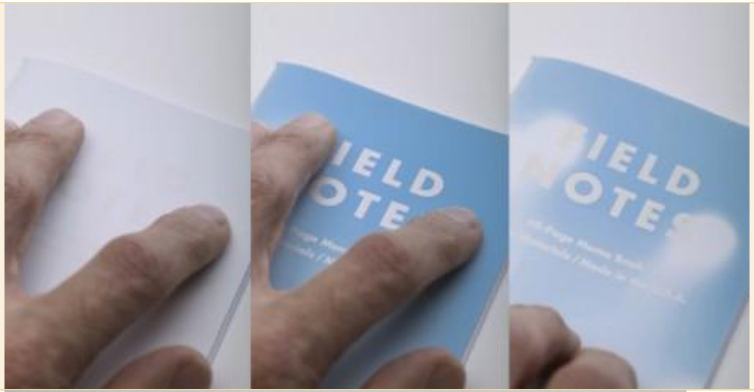
Faraday Film	Faraday film is a clear plastic film that has a conductive coating that can be made into circuits by scratching the surface. This film is completely clear with a very light tint providing a way to create completely clear circuits. Printed on a stiff plastic like cellulose it can house small low power circuits and components.		See-through, conductive, spray
Ferro-fluid	Oil impregnated with tiny iron fillings, reacts to the presence of electrical currents by attaching to the magnetic field and becoming more viscous. Ferro-fluid has been around for a while and you can find a lot of videos of the odd patterns and shapes the liquid can produce. However, the practical uses of this material have been so far limited to engineering applications. While its limited use in design is understandable as touching Ferro-fluid is a good way to get stains all over your hands it has some unique properties that make it different to anything else on the market.		More viscous under magnetism, maps magnetic fields in three dimensions

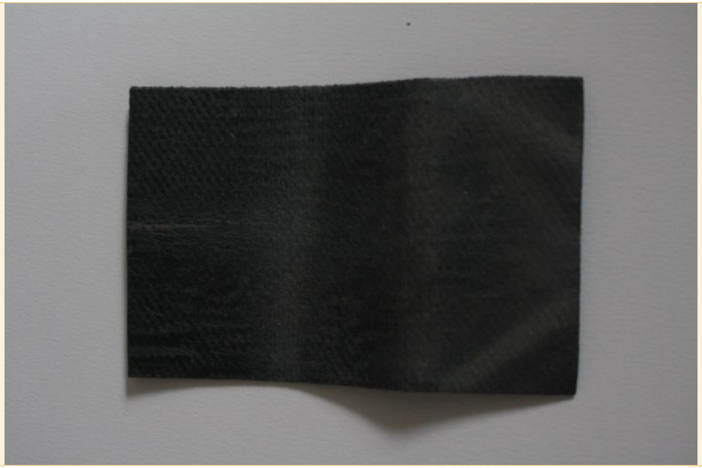
UPM Formi	Polypropylene filled with 30-50% natural fibre, making stronger and stiffer than most plastics UPM is a satisfying plastic to hold it has smooth satin finish that is quite nice to hold and a warm stiff feel to it. Looking at it there is very little to indicate that up to half its content is from cellulose fibre it's for all appearance a less flexible polypropylene. This material can reduce the impact from the plastic by 30%-60% and as polypropylene is one of the most common plastics in consumer products it may be really good option.			Bioplastic, fully food-safe, high heat safe
EL Panel	These are panels of plastic with a thin layer of electro luminescent coating that emits light when electrically charged. Often seen as a bit of a Tron look El panels are flexible thin laminates which glow when they have power running through them. The material feels like a thick card and is encased in something like cellulose. The light it gives off is pretty good, but they are power hungry and large panels requires a power supply to get the full brightness. They can be worked on with conventional materials however they are sensitive to damage and can be easily broken if creased or cut in the wrong way.			Emits light, is flat and bendable, waterproof, functions in extreme temps

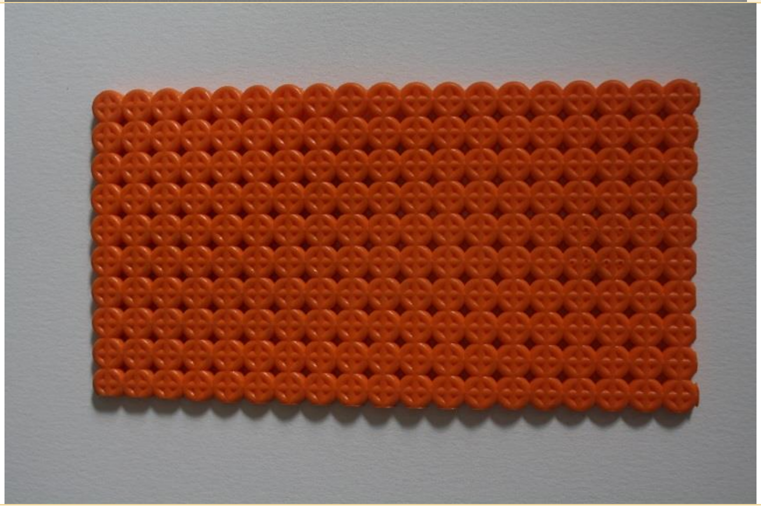
Cellular metal	Small spheres of sintered metal, with a very high strength weight ratio. Cellular metals are a distinctly odd material to hold, they feel light and gritty, but you can sense their strength if you try and compress them. Even taking a single bead which weighs next to nothing you can't compress with your fingers alone. Commonly found in crumple zones in cars to help absorb damage this lightweight material may have many more uses			Light, weigh, formed with individual components, the shape can be easily defined by the sintering mould
LifoCork	LifoCork is a plastic that contains shredded cork to gives it a nice cork texture and reduces the use of plastic. Cork is a great renewable resource, harvesting cork doesn't kill the tree that it is grown on, and it can be seen almost as a crop. The downside is that cork on its own is quite soft and not suited to heavy use. LifoCork takes the renewable cork side of things and wraps different plastics around cork granules to produce a wholly new material.			Made from cork, is very light, removes harmful chemical waste

Intumescent foam	Foam that expands when exposed to high heat and after exposure chars stopping heat conduction. This foam is primarily used to protect buildings from fires as it allows for airflow in normal conditions but during fire expands sealing gaps and stopping oxygen flow. The foam is surprisingly spongy and cool to the touch, small bits of graphite can be seen in the material which is otherwise a dull ruddy brown.			Grows when exposed to heat, non-reversible, chars like wood absorbing heat
Phase change fabric	Phase change materials can manipulate heat in really special way. They slowly absorb heat feeling unnaturally cool on the skin and then slowly release that heat as it cools down. The material is available in a few forms, but we are going to look at a great sample of Outlast cloth we have in the office. This is designed to be added to other clothing either in direct skin contact or in-between layers and feels unnaturally cool to the touch but given the nice weather it's quite pleasant.			Absorbs heat, releases heat when cooled, storage amount is defined by the quantity of the material.

Nitinol wire	Nitinol wire is a shape memory alloys (SMAs) are a smart material that can 'remember' a shape. SMAs will try a return to a remembered shape when heated. The effect of nitinol wire has to be seen to be believed, the odd metal will happily change shape and unknot itself. The shape change also exerts some force when doing so allowing it to be used as an actuator. The material gets some use in engineering and medical applications but considering its unique properties it should have some more uses by now. Mostly it can be purchased with a memory of being straight or as a spring, but other samples do exist.		Changes shape under heat, remembers past shapes, creates a force when shape changing
Bright green	Bright Green is an awesome preserved moss where all the water has been replaced with glycine, so it does not decompose. It's feels like a cross between a living organism and a rubber plant, but it thinks that's mainly the dryness. As for colour I've had it on my table for couple of months now and it's showing no sign of degradation. The moss is very pleasing to look at and anyone who wants a perfect green sign to look no further.		Made from actual plants, can be grown to shape, highly durable

Photochromic pigments	Pigments that react to light by changing colour on exposure. The pigments can be mixed into plastics or varnishes and change colour after while exposed to UV light. The colour changes are gradual but fairly swift with about 30 seconds in direct sunlight being enough to change from one colour to another, though that depends on the exact type of pigment and the material they are embedded in. The colour tends towards the more pastel with vivid colours either impossible or hard to obtain.		Changes colour due to exposure to light, reverses after light source removed
Fiberline	Polyester reinforced with layers of carefully aligned glass fibre. This plastic is stronger, harder and more durable than other plastics and can perform well in tasks that other plastics would not be able to stand up to. It should be noted it is different to fibre glass which is glass fibres in a resin. Instead this is where the plastic and fibre are carefully aligned to a specific geometry for the application though some cheaper version exist which merely use the glass as an additive.		Incredible strength to weight ratio, highly durable, very formable

Shape Memory Polymer	Plastic that can remember its prior shape after remoulding at low temperature, will return to this shape if heated again. Suitable for moulding with thermoforming methods like injection moulding the plastic can have come in different shapes. After forming unlike shape memory alloy, it cannot be reprogrammed short of completely melting and reforming the plastic. However, after heating past 70° the plastic can be deformed and cooled to now have a new shape. Bringing this new deformed shape up again to 70° will cause the plastic to return to its original shape.		Changes shape under heat, remembers past shapes, creates a force when shape changing
Microsuction tape	Micro-suction tape offers an alternative to most adhesive products like glue and tape by using a layer of microscopic suction cups, each a tiny bubble cut in half that when pressure is applied act together to grip with a lot of force. The black tape looks like a piece of bog-standard black rubber but it's holding force is amazing, 5 square centimetres and it will be difficult to remove any thing small if you don't have a good grip.		Surface acts as a suction cup, infinitely repeatable action

Dry Inside	Dry-Inside has an apparently unique property, water can only move through it in one direction. Dry-inside works because it is treated to be hydrophobic on only one surface, this makes a gradient that pushes water away from that side to the other side by wicking along the material fibres. The resulting effect means that the water will be pulled through the material leaving the hydrophobic side dry. This allows it to move liquid water rather than just water vapor effectively making the hydrophobic side waterproof in one direction.		Forces water from one side to other, one side is unwettable
D3O	D3O is a material with a rare feature when impacted upon it becomes harder and more rigid while being flexible in its normal state. It has surged into the forefront of the protective clothing industry as a result. It comes in only orange, but the rubbery plastic allows for thin flexible shapes to be made which massively increase the impact absorbing qualities of any product they are incorporated into.		Hardness has increased in reaction to being struck, becomes more brittle less flexible, immediately reverses after impact

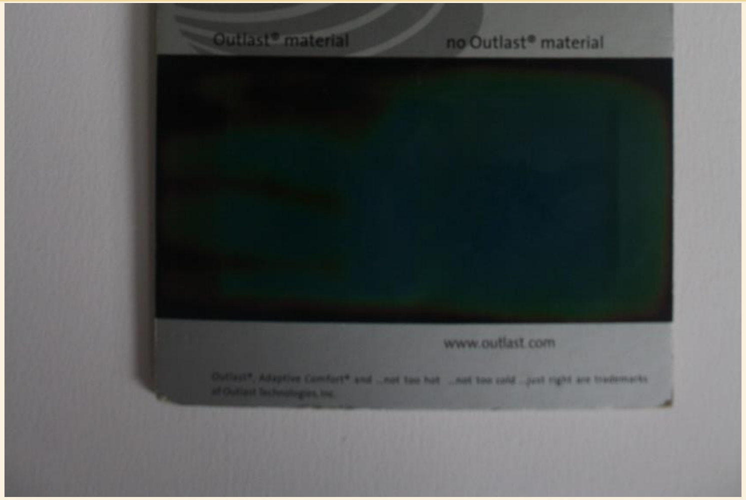
Thermochromic sheet	Thermochromic pigment is a smart material which changes colour in reaction to differences in heat. You will most likely to have encountered it as a novelty item often on mugs that rely on the most prevalent type which becomes transparent when heated revealing a message. The colour change actually comes from the microscopic change in the material composition when heated that causes the crystal structure to realign. The accuracy varies between different products some are so accurate they can be used as thermometers while others require boiling water to make changes happen.		Colour changes due to heat can accurately reflect the temperature of objects

Table 30: Assessing innovations of materials being tested

7.2.2 **Sorting by type**

In the first stage, each material had to be filtered by using the innovation map. Each material was examined and filtered into the according to groups. How the materials mapped out is recorded below, it is worth noting that many materials appear in more than one category. Each material may have multiple innovations that make it radical and rather than bundling together it is essential to split them up to be adequately explained.

New Form	**Improve attribute**	**Irreversible change**
Cellular metal	Cellular metal	Bare Conductive
Bright green	Fiberline	Intumescent foam
Hybrix		
New material	Remove negative attribute	Reversible change
UPM Formi	Cellular metal	Ferro-fluid
LifoCork	Fiberline	Phase change
Bright green	Hybrix	Nitinol wire
	Bright green	Photochromic pigments
		Shape Memory Polymer
		D3O
		Thermochromic sheet
Reduction of by-product	Add an attribute	Affect without change
UPM Formi	Faraday Film	EL Panel
LifoCork	Microsuction tape	Phase change
	Fibre-optic fabric	Microsuction tape
		Dry Inside

Table 31: Assessing which category the material innovations belong to

When the materials were first selected, an intentionally diverse range was used. This means that each group has at least two representatives who will allow testing of all groups outlined by the innovation map.

7.3 GENERATING EXPLANATIONS

7.3.1 **Three-pronged explanations**

Explanation generation follows the guidelines set out in the innovation map. Each explanation though needs to be crafted for the individual feature it is trying to describe. Most explanations contain three parts, Subjective, Comparison and Context.

Subjective is most often used first to bring attention to the feature being described. The comparison is used to explain the feature. Context has used the end to clarify potential uses. This three-pronged description gives little room for confusion and is simple to create.

For example, Faraday film is transparent and conductive, functioning like wire or conductive plate made of clear plastic. It is currently used on aircraft windshields to give them a conductive surface without reducing visibility.

In this example you can see all three tools working together, the subjective description brings immediate attention to the essential features, the comparison explains the functionality, and the context ensures the material can be pictured working.

Focus groups supported this system, and it is supported by prior research. However, it does vary based on innovation type. Some of the radical innovation types prefer different focuses for communicating the property. Chart 28 describes each material type and preferred method of communication, how this works with the three-pronged explanation and then provides an example using material from the workshop.

Innovation type	Preferred	Scene Setter	Explainer	Summary
New form	Comparison	Subjective	Comparison	Context
Cellular metal		Cellular metal is a very light but strong steel structure.	Made of hollow polystyrene like balls it is bonded in shape like polystyrene packaging. All the sphere makes it as light as many plastics while retaining much of its strength.	It is useful in the crumple zone of cars as it is strong and light.
New material	Subjective	Comparison	Subjective	Context
LifoCork		LifoCork is like a wood-based plastic.	It is used cork to replace most of the silicone in the mix.	It is great to natural looking grips for handlebars.
Reduction of by-product	Context	Subjective	Comparison	Context
UPM Formi		It is an eco-plastic.	Compared to regular plastics it produces 95% less carbon emissions.	It is good for all traditional plastic roles.
Improved attribute	Comparison	Subjective	Comparison	Context
Fiberline		It is a strong and tough plastic.	It is got a similar strength and toughness to steel but doesn't weigh as much.	It is been used to build a bridge that was airlifted.
Removed negative attribute	Comparison	Subjective	Comparison	Context
Bright Green		It is a plant that will never wilt.	Bright green is like a preserved animal, all the parts that can decompose have been removed.	It is good for natural looking permanent displays.
Add an attribute	Comparison	Subjective	Comparison	Context
Faraday film		It a clear conductive coating.	Faraday film is like a grid of invisible wires if cut they can be used to create circuits.	Used to help display content on shop windows.
Irreversible change	Metaphor	Subjective	Metaphor	Context

Bare Conductive		It is a conductive ink.	Like oil paint that goes from liquid to a permanent form bare conductive does much the same, able to be worked with and shaped until dry.	It can be used to draw circuits on paper.
Reversible change	Metaphor	Subjective	Metaphor	Context
PCM material		It is a material that absorbs body heat and then releases it.	PCM is like a heat battery, like a battery it can store a certain amount of energy drawing it from a power source, until it is full. It then discharges it later. PCM does this with heat, charging up when warm, up to a limit, and then discharging when cold.	PCM works well to regulate your body heat when jogging.
Affect without change	Metaphor	Subjective	Metaphor	Context
Dry inside		The fabric pushes water to one side of it.	Working like a hill, water will fall from to top to the bottom, though too much water will sink the hill and too much pressure will push water uphill.	This is good for clothes that can keep you dry.

Table 32: Generating three-point communications for the innovative materials

7.3.2 Comparison

Generating a comparison uses the tools laid out in chapter 6. In this tool, the feature is broken down into what it provides, and another item that is more relevant to designers is chosen to act as a baseline for the comparison. In the focus groups, it was found that designers prefer comparisons to conventional materials. Alongside selecting common materials, it is essential to use common words to explore them

Features are then framed through one of three tools. If these are not enough to fully describe the material, then stacked comparisons were used as well. Picking a comparison is of pinnacle importance.

- Direct comparison.
- Direct comparison with property qualifier.
- Direct comparison with a numerical qualifier.
- Stacked comparison.
- Analogy

7.3.3 Subjective

Subjective comparisons are relatively simple. The material feature is described subjectively by the researcher to try and communicate the material's property. To ensure that others can benefit from this subjective description, the researcher needs to ensure the descriptors are as unambiguous as possible, avoiding terms that are likely to be misunderstood by others. They should also avoid colloquialisms and industry-specific terms. These restrictions ensure the terms are as clear as possible to the broadest group of people.

Examples of Unambiguous terms	**Ambiguous/colloquialisms/industry terms**
Soft	Friendly
Hard	Emotional
Tough	Authentic
Strong	Cool
Heavy	Fresh
Stretchy	Multi-Sensory
Flexible	Weak
Fragile	Warm

Table 33: Example of subjective descriptions

7.3.4 Context

Giving context for the use of the materials allows the participants to see the environment the material functions well in. Using this knowledge, they can then infer the qualities that the material should have to be able to function well in this role. When providing context, it is important to make it showcase the features of the material not to confuse the participant. There are two core ways to ensure that a contextual descriptor is effective.

- **Well-known context** – If the context used is of an item that is well known and understood, then it is very effective. For instance, a very common item in the world is a bike's frame. Bike frames are a great context as the materials needed for them are light, strong and rigid. If instead the context picked for that was 'formula one car chassis' the group who knows and understands that context is significantly more limited, though the properties required are identical.
- **The context provided requires specific properties to function** – When a context is selected, the properties the application demands of the material must match those properties the material offers. What needs to be avoided though is contextual examples that can be supported by many properties. Using bike frames again, the frame benefits from being light, strong and rigid. These properties cannot be replaced or easily substituted if the frame is to function. Compare this to a chair frame. Chairs certainly work well if they are strong, rigid and light. But equally some chair's frames are soft, flexible and heavy. This does not impede their function. This can confuse those being communicated to as what properties are relevant becomes unclear.

7.3.5 The results of the second workshop series

With workshops completed involving over a hundred designers, each workshop was as identical as possible, the results were collated. They showed a marked improvement over the original workshops. The average number of ideas generated increased, and the percentage of ideas that were entirely achievable with the radically innovative materials also increased by a significant margin.

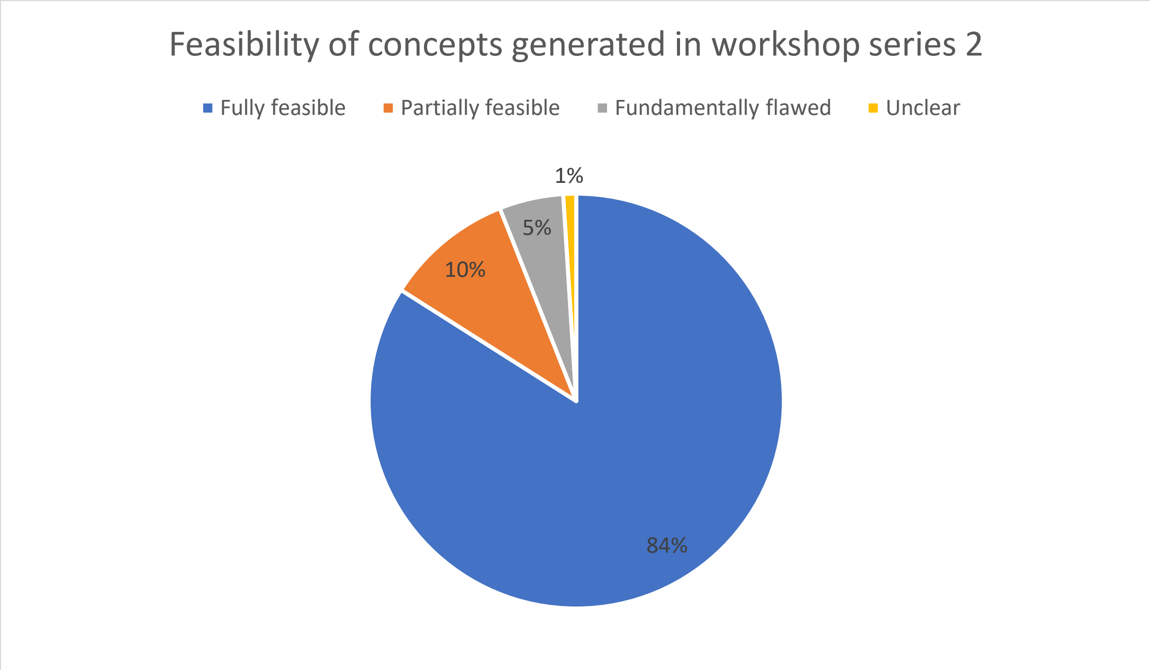


Figure 32: Assessment of the feasibility of concepts generated in workshop series 2

Of ideas generated, 84% were completely feasible. This comes from an analysis of 72 concepts generated from the second workshop. For an extensive break down of the results and their meaning please see the validation section below.

7.3.6 **Other feedback from workshops**

7.3.7 **Reduction in the copying of contextual examples to create**

In the first workshop it was observed that designers were creating similar concepts across different workshops, these concepts were directly analogous to the contextual examples. The hypothesis of the researcher was that the designers were using the contextual examples to create designs, that while feasible required minimal understanding of the material. An example of this – a contextual example of PCM fabric was provided that showed it being embedded into pillows to enable better temperature control in bed, designers then suggested that the PCM fabric could be used in wider bedding applications.

This trend of highly analogous examples and concepts was lowered in the second workshop series. In the first workshop series, up to 64% of the feasible ideas created could be deemed to be strongly analogous to contextual examples in the second workshop this fell to 42%. This change implies that designers were relying less on the contextual examples to create their designs. However, without additional research this cannot be stated for certain.

7.3.8 **Ease of understanding**

A few participants mentioned that they felt it was straightforward to understand the materials, commenting that they found it far more accessible than other methods. Others often agreed with them, stating that while other methods worked, the tested method was easy to comprehend and required little mental effort. The ease of communication has not been an area of study in this research. However, it is a good indicator as to the effectiveness of the tool.

7.3.9 **The success of the three-pronged description**

The three-pronged description tool was very effective, and a lot of feedback focused on how helpful it was. Some participants, while unable to articulate the exact structure of the description, did notice that the same pattern repeated in every explanation. The overall support for the concept was high. The results show it was effective. Examples of the comments that were made are below.

"I liked knowing what we were talking about for every material. You said that at the very beginning every time."

"The comparisons followed up by the example really helped me check that I understood the material."

"It was really helpful. Everything was explained the same way. I knew what to focus on, how it worked and then the example made it feel more real."

7.3.10 **Criticism of depth**

One of the criticisms levelled at the communication tool was that the information provided wasn't in-depth enough. With some designers wanting a very detailed account of the material and its abilities.

> "It is kind of frustrating not having all the details, I feel I have to make do."

While most designers were happy with the level of information provided, a small portion looked for more information. While there was a significant amount of information available for each material, further exploration found that these designers mostly had specific information in mind, with most wanting a complete accounting of the material's current applications. This particular research was inconclusive as to what designers wanted from this and exploration of this would need to be conducted in future research.

7.3.11 **Groups helped reduce communications being lost.**

One element that appeared across the research was the importance of groups. This was both observed and explicitly mentioned by the designers involved. As the designers worked in groups, they were able to correct each other and explore the concepts together. This ability will likely have influenced the success of the framework, with it being possible that the groups collective reasoning contributed to the creation of feasible concepts. Designers also showed appreciation for each other during the tests and openly acknowledged that other designers were helping them understand.

The influence of the group on the ability to communicate is consistent across both workshop series, with both tests using the group approach. The original logic was so that designers could work together to explore the material, but especially with the introduction of comparisons and context communications, it is possible that groups are actively supporting this communication process. The effect of this on the outcomes of the research is unclear. While it does not reduce the fact that the communication is now more likely to be successful, it would be essential to conduct further testing which specifically targets individual designers to ensure the framework is useful when designers are not working in a group.

7.4 VALIDATION

In this section the focus will be on validating the effectiveness and usefulness of the CRIM framework. In this sense validation means that the CRIM framework has a sound basis in logic and is reasonable in what offers and delivers. The validation of this work is split into two elements, firstly a focus on the testing results, comparing workshop series 1 – which used only currently available communication tools, and workshop 2 – which used the CRIM framework and currently supported communication tools. The difference in these two sets of results offers the first method of validation. As the two tests were functionally identical apart from the inclusion of the CRIM framework any change in designer's ability to create feasible ideas would be down to the CRIM.

The second part of the validation focused on reaching out to experts, both designers and material communicators were sought to give their feedback on the CRIM framework. By reaching out to several different experts with different backgrounds the question as to whether CRIM is 'reasonable in what it offers, and delivers' could be assessed. The experts could give feedback on if the results were significant enough for them to be interested by the tool and they could also explore the framework and give feedback on whether the system was reasonable to use. Combining both these elements would offer the validation necessary to understand if the CRIM framework has effectively helped resolve the challenges it aimed to.

7.4.1 **Validation through testing**

All the ideas generated were assessed using the feasibility assessment system outlined in section *3.4.6*, 84% were completely feasible, compared to 48% in earlier tests showing an increase of 38% feasible ideas. This comes from an analysis of 72 concepts generated from the second workshop series compared to 51 ideas generated in the first workshop series. This evidence shows that methods laid out above have improved the understanding and comprehension of the properties of the material. The increase in ideas can also be seen to show that the communication method has not hindered idea generation.

Misconceptions that previously caused ideas to be generated that required minor alterations have been, proportionally, severely reduced. However, fundamentally flawed ideas have not reduced in the same proportion (reducing from 6% to 5%). While it is likely easier to clear up misconceptions of those who had mostly understood the concept, the fact that this group remain shows the is more work to be done. There is the potential though that this group can never be truly removed as it may account for those who are not paying attention or are not strong ideators. However, this cannot be presumed and as such would warrant further research at some junction.

In addition to the analysis of the feasibility of the concept, there was also an assessment of the concepts generated. In the first workshop series, there were 51 ideas generated by 127 designers. In the second workshop series, 122 designers were able to produce 72 concepts. The increase in concepts generated despite the testing conditions remaining the same shows that the is potential that the new communications aided in either the speed with which designers processed the new materials or actively supported the design thinking process. The communications further supported the design process by reducing the proportion of concepts which were directly analogous to the examples provided in the communication. In the first workshop series, approximately a third of all the ideas generated were variations on the examples provided (for instance learning a material was used in motorcycle helmets and creating an idea that used the material in bicycle helmets.) In this test, only 15 ideas showed this highly linked relationship with the contextual examples. This increase in what can be seen as more unique ideas provides some evidence that the design thinking process is being supported. However, as this was not the focus of the test, it is something that should be explored in future research.

7.4.2 **Validation of the framework through interviews**

With the final workshops complete the tool was revised in some small areas. Once revised an explanation of the tool and the research process that was conducted to create it was given to six experts. These included three professional designers at different points in their careers and three material communicators working for material libraries or as part of teams who look to communicate new materials to designers. These interviews were conducted to gain insight into how both groups viewed the tool as well as the methodology followed to create it.

To conduct these interviews as consistent approach was followed, the researcher communicated to each interviewee the same information, this included:

- The origins of the research – covering the research's beginning in the Light Touch Matters project
- The research process – discussing the research covered in descriptive study 1 – the prescriptive study and descriptive study 2.
- The tool and its effect on communication – Covering the key elements of the tool and how it improved the ability of designers to create new concepts.
- The outcomes of the research – The creation of the final framework detailed in chapter 8.

Once this was explained the interviewee was encouraged to discuss the topics and they were asked four specific questions:

- What do you think of the process through which the research has been conducted?
- What thoughts do you have about the tool?
- How might it be used by you or your industry?
- Do you have any questions or criticisms?

Their responses were recorded and brought together. The aim is to understand how those in the industry perceive the tool and establish if they see it as valuable in improving communication amongst designers.

7.4.2.1 ***Interview 1 – Designer - Adam***

In this interview designer Adam was contacted for comment. Adam has worked as a designer for the last X years, and BA in Industrial Design. His particular specialities include the designer of medical products. Adam has some limited prior knowledge of this research but was given the same introduction as every other individual interviewed.

Thoughts on the research process: Adam approved of challenging designers to create designs using the material. He felt that this created the ability to actually test their understanding. "I think that makes the research really clear and it makes sense as that's what I'd expect to be able to do." Adam didn't otherwise question the research process.

Thoughts on the tool: How they imagined their industry using the tool: Adam explored the fact that he felt the use to him would be limited as; "The majority of the work I am involved with if medical and they are very conservative with using new materials." He did also felt that in design consultancies he had experience of the tool might not have the most use due to the frequently tight timelines they were under, 'I'd say being in consultancies as well it would be tough to use. Our timelines are quite short for those pieces of work and we don't necessarily have the scope to easily incorporate new materials into the design.' However, Adam clarified that is more a reflection of using any new materials not just materials communicated using the tool.

Adam did explain that he felt the best place for this tool was to be used by in-house designers or in conjunction with data sheets. For the in-house designer he felt that had more freedom to explore the options available to them, "I can see this being more like the tool I can go to if you're like an in-house designer. Where it's like, is this new material? Can we do something with this?" The value to them was that with looser timelines they could look to build the material into their work compared to consultants who often dealt with clients who knew what they wanted when they contacted him. He also felt it could support datasheets which he viewed as 'really need that level of detail' but he also noted that they could be hard to understand and the 'marketing spiel' at the top rarely was helpful. He noted that currently data sheets are 'what's available' and lack clarity, often being so detailed that they miss what is important about the material. In Adam's opinion is allowed designers to ask. 'Can I use this material; will this material support that concept and allow us to do the thing we want to do.' Which he felt would be a useful addition

Criticisms and questions: Adam's big question was around manufacturing. He felt that it needed to really clear how you could shape the material and 'make it work'. Adam stated that a key question he felt was unanswered was 'What's the status in the terms of making a part of this material? Like how that is going to work?' He felt that the tool was missing was a clear guide on how to shape the material and manufacture it as that is critical to the work of designers. He felt that is was essential to be able to communicated to clients and others that this would work, explaining 'When working with a new material you've got to kind of reassure them that no, this is something we can implement, we can make this'.

7.4.2.2 ***Interview 2 – Designer – Linda***

Linda was contacted for an interview. Linda has a long career in the design field having worked on range of projects including the development of the memorial fountain for Princess Diana. This work has for, many years, been through her design agency which she owns with her husband. Her career has given her a great deal of insight into the process of getting new materials into the hands of designers, she believes this is so important that she helped to find the Materials and Design Exchange to further this goal.

Thoughts on the research process: Linda was interested in how feasibility was calculated. She felt that the process of having the different levels of feasibility was essential as in her mind the 'is a significant gap between understanding and not understanding.' She approved of the system used to assess these levels. She also liked the process of challenging designers to use the materials as it enabled them to 'do a real exploration,' of what it would be like to be using the tool in a practical setting.

Thoughts on the tool: Linda felt that the tool offered a valuable addition to the communication of materials, a big part of this was because she felt it would allow for consistency in communication, something she feels is difficult currently 'I think that if you can have one sort of system like this is proven to be effective. It's much easier to keep that explanation.' She also felt that this would be a benefit as the text was more memorable than the complex explanations that had come before. This was valuable in her mind as it stopped 'the entire Chinese whispers scenario,' that she currently perceives. This being a situation where each retelling of the innovation is subtly different as each person explaining it remembers it slightly differently, ending up with those who hear about it through a chain of people understanding the concept as wildly different than it actually is.

She felt that the benefit of the tool would be felt most by those on 'a longer timeline, like architects.' She felt that currently most designers struggle to have the time to include new materials, often having to push back on clients to get the time needed to explore new things. She felt there was a role for the tool in design and that was to help educate designers about the materials in general so they were more aware of their options, but didn't see it as something that would be used by every consultant, again this was more to do with their timelines and the fact that 'they don't use new materials anywhere near often enough,' rather than the tool itself.

Criticisms and questions: Linda's only criticism was that the process could have involved more tests to take the materials through additional design stages. 'It would be interesting to go further.' This is in part due to her experience of the challenge of introducing new materials to designers which she is familiar with due to her work with MaDE, and she felt that the has been a lot other work in this area that has never be realised. She felt having a full design process, supported by the tool, being monitored would perhaps have been better proof to her and others.

7.4.2.3 *Interview 3 – Designer – Alma*

Alma is the innovation manager at the Crafts Council, where she looks to develop innovative initiatives with a wide range of designer and makers. She has worked as a designer in the past and has a wide range of knowledge of around the use of new materials by small design groups.

Thoughts on the research process: Alma challenged how the feasibility was assessed of the designers. She liked the fact that there were different ways to assess to what degree the concepts were feasible as 'the designers could have got it mostly right and that's different from getting it mostly wrong.' She liked the assessment system and felt it was 'robust'.

Thoughts on the framework: Alma felt the tool had a great deal of value, her work brings into a position where she connects designers with material specialists and she felt that this would be invaluable to improving that process, 'we bring together a lot of people and they don't know how to work together.' She was particularly taken with the use of comparison, 'I work with lots of makers and they all talk in terms of stories and metaphors, I really think this will speak their language and be easy for them to pick up.' The use of comparison was important as Alma felt it would work well with the contextual explanation to fit with how the designers and makers, she works with currently think. In her opinion the tool has the opportunity to 'bring together people from different areas' which she currently finds challenging and is pleased to have something that can support her in that goal.

Criticisms and questions: Alma felt that the materials possible production methods needed to be covered in more detail. She feels that a lot of designs are built on presumptions of how they look rather than how they are manufactured. 'These new leathers are more like felt in some ways, but people see leather and try and use it like leather.' Alma felt that the tool should highlight this manufacturing element to help bring context to the design and allow the designers to see the full spectrum of what they can do.

7.4.2.4 *Interview 4 – Material communicator – Veronica*

Veronica Sarbarch was first involved in this research when she arranged for the workshops in Italy as part of the descriptive study 1, she was not involved outside of that connection. Her background is in materials, she was worked for Material Connexion for nearly 5 years helping to support their innovation projects with the EU.

Thoughts on the research process: Veronica felt that the research process was clear as it helped to build up from the original workshop series to having a clear proof of improvement in second workshop series. 'So, you can see the difference between when you started and the end result, I think that's really clear.' Veronica also felt that the topic of the research was very relevant as she was currently involved in projects with similar goals, 'it's really interesting what you're doing because we are involved in a European funded project that is dealing with design teaching methodologies for emerging materials and technologies.'

Thoughts on the framework: Veronica felt the tool could be very useful to support her work. She acknowledges that there are 'some periods where it may be difficult to understand what the material actually is able to do.' She felt that a system that supported this could be valuable as it would allow for more consistency in the communication. In her opinion the consistency and simplicity would make training more effective, 'It would be helpful for consultancy activities, it would be useful for internal training as I think this is from communication wise, much more understandable.'

Veronica pointed out that she felt that the tool should be part of a 'kit' of tools used to communicate materials to designers and design students. She felt that it would help build up their knowledge of the material as part of that eco-system. Allowing for questions to be asked after they've understood the main functions of the material.

Criticisms and questions: Veronica's key question was how the tool could help to support the questions that might come after the initial explanation. She was unsure of the questions that designers would ask after hearing about the material as that wasn't her role in Material Connexion, but she still felt that was likely more would be asked, and she felt that to be effective the framework had to connect well with other systems that could answer these questions.

7.4.2.5 *Interview 5 – Material communicator – John*

John is a knowledge transfer manager with the Knowledge Transfer Network and has been for 8 years. In this role he focuses on innovation and design. He also supports the MaDE organisation, where he works to help share materials created through research and get them into the hands of designers. This is in addition to a lifetime of experience in the sector.

Thoughts on the research process: John approved of the research process appreciating that it was 'a real-world test' and felt that challenging designers to create using new knowledge was 'a compelling argument'. John did feel that the research had missed out on collecting testimonials from designers but didn't feel this was a critical issue and something that could be collected later.

Thoughts on the framework: John felt the framework balanced the need to avoid complication while not losing the material's key aspects, 'you end up with it getting more complicated as it kind of gets restated in different ways, and you end up just losing the innovative aspect of the material.' John also valued the fact that it opened up conversation allowing designers to understand the materials value and making designers more likely to then talk to their colleagues who were more technically minded to understand how exactly the material works, 'There can be technical people in companies but you need to get designers interested in the behaviour of the material first.'

John also felt that it was valuable and valid in his area, he's seen past projects in the area of communicating materials (but not innovations to designers), and the indication is that there understanding is very different from the technical one, so he believes there is a need for a different approach. John felt that the framework was a useful addition to this area of study as 'the framework is entirely reasonable given that the experiments validate the work, it makes a lot of sense to me.'

Criticisms and questions: John was interested in seeing how effective the framework was for different groups involved in the communication of materials. He felt that learning curve for being able to use the framework would differ largely between 'a PR person or a technical director in a manufacturing company.' He felt this area should in particular be examined to see if the needed to be a more prescriptive approach or more examples provided to help the communicator use the tool.

7.4.3 Interview 6 – Material communicator – Ian

Ian runs the Materials Council, a company that offers to create material libraries and offers consultation on new materials to companies who want to investigate new solutions. They have created a number of material libraries including a library of radical materials that was used in this research.

Thoughts on the research process: Ian approved of the research process, 'I love the methodology,' he found the testing process rigorous and described it as 'the tests I'd want to see to prove something like this.' Ian felt that challenging designers to use the new material was essential as it enabled actual testing of the communication in a practical way. He also approved of the scope of the research as he felt that the 'would be a lot of variety among the designers' in their ability to explore the materials.

Thoughts on the framework: Ian felt the tool was an effective method to 'try and get people excited about the future of materials.' He did feel that hit offered a methodology that helped to communicate materials would be very useful to him and his industry, 'I would say that in terms of methodology of communication. It would be very, very useful. Just for my general work for communicating. any and all materials.'

Ian's point of view on the framework was that it was best positioned to support educators and those who have the time to explore new materials in detail. He noticed that currently as part of his work as an educator he's been moving designers away from 'the cutting-edge,' as he felt it was more important to understand the basics first. He felt this framework could serve as a platform to support those who have understood the basics and then want to explore the other options available to them.

Criticisms and questions: Ian discussed how there were limitations to the frameworks communication approach, in the industry he finds he has to 'actively stay away from radical materials, because the nature of the industry wants more security'. Ian wasn't sure that the framework helped solve this challenge but equally he recognized that this wasn't the goal of the tool. He felt that the tool could have made helped covered how the materials could be produced at scale.

7.4.3.1 ***Summary of interview feedback***

From the interviews some consistent feedback kept appearing across all those spoken too:

- **Importance of having the different levels of feasibility** – Much of the questions about the methodology focused on how the feasibility of the concepts was assessed. The issue that was raised was that there was a great difference between an idea that was mostly possible, showing an almost complete understanding, and an idea that was mostly impossible showing an almost incomplete understanding. Those who questioned this approved of the decision to assess the feasibility into different categories. When the topic was discussed further, they recognized though that methodology that broke down the feasibility of the concepts into only four different levels of understanding was enough to reflect this large gap.
- **Validity of testing communication by challenging designers** – Both designers and material communicators approved of testing the effectiveness of the communication by challenging designers to create new designs. The test was seen as a real-world simulation of how the communication might be received by a designer outside of the test. The was criticism that this didn't go far enough but those who raised this topic felt happy that this test was sufficient for the test to be respected.
- **Limitations on designers using new materials of any description** – A topic that came up in three of the six interviews was that designers often struggle to build new materials into their designs, regardless of how well communicated they are. This comes from the fact that timescales to develop new products can be short and clients demand a great deal of clarity around how the material will be produced. The feedback was that this might limit the use the framework, not because it's not helpful but because only those, such as in-house designers would have the time to learn and use radical new materials.
- **Interest in expanding information around the manufacturing ability of the material** – One of the pieces of feedback that came from both designers and materials communicators was that having more detail around the manufacturing processes would add a great deal of value to the framework. The ability to produce products at scale and in the shape desired was a key question of the clients of designers and the designers who clients of material communicators are. While the present framework's goal is to communicate just the radical innovation it shows that supporting this with a clear explanation of how the material can be processed would be invaluable.

- **Value of the framework to both designers and material communicators** – Each expert interviewed saw the framework as offering a valuable addition to the use of new materials. While there were limitations to at what stage the framework would be most useful all those interviewed saw it as adding some useful support to the process of communication.

7.5 SUMMARY AND CONTRIBUTION TO KNOWLEDGE

In this study, the communication framework that has been built upon the learning of all the previous research and understanding that has been gained was put to the test. Designers using this tool were able to generate concepts that were feasible more effectively. Creating more concepts and seeing a higher proportion of them be feasible than in the identical test in descriptive study 1. This effectively answers **research question 5** and shows that the application of the communication tools is reliable, an essential aspect of **research question 4**.

This chapter validates the research in two core ways. The testing in descriptive study 2 shows that the communication using this tool is more effective than communication that doesn't use this tool. The increase in the ability of designers to create feasible designs rose notably. This increase in ability to create feasible designs in test which only differed in communication method shows that material communicators can use the framework to create communications that are more reliable and allow designers to create ideas more effectively.

In addition to testing the framework practically it was also shared with design experts and material communication experts. These experts provided insight into how they felt the framework could be applied to their sector. The material communicators showed interest in using this tool to help them connect with designers and appreciated the ability to follow a proven process to achieve a goal, that they admitted is often a challenge. The designers felt that the output and goals of the tool could help them as well, noting that a great deal of new materials aren't used as there is little confidence in using them. While both groups did have recommendations to expand the development of the tool both felt confident it could be of use at its current stage of development.

While feedback was collected that could enable the framework to improve, the overall research can be seen to have been completed, and that research must now look at next steps it can take to build on this understanding.

In the next chapter the final version of the framework is detailed. This framework builds on the results of chapters 6 and pulls in the findings from this chapter to create a more effective framework.

8 FINAL VERSION OF THE CRIM FRAMEWORK

This framework aims to Communicate Radically Innovative Materials and as a result, is referred to by the acronym 'CRIM'. Its goal is to enable material communicators to share radical innovations in materials to designers in a manner that enables those designers to build the materials into their design process. This allows the designers to not only create more ideas but also to create consistently feasible concepts. The framework does this through five steps. An overview is shown in Figure 25.

By following the framework, the user should be able to generate a communication that is effective at communicating the material's radical innovation. This includes a short three-part statement, supported by additional information.

CRIM has been shown in tests to improve the comprehension of radical materials properties over the current methods in use by material libraries and materials producers. Prior methods were found to have over half designers fail to understand the material (52% failed). With 10% of all designers critically failing to understand the material at all. In testing, CRIM shows that 80% of designers understand the material with only a brief introduction. And, only 6% of designers critically fail to understand a material's function.

8.1 INFORMATION ABOUT THE FRAMEWORK

4.1.1 Who is this framework for and what resources are required?

CRIM is for all those who are looking to communicate radical material innovations to designers. It is most useful to those who have a strong understanding of the material's features and abilities such as material scientists. To use the framework the user must have a strong understanding of the material that they wish to communicate, this material will henceforth be referred to as the 'target material'. What is also essential is access to designers with which to test the communications generated and knowledge of the material's potential or current applications. These three elements are essential to the function of the framework, but it is strongly advised that the user of the framework have some knowledge or do some research into how materials that similarities to the target material have been used by designers. Having this information will greatly improve the ability to create useful communications.

4.1.2 What materials does this support?

The materials that CRIM supports are those which have radically innovative material properties. Any target material should have at least one property that fits the description below.

> 'Radical innovations introduce new concepts that depart significantly from past practices and help create products or processes based on a different set of engineering or scientific principles and often open up entirely new markets and potential applications. They provide 'a brand-new functional capability which is a discontinuity in the then-current technological capabilities.' *(Carayannis, Gonzalez et al. 2003)*

While the material can be mostly anything, currently this framework has only been tested with materials which fit into the categories listed below.

- Metals
- Plastics
- Ceramics
- Composites
- Woods
- Fabrics
- Natural materials
- Smart materials

4.1.3 **What will the output look like?**

The final output of CRIM will generate a table like the one shown below. This can then be added to with additional information if so required. The main components are; The innovation and its three-part communication highlighted in blue. This summarises how to communicate the materials radical innovation as well as its abilities and limitations. The name, material and innovation categorisations highlighted in green. This summarises what category of materials the material belongs to and what kind of innovation category it belongs to. The summary of other features highlighted in red. These are the features other than the innovation that are important to designers.

This system from the Material Connexion library was used as it is currently a system has proven effective at communicating materials. The Material Connexion library has been used over other systems, such as Granta's CES system, as it flexible and focuses on using subjective, comparative or contextual language which makes it consistent with the CRIM framework.

While it would be useful to explore what material properties should appear on this list and properties are most valuable for designers this would add a vast area of research to this thesis. This research would also cause the study to stray far from the intent of supporting specifically the communication of the radical innovation rather than the material as a whole. To ensure the research remains manageable the decision was made to use an existing and proven tool.

4.1.4 **What are the limits of CRIM?**

The framework is aimed at increasing designers understanding and use of radically innovative materials at the early stages of the design process. This framework is not intended to support the understanding of the material when it comes to complex prototyping or fabrication questions once initial ideas have been generated. CRIM is not infallible, while it remains effective in over 80% of tested communications, it still has some room for error and should not be seen as an infallible tool. The framework also presumes that designers will have access to samples of the target material. This has been shown to be a core part of their ability to understand the material's functions, the communication while possibly effective without a sample may lose some reliability if no sample is provided.

Finally, the framework assumes that designers are interested and engaged with learning about these new materials. This approach does not guarantee that designers will find the content interesting and if designers are not motivated to learn, this approach is less likely to succeed.

Name:	Material type:	Innovation category:
Processing	Usage properties	Physical properties
Injection moulding:	Flame retardant:	Stiffness:
Extrusion:	Usage temperature:	Impact resistance:
Cold pressing- Deep drawing:	Water resistance:	Surface/texture:
Blow moulding:	Wear resistance:	Transparency:
Thermoforming:	Acoustics:	Surface Hardness:
Lamination:	Chemical resistance:	Additional properties
Printable:	UV resistance:	
Stitchable:	Scratch resistance:	
Weldable:	Outdoor use:	
Die Cut:	Tear resistance:	
Wood Working tools:	Reflectivity:	
Die-cut:	Stain resistance:	
Metalworking tools:	Thermal conductivity:	
Castable:		
Innovative property:		
Innovation Benefits	Innovation limitations	
Three-part communication		
Subjective element	Comparison element	Contextual element

Table 34: Example of the CRIM output

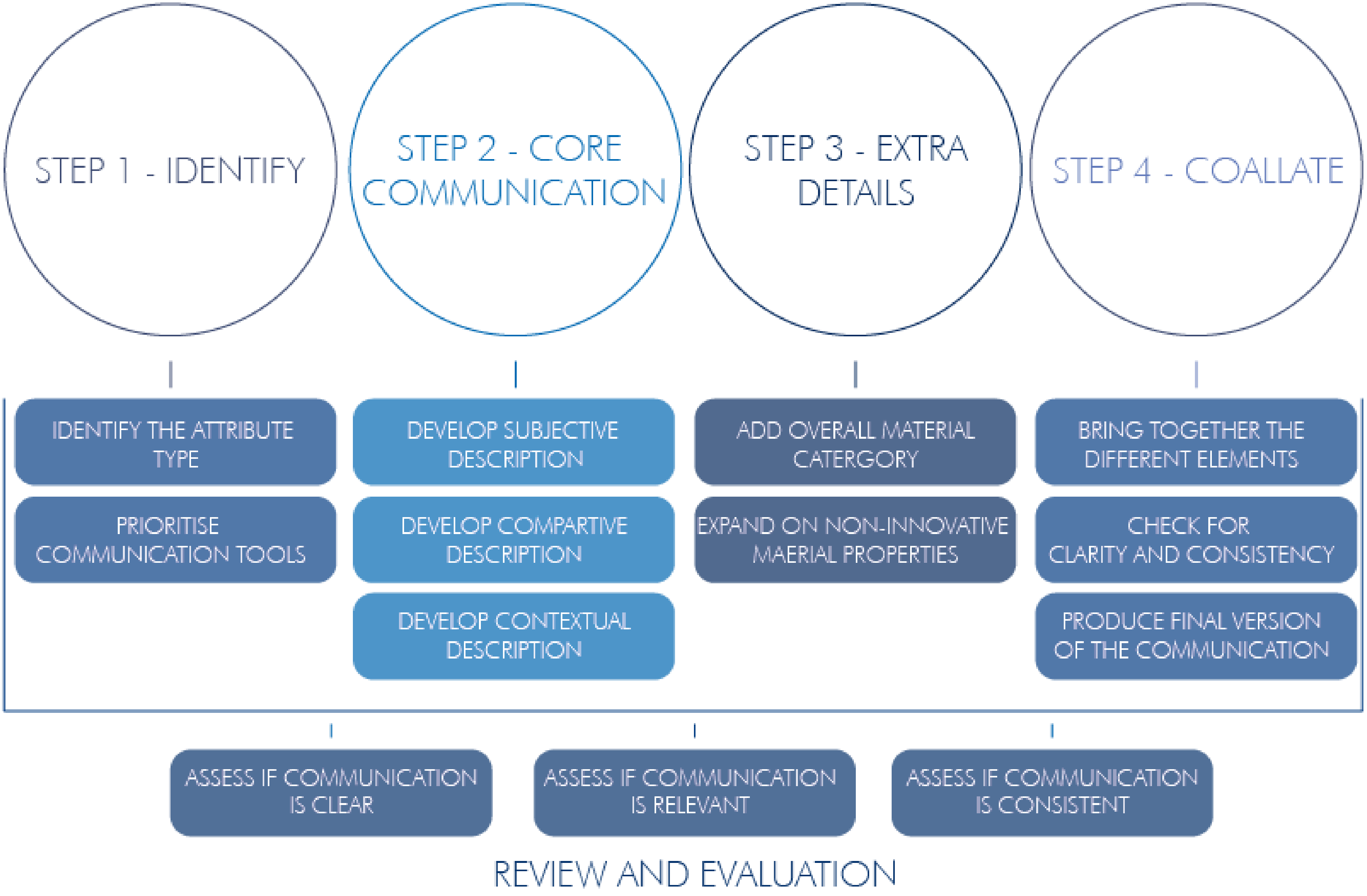
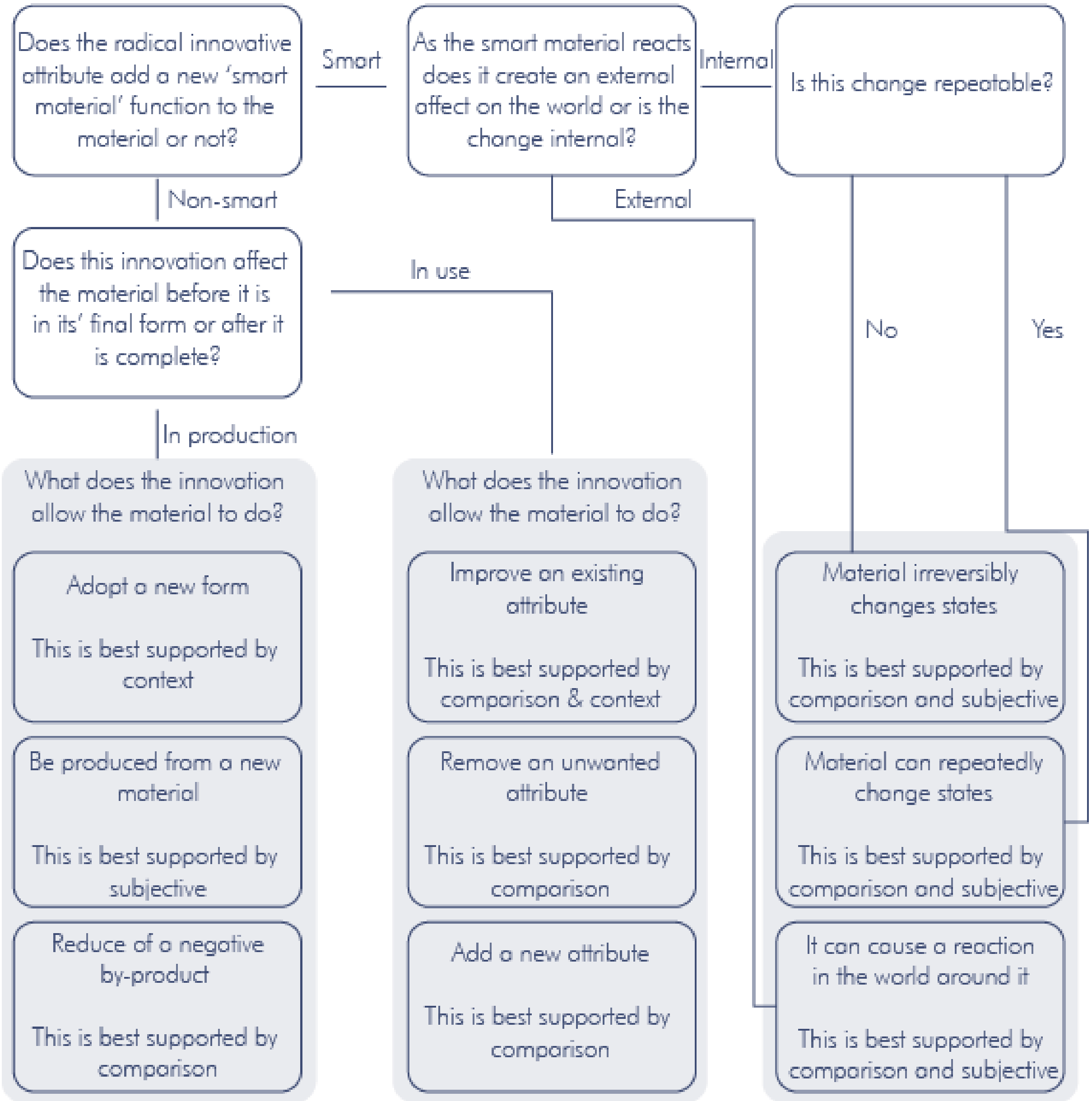


Figure 33: CRIM framework

STEP 1 - IDENTIFY

Radical innovations differ greatly but can be grouped into larger catergories based on a handful of attributes. Knowing a materials catergory can help in the next step of building the communication as it gives insight as to what is the best strategy to communicate those materials.

Before engaging in this step though it is important to for the material communicator to understand what the materials radical innovation is and if this is a multitude of different attributes or a single attribute. Once the attributes are understood (this is something the material communicator must do and cannot be aided by this research,) each attribute must be assessed using the following criteria.



REVIEW AND EVALUATION

While producing the communication it is important to constantly review and evaluate the text being produced. The are three main attributes that a communication must have to be effective. These attributes are clarity, relevance, and consistentency.

What is essential is to spend this reveiw period checking in with designers to ensure that the the communicator's understanding of clarity, relevance and consistency is the same as the designers view on these topics.

Assess if communication is clear

To create a meaningful communication, the content must be clear in how it communicates. Clarity requires that the communications be accurate to the concept being explored, contain the information necessary for that communication to be accurate and to not contain confusing or ambiguous references.

Assess if communication is relevant

Creating meaningful communications is best supported by ensuring that the content used to communicate the target material is relevant to designers. Relevance is found through ensuring examples and concepts connect with those that designers recognize and ideally are interested in. The more relevant the concepts used the more likely designers are to take an interest in them and be able to apply past knowledge.

To gain an undestanding of what is relevant to designers it is best to speak to them and explore with a variety of designers what they are interested in how great of an understanding they have for the communications that are being produced through the framework.

Assess if communication is consistent

All the elements generated by the framework should complement each other while not being purely repetitions of the same information. Concepts that do not appear linked to each other, either by their approximate nature or their use can sow confusion in the minds of designers.

This is most important when considering comparisons and context. If the elements that comparison and context are using as reference points are so unrelated as to not have clear connection this can cause issues for the designer as the contextual communication is meant to serve as a way for them to assess how they've understood the rest of the communication. In best practice this means, for example, that comparisons which reference a materials hardness should be followed by contextual examples clearly showcasing hardness.

STEP 2 - CORE COMMUNICATION

Once the innovation is understood the three steps of the core communication can be produced. These three tools work together to effeciently communicate the materials innovative property.

While each tool is important and all three should be produced Step 1 should have also provided an understanding of which tools are most important for the particular innovation. The tools highlighted should be the focus of the communication, as they will be what designers look to, to understand the material

Develop the subjective description

The subjective stage aims to set the scene, it uses emotive and uncomplicated language to bring attention to the material's innovative property. This allows the next two stages to expand on this information providing more detail. It can also be used to add extra details to a comparison which might otherwise not be able to build them in.

Subjective terms can be used in two ways, either as a statement with a quantifier and then an ad-jective. This creates statements such as 'very strong.' This is because with a quantifier it is easy to add emphasis, which draws attention, to important material quality. The other method is to just use an adjective, such as 'red'. This method is better when the mate-rial quality isn't as important, or if the material property is just being added to help visualise the material.

Develop the comparitive description

Comparison is the most important tool for accurate communication when using CRIM. There are several different ways to use comparison. Each method can guide how to phrase the explanation. However, they do not cover what to compare to. The full write up contains additional information on these different approaches.

Direct comparison: 'It is like X.'

Direct comparison with property qualifier: "It has the qualities of X but with Y property improved."

Direct comparison with numerical qualifier: "It has the qualities of X but with half the property of Y"

Stacked comparisons: "It's got the property of X but it's also like Y."

Analogy: Analogies allow more complex communication

Develop the contextual description

The contextual communication stage capitalises on designer's ability to infer what material properties are required in materials used by specific products. When a material is labelled as an appropriate material for a specific scenario designers' will be able to expand their mental model of that material. This serves two purposes, both informing designers but also allowing them to check that the understanding they have already gained is correct.

The different forms of comparison allow for the communication to be as targetted to the radical innovation as possible. The different tools outlined below provide insight into how best to construct the a comparison for different situations. In noting how the language is used the below text refers to the 'base' and 'target'. The 'base' is the material or concept that the designer knows and is familiar with. The 'target' is the new material that is trying to be communicated.

Direct comparison

"It is like X."

Advantages: Using a direct comparison to another material with an almost identical quality is one of the best ways to communicate a material property or an overall similarity to a material type.

Disadvantages: The limitation of direct comparison is that the material must be directly compara-ble. If there is no old material that offers an exact match to the material, then this option will not be viable.

How the comparison is used in practice: Select a material with similar properties to the innovation. The exact property doesn't have to be the same if you have found the closest material and can think of no other materials with a much closer property which are relevant. However, make sure to pick materials that designers are likely to have encountered either professionally or in their every-day lives. It's of higher priority that you pick a material that they are likely to know than pick a ma-terial that is unknown but a perfect comparison. If no materials present themselves, look to the 'Direct comparison with the numerical qualifier' method.

Example: BrightGreen looks identical to normal moss.

Direct comparison with property qualifier

"It has the qualities of X but with Y property improved/removed/added."

Advantages: This method is useful to communicate innovations materials the designers might know or the crea-tion of a new material that is like an old material but with added properties.

Disadvantages: The issue with this form of comparison is that there must be a relevant material for designers to use as the base. In addition, if there are other significant differences between the base and target other than those highlighted in this comparison, then this method risks confusing the designers and hiding those changes.

How the comparison is used in practice: First pick a base material (X). This is what those listening to the comparison will base their under-standing off. If this is an innovation to existing material base it off that one. Otherwise use a material that is very similar apart from in the innovation you wish to highlight with Y. Y is the innovation you want to bring attention to, so whatever property has been changed this is then communicated in place of Y.

Example: This plastic is as strong as mild steel but weighs considerably less.

Communicating limitations - Clarify within existing communication

The limitations of materials abilities is something that must be communicated to enable designers to accurately use the material. To achieve this there are two methods.

Clarify within existing communication

When either the subjective or comparison tools are being written the limitation must be explicitly added to the communication. This may involve naming the specific limitation of the material as part of that communication. An example of this type of clarification is below.

Photochromic ink has the ability to change colour when exposed to sunlight. It gradually shifts from one colour to another. It cannot change between more than these two colours.

An example of a three-point communication without limitations clarified.

Photochromic ink changes colour when exposed to the UV light, similar to skin becoming sunburnt, it works well in anti-counterfeiting applications by hiding UV sensitive data.

An example of a three-point communication with clarity,

Photochromic ink changes from one colour to another when exposed to the UV light, similar to skin becoming sunburnt before rapidly changing back, it works well in anti-counterfeiting applications by hiding UV sensitive data.

Direct comparison with numerical qualifier

"This has the qualities of X but with half/quaduprle/33% less/100% more (Using any amount) of Y"
Advantages: Using a property with a numerical qualifier is useful in many situations. It's best used when an existing material is innovated but it can also be used for new materials that have strong similarities to other materials but aren't identical.
Disadvantages: Designers expect this comparison to be accurate to the materials abilities. If the material is stated to be 'twice as strong' as another designers expect that to reflect objective measurements of the materials qualities. Not being accurate can lead to frustration amongst designers.
How the comparison is used in practice: The exact property doesn't have to be the same, as long as you have found the closest material and can think of no other materials with a much closer property. However, make sure to pick materials that designers are likely to have encountered either professionally or in their everyday lives. It's of higher priority that you pick a material that they are likely to know than pick a material that is unknown but a perfect comparison. If no materials present themselves, look to the 'Direct com-parison with the numerical qualifier' method.
Example: This lifocork can be moulded the same as regular silicone but uses only a fifth of the plastic of solid silicone.

Stacked comparisons

"It's got the property of X but it's also like Y."
Advantages: Stacked comparisons allow for a collection of comparisons to be assembled to create a more comprehensive view of the material being communicated. It is particularly useful if the material is innovation is complex and has different facets.
Disadvantages: By combining the different comparisons the is a risk that the overall message will become confused.
How the comparison is used in practice: The stacked comparison brings together other comparisons outlined in this document. It appeals to designers as it allows multiple reliable comparisons to be brought together into a cohesive whole, adding a much greater deal of complexity to the communication. When creating this communication though the are several considerations that must be taken into account.

- The goal of the comparison must be clearly defined, it should be obvious to the reader what attributes the target and base have in common. This means that the communication should clearly highlight the attribute being transfered between base and target.
- Both the subjective and contextual communications need to focus on supporting the aspects featured in the comparison, without if they only feature one aspect of the stacked comparison this can lead to a communication failure.
- Keep the language as consistent as possible, if using one direct comparison, try and use another if possible.

Example: Faraday film is conductive like copper but is also transparent like glass.

Communicating limitations - Add extra details to the comparison

The other approach to communicating limitations is in adding additional information to the comparison component of the communication. Adding extra details should build on the comparison or analogy being used rather than adding a separate step to the communication. This can be enabled for smart material by expanding and carefully considering the analogy being used.
An example of a three-point communication without added detail.
D3O is a rubbery plastic that gets more rigid the harder it gets hit. The reaction is like falling into wa-ter at low speeds the water moves around you but at high speeds the water feels more solid. D3O works well in making flexible and protective clothing for sports like snowboarding.
An example of a three-point communication with added detail.
D3O is a rubbery plastic that gets more rigid the harder it gets hit. The reaction is like falling into wa-ter at low speeds the water moves around you but at high speeds the water feels more solid, like water this resistance can be overcome by either, moving so fast the water is blasted out of the way or by diving, allowing you to cut through the water. D3O works well in making flexible and protective clothing for sports like snowboarding.

Analogy

To assess the two different elements, they must be mapped into how each concept functions and then the two can be compared. This does mean that a specific element of creative thinking from the modeller is required; it is not possible to map every possible base and then compare it to a tar-get. Those creating the analogy are expected to use their intuition to select two systems that appear close and then evaluate how effective an analogy between the two may be using these tools.
The first step in creating an analogy this though, is to map the target, as this is a known quantity that will not change. Mapping the target first can also help guide the intuitive selection of the base.

Mapping concepts
The process of mapping concepts asks that they are broken down into a series of objects, relationships and attributes. To start mapping a concept, the target must be chosen and then broken down into its components.
Objects
Objects are the different components in the system. They do not need to be physically separate entities, as seen in this example, the first object is the material in its soft state and the second the material in its solid-state. The different objects in the system have to be connected to each other through some form of interaction, called a relationship.
Relationships
Relationships are the connections between two or more objects. They often represent a force; someway one object acts upon another. They can equally represent a change that is invoked in an object by another object. These relationships are perhaps the most crucial element of the analogy as they often describe the systems change, providing the information the analogy was created to convey.
Attributes
Attributes are the physical properties of the objects. They are the least important part of the anal-ogy but must be included to ensure they do not cause confusion when used in the analogy. As analogies often have no aesthetic resemblance between the base and target, many attributes are immediately discounted as not being similar. Sometimes though this overlap of content must be looked at if the two systems share aesthetic similarities that could confuse the analogy. An excellent example of this is in a classic science analo-gy of a nucleus (target) being like the solar system(base). A solar system has a large body (sun) in the centre which due to gravity means smaller bodies (planets) orbit it. An atom has a large central body (nucleus) that due to its charge, causes smaller bodies(electrons) to orbit it.
While the relationships are the same, some attributes could be confused to be affecting the sys-tem. Looking at the base those who understand gravity know that the size of the central body is directly connected to its ability to affect the smaller bodies. This not the same for the nucleus its size has is not the reason it attracts electrons.
Inconsistencies like these need to be identified and clarified as part of the analogy so as not to con-fuse those using it. This can be as simple as stating that the similarities in scale are incidental and are not be considered as part of the analogy.

Evaluating the comparison
Structure
The structure of the objects and relationships should appear in a similar fashion; this perhaps the most prominent issue. If for instance a base has an object A with relationships with object B and object C and the target has relationships between object A and object C but not between object B the structure doesn't line. This shows a clear sign that the analogy won't work as the interactions are not similar.
Clarity
The clarity comes from how effectively the base and target map to each other. Perfectly clarity has a similar number of objects connected by a similar number of relationships. This is often not the case with the target or base having unique relationships or objects that don't map, these don't necessarily ruin the analogy if the most of the elements of the target are similar enough to create a direct map. It does, however lower clarity and can confuse the analogy.
Richness
The richness of the map is how much of the analogy maps. If only the core aspects map and there are other elements of the target which are not covered wholly, then there is a lack of richness. The ideal situation is to have the whole of the system accurately map to the other, matching all the re-lationships and objects of the target to the base. This can be rare though, so if two potential bases are available that map correctly, the one that is richer that should be the preferred option.

STEP 3 - EXTRA DETAILS

With the three step communication in place it is important to flesh out the other details of the communication. These include what larger material catergory the material belongs to and the other attributes the material has.

This step is important as designers do not see materials as existing in isolation. Many designers look to materials they know to understand materials they do not, providing this information as well as a summary of the materials other attributes not only allows the designer to better understand the material but also helps them explore how they can apply the new material in the future.

Add the overall material catergory

As part of the communication, the group the material belongs to should be communicated. This is not a detailed outline of the materials specific classification but more connecting the material to the larger branch of materials it belongs to. The purpose is to give designers an understanding of how the material might behave.Examples of this kind of categorisation include:

- Brass
- Steel
- Ceramics
- Plastics
  a. Thermoplastics
  b. Thermosets
- Composites
- Woods
- Smart materials

Expand on Nnon-innovative properties

The final step in assembling the material communication is to populate the other aspects of what the material can achieve. While this is not the focus of the framework it is essential to designers to understand the wider material. The full page can be found at the end of this document. It is not essential to fill in every box if the particular attribute does not apply to the material in question but it should be completed in as great a detail as is feasible. Examples of a completed page can also be found to show how best to complete the document.

STEP 4 - COALLATE

The final stage is to bring the different elements together. The three part communication and other details need to be collected and reviewed as a whole. The goals of this combined review is to ensure that as a collected whole the communication makes sense, and that the communication is ready to be distribute to designers.

Bring together different elements

The first step is to bring together the different elements. The method for doing this can be found on the last page of this document.
This collected document should include:

- The material three step communication
- The materials catergory
- The materials additional attributes

Check for clarity, consistency and relevance

While the review and evaluation element of the framework should help to keep an eye on if the communication is effective, it is important to review the communication now it is whole. The benefit of reviewing at this stage is that each element of the communication can be checked to see if clarity, consistency and relevance have been maintained. It is important that to check that the different elements don't appear to contradict each other and that the language and examples used build on each other.

Review with designers

The draft version of the communication is now ready. Before circulating it the final copy should be shared with a range of designers who have limited knowledge of the material. This step ensure that the language used will be suitable for them and allows the communication to be tested. It is important at this stage to ask designers what they could create from the material. This challenge will allow the communication to be assessed, if the designers can realiably create feasible concepts the communication is effective, if it can't designers should interviewed to understand where the communication failed. The changes can then be implemented to help the designers understand the material better. This step can then be repeated until the communication is effective enough that most designers can use create feasible designs from it.

Name:	Material type:	Innovation category:
Processing	Usage properties	Physical properties
Injection moulding:	Flame retardant:	Stiffness:
Extrusion:	Usage temperature:	Impact resistance:
Cold pressing- Deep drawing:	Water resistance:	Surface/texture:
Blow moulding:	Wear resistance:	Transparency:
Thermoforming:	Acoustics:	Surface Hardness:
Lamination:	Chemical resistance:	Additional properties
Printable:	UV resistance:	
Stitchable:	Scratch resistance:	
Weldable:	Outdoor use:	
Die Cut:	Tear resistance:	
Wood Working tools:	Reflectivity:	
Die-cut:	Stain resistance:	
Metalworking tools:	Thermal conductivity:	
Castable:		
Innovative property:		
Innovation Benefits	Innovation limitations	
Three-part communication		
Subjective element	Comparison element	Contextual element

Empty copy of the communication framework form

9 CONCLUSION

9.1 ANSWERING THE RESEARCH QUESTIONS

Over the course of this research, five questions have guided its development. These five questions have answered the overarching research objective of how radical innovations in materials can be explained to designers.

Research question 1: What communication techniques exist to communicate radically innovative materials to designers?

This research question became a focus of study as a result of the discovery that while radical communications are currently communicated by material libraries, there is no specific strategy used to communicate by them. This communication may not be useful as there is likely a need for a specific strategy to create reliable communications due to the complex nature of the innovations and the method of 'design thinking' used by designers.

When beginning the literature review there was a clear lack of specific approaches to the communication of radical innovations which was surprising to the author. The surprise came from the fact a large quantity of literature explored how there were different innovation types and that of them, radical innovation was so unique as to be dangerous to businesses. There were articles on how radical innovation required specific management styles, developmental approaches, company hierarchies and language to be effective but few studies on how to communicate these developments outside of the company. Only innovation journalists had anything concrete to say on the matter and even then, the suggestions were limited and not specific to any particular industry. This significant blind spot of the academic community showed that there was likely a need for some guidance in this area. Bringing the support for communication of radical innovation in line with the support offered to other key steps in its development.

The need for support becomes only more essential when looking at the interaction between radical innovations in materials and designers. The more extensive research of the literature review highlighted evidence that radical innovations could struggle to be communicated effectively to designers. This was due to how radical innovations are defined. Unlike incremental innovations which build on what came before, radical innovations are a great departure from what has come before often being only tangentially related to past concepts. This poses a unique challenge for designers who, through the process of design thinking, rely heavily on past knowledge to create new designs. With designers unable to use past knowledge or applying past knowledge incorrectly, there is increased likelihood that the designers will struggle with comprehension of radical materials. This conflict is not highlighted by any other research and was exposed through the literature review compounding the need for research in this area as not only is there a gap in how radical innovations are communicated but there is evidence that designers will struggle due to their specific ways of working.

To further clarify how designers are currently being communicated to a review of the existing material libraries was undertaken. This review looked at the disparate tools for communicating materials to designers, in these certain similarities were noticed. With the focus of the communication being on outlining a material in piece of explanatory text, supported by images. A review of these tools though found that radically innovative materials did not have specifically different communication approaches than their incrementally innovative counterparts. This showed that the industry had not created its own approach to this challenge outside of academic support. Only further illustrating the need for research to support this communication.

Research question 2: How effective are communication materials explicitly aimed at sharing radically innovative materials with designers at enabling them to create concepts that are feasible and use that knowledge accurately?

This research question identified that innovative materials are harder to understand than more familiar materials. This challenge was quantified by a series of workshops that showed that when challenged to use current material communications to create new concepts designers fail to accurately apply the radical innovation in 52% of the concepts they create. This shows the is a fundamental flaw in this communication approach.

The first test of this thesis explored how designers were able to use materials that were familiar to them and materials that were unfamiliar to them. The materials were a selection of smart materials, some of which had reached market saturation and already gone through several incremental innovations since their release and others which were radical innovations that were new to the designers. The reaction of the designers showed the first evidence of the depth of the issue. While the designers rated the radically innovative materials as most interesting, when it was time to use the materials to create concepts the incremental innovations were far more utilised by designers to create design. Designers completely avoided using some of the radically innovative materials for any designs at all. In addition, those designs that did use radical innovations were more likely to see the concepts created use the materials inaccurately. This challenge shows that designers, even when excited and interested by radically innovative materials are unable to use the materials without support to create designs. This cements the need for the research covered in this thesis.

The first workshop series expanded on this work, challenging 127 designers to pick a radically innovative material from a list of 20 possible options to create design concepts from it. The materials were provided with a selection of the information provided by material communicators. The workshops not only found that of the concepts created only 48% of the were fully feasible but also found that designers struggled to create original ideas with many of those 'Fully feasible' concepts being variations on the current applications described in the communication provided to the designers. The fact that designers struggle with understanding how to apply the materials is a critical failing by materials communicators. The communication failure leads to wasted energy by designers who spend time creating impossible concepts, and it could also lead to designers being less likely to use new materials they are unfamiliar with, as these past mistakes may make them hesitant to risk using new materials again. Fixing this communication would not only make designers more able to use the materials but could encourage designers to explore using radically innovative materials in their designs as they would have more confidence in using unfamiliar materials.

Research question 3: What text-based communication techniques enable designers to better understand radically innovative materials?

This research question was complex, working to both identify communication techniques and how those techniques could be applied. Four core methods to communicate were found through testing. Of them comparison proved to be the most popular method by which designers communicated innovations. The research also categorised innovations into distinct types and while the comparison communication method proved most popular for nearly all categories, other methods were also seen as being useful. This fed into the focus groups which expanded how comparison could be applied but also explored how the subjective, comparison and contextual methods of communication could be combined to make a more effective and reliable communication.

Existing research of designers use of text-based communication is limited. While there is focus on how communication strategies, sketching and multimedia tools can be used to communicate complex topics to designers there is little discussion on exactly how this is reflected in the language used to communicate. This poses an issue considering the existing material libraries and much of materials communication uses the written word extensively. To establish what language would enable designers to better understand new materials, the literature review identified that core to how designers understand challenges is through connecting the new ideas with old experiences. This method allows them to use their existing knowledge to create solutions. This theory was supported by evidence that appeared throughout testing which showed that designers liked to use comparisons between new and old materials when discussing radically innovative materials. Building on the work of Cross (2011) and Brown (2008) to add validity to their observations of design thinking.

To gain insight into what forms of communication tools designers prefer to use when communicating materials, a series of short interviews were conducted and assessed by thematic review. These interviews tasked designers with communicating incremental and radical innovative materials. This review identified four principal methods of communicating, comparative statements, subjective statements, objective statements and placing the material in a real-world scenario, known as contextual statement. These methods of communication while not unique to designers help to further the understanding of the designers thought processes. Of the tools comparison and subjective communication were seen most frequently. The fact that comparison was seen so frequently was of particular interest as it built on the understanding outlined in the above paragraph that designers prefer to be communicated through connecting their understanding to concepts, they have existing knowledge of. In fact, the majority of the comparisons in this interview series focused on exploring the complexities of the radical innovation of the smart material, this added additional evidence that comparison is an important tool to communicate new concepts to designers.

The view of comparison as an essential tool for communicating with designers was only compounded further by the responses of designers at the first workshop series. As part of the workshop what language tools designers used was recorded. This assessment was conducted when designers discussed the abilities of the material amongst themselves and it found that comparison was consistently the most used method to communicate one designer's understanding of a material to another. These comparisons were also created by the designers, not pulled from the information that was already available. This consistent interest in comparison was a key learning of the entire thesis. Not only were designers relying on comparison to communicate they also were willing to invest mental energy into creating the comparisons rather than using the supplied information. While other academic research in the area of design thinking had highlighted how designers use comparison to create designs none of the research focused on how comparison could be used to help designers understand innovative materials and build them into their designs. This offered a new insight into how material communicators should interact with designers.

The next step in the research was to develop a better understanding of radically innovative materials. By exploring the different types of innovation, categories could be extrapolated. The review looked at a range of radical material innovations, recognized by material communicators, and sorted them into nine distinct categories which were sorted into three distinct themes. This research was important as despite radical innovations in materials being so varied there is no current system to categorise the materials. By building these categories the research not only added to the existing systems used by material communicators to define the materials category, but it also enabled the researcher to split materials into distinct categories that could be explored in more detail. Trying to create a one size fits all system which could communicate each innovation accurately would be unlikely given this variance. The importance of this review of material types was only added to by a survey which reviewed how effective designers felt the four types of communication, that were exposed by the interviews and thematic review, were at explaining the different categories.

This review found that again comparison was ranked the most important tool to communicate materials overall, but this was not true for every innovation category. Designers also saw contextual and subjective language as particularly important for some categories. The fact that designers seemed to need different communication strategies based on innovation category proves how important it is to assess the categories of radical innovation and add it to the available knowledge about radically innovative materials.

To gain a complete understanding of how comparison and the other communication tools could best be used a series of focus groups were then conducted. These focus groups challenged designers to both explain how they would use comparison and what other tools were important to aid their understanding. Through these focus groups, it became evident that while comparison remains a key factor in communication the support of subjective and contextual phrases cannot be underestimated. Appearing in the workshops was a clear preference for using a three-stage communication method, this used subjective descriptions to highlight the radical innovation, comparisons to help connect the new material to old experiences and context to further understanding and create a method to test if their understanding was accurate. This understanding is perhaps one of the most important of the whole research process. Currently this offers a far more specific piece of guidance on how to communications than was provided by any source found in the literature review. It also adds to the knowledge this research has developed on how comparison can be used to communicate materials innovations. Designers understand communications best when using comparison, which fits into their method of thinking, in combination with other tools, the use of these tools can change based on the innovation category type but the overall result is that designers feel comfortable with the communication and are able to use the innovative properties of the material. This information is not only valuable to those who work as material communicators but also to academics in the innovation journalism whose recommendations on how to communicate radical innovations are not specific to this challenge.

Research question 4: How can these communication techniques be applied in a systematic fashion to enable design communicators to reliably communicate radically innovative materials through text?

This research question produced a framework that pulled on all the research conducted in this thesis. It built a system that provided material communicators guidance on how best to communicate their radical innovations. This framework was then tested, and insights on how to improve it were applied to increase it is reliability and accuracy.

With the knowledge of how best to communicate radical innovations explored, chapter 6 focused on bringing those understandings together to create a new framework to communicate radically innovative materials. This process brought together the research on; innovation tools used to communicate, the importance of comparison to designers, the innovation categories, the tools best suited to communicate each category and finally the three-stage tool explored in the focus groups. By creating this framework not only was the research producing something that could be used by material communicators regardless of their background but also offered a method to standardise communications of this confusing topic. This was particularly important to material libraries, which follow consistent designs to communicate each material. By building a framework that allowed each entry to take on a similar appearance, but with different text, the communications could be easily added to the entries in the material libraries without disturbing their current configuration. This not only made the framework more relevant to the industry but also meant that the industry could use it without needing to change their current systems.

Research question 5: Does this new communication system function notably better than the tools currently used by material communicators?

This research question used earlier tests to establish if they had been an improvement between the communications currently provided by material communicators and communications created by the framework. The first workshop series established that current communications systems created more unfeasible ideas than feasible ideas. The second workshop series which used the framework found that it created feasible ideas 84% of the time. The second workshop also saw more concepts generated and those concepts to be more varied. Overall, this shows that the new system is a marked improvement on the old communications.

To test the framework a series of the workshop was conducted which was as identical as possible to the first workshop series conducted in descriptive study 1. The only meaningful change was that the materials that would be communicated utilised in descriptions created by the framework rather than using the original information provided by materials communicators. This methodology allows for the comparison of the results of the two-workshop series. The change was significant. The initial workshop created 51 ideas of which 48% were fully feasible, however the second workshop series created 72 ideas of which 84% were fully feasible. In the first test designers avoided creating ideas at all with materials that they didn't understand. The fact that designers were able to create more ideas and have these ideas be feasible shows just how effective the new communication framework was at sharing the materials. In addition, the framework communication method saw a lower proportion of ideas that appeared to be altered versions of the contextual examples. This research proves how important this framework could be to the material communicator community. Allowing designers to create more original ideas that are actually feasible.

9.2 CONTRIBUTIONS TO KNOWLEDGE

In this thesis, a review of the current methods by which radical material innovations are communicated to designers has been conducted. Workshops involving over 100 designers reviewing 20 materials showed that over 50% of communications of these materials failed in some way to explain the material and allow the designers to create functional concepts. This thesis has worked to rectify this issue. Firstly, by identifying, through interviews, the essential methods by which designers prefer to communicate, described below as; Subjective, Comparison and Contextual communication. Secondly by then exploring how to combine these communication tools to most effectively explain the materials. This involved understanding the different forms of innovation by assessing a collection of radical innovations. Finally, a series of focus groups explored how these tools could be best applied to the specific radical innovations. The framework this research generated is described in Figure 29.

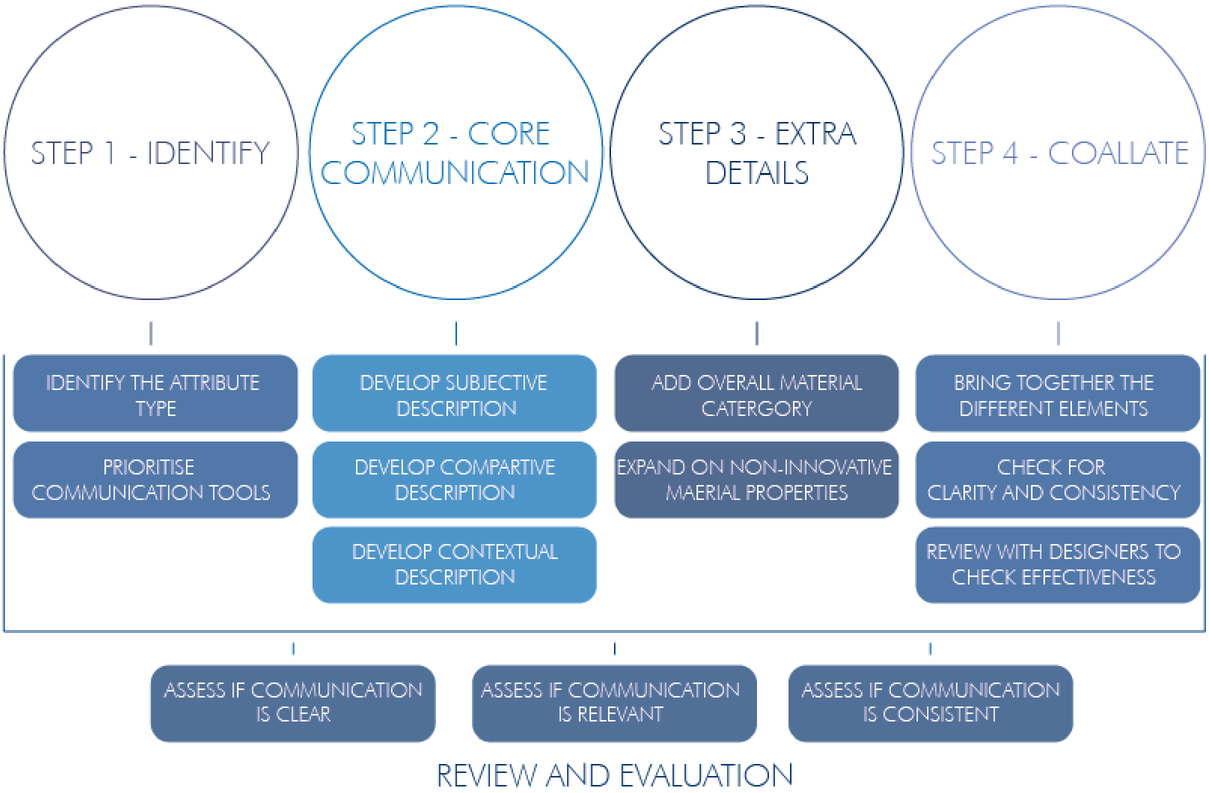


Figure 34: Summary of the CRIM framework

After building the comparison and testing it with small groups of designers, the communication can be shared to communicate the material with designers at large. Communications built in this way were shared in workshops reaching over 100 designers. The concepts that designers generated with these communications were consistently more feasible, with 84% being considered fully feasible compared to 48% in earlier testing. In addition, more ideas were generated through these workshops. This provides evidence that this research has contributed an understanding of what communication tools designers use, how they can be combined effectively, and has produced a practical framework that others can use to communicate radical innovations in materials to designers.

Previous research has not explored the linguistic communication methods that designers use, with most adjacent research focusing on the other communication tools including sketching, modelling and technological solutions. This research approached the communication entirely linguistically, aiming to use the most basic tools to create the greatest benefit. The results, which were sourced from detailed interviews, focus groups and workshops, identified not only the preferred communication methods of designers but also the most popular methods among these methods. The methods used to communicate where; Subjective communication, Comparative communication, Contextual communication and Objective communication. Objective communication though was very rarely used and was not tool designers relished using and its use in the framework was minimised. The most popular tool was that of comparison, which designers used the most to discuss innovative materials.

When comparing the effectiveness of this framework to other systems aimed at communicating new concepts to designers there is not a parallel system that can be used. However, systems to improve communication of material's sensorial properties to designers do exist and have been used by designers and effectively and offer a viable comparison. The tools that will be explored for comparison are the 'Materials in Products selection tool' and the 'Sensorial Atlas'(Rognoli 2010, Van Kesteren, Stappers et al. 2007). Both of these tools remain relevant as they feed into a larger push for materials experience to lead the communication of material properties (Pedgley, Rognoli et al. 2016). In a recent literature review by Veelaert, materials communication still focuses on the use on systems of experience, believing this to be an essential method to communicate materials properties. (Veelaert, Du Bois et al. 2020) These tools have many similarities, focusing on the use of resources that are meaningful to designers, swatches, contextual examples and comparisons to known materials to help designers communicate more effectively.

These systems aim to help designers build up a standardised language, by using these communication methods as range of samples tied to more objective language. While 'Materials in Products selection tool' aims to do this is so designers can discuss more among themselves, the 'Sensorial Atlas' aims to do this acquaint designers with the objective language used by engineers and other practioners. Both though wish to equip designers with resources to discuss materials in a more standardised way. This is part of a larger move by design academics to improve 'language', this language including physical samples or visual content, around the intersection between design and materials.

The research builds on the existing academic and industrial exploration of different areas covered in the literature review. When exploring communication there is a great deal of research focused on how important it was to generate an understanding of what had to be communicated and how to communicate this content. This research supports those goals by focusing on creating a clear guideline for what must be communicated and how to help designers understand radical innovation. Current communication approaches that focus on communication between industries rarely focus on communicating 'new' concepts. Therefore, this a useful addition to this area of study as it provides an example of how to communicate entirely new information.

As part of this drive to support communication, this research can also be seen to support aspects of innovation journalism. Innovation journalists who frequently discuss materials can be seen as material communicators who may benefit from this research. The content builds on the key pillars that form good innovation journalism, providing a strategy for communicating content, clearly while making it relevant to the those it is targeted at. To best support innovation journalism, it could have done more to offer creative suggestions as to how to resolve these challenges a key need outlined by the INJECT system (Andreassen, Polden et al. 2018). Despite this lack of creative support, the CRIM framework may be well placed to support systems such as INJECT offering a process that paired with a system that is already capable of offering creative examples and connections could create a valuable output. The challenge set out by Nonaka (1994) to create a clearly definable knowledge base and to create clear limitations on what should be communicated has been met. The framework now allows for any innovation, to gain a specific category and recommendations to how it should be communicated as well as explaining what that communication should be limited too. The fact that the framework is successful 84% of the time helps ensure that the tool is seen as reliable, a key recommendation outlined by those who focus on communication between industries.

This research not only built up a greater understanding of the communication methods in a general sense but also allowed for the creation of a framework that would enable a material communicator to take their knowledge of radically innovative material and create a reliable communication method for designers. When looking specifically at design communication, this research has aimed to support this discipline's focus on how language, visual, tactile, verbal and written communication can be shaped for maximum impact as well as clearly codifying the content to be shared. These are core elements to creating a formal communication that is invaluable to designers and material communicators. Something that occurs in most design communication tools.

When looking at those processes that aim to support the communication of materials, little around communication of material innovations has been explored. The study of materials impact on designers is gaining traction, with Material Driven Design (Van Bezooyen 2014) having additional research focused on it and studies on how the experience of materials can inform designers work before being completed (Pedgley, Rognoli et al. 2016). However, this research goes some significant way to plugging a gap in materials communication to designers. The work of Lefteri (2014) and Ashby & Johnson (2013) provides detailed information on materials but does not approach radically innovative materials in a distinctly different way to other materials. This research helps plug that gap, offering a proven way to help explore radically innovative materials. The communication in these books focuses heavily on the use of comparison and context, aspects that appeared through the independent research in this thesis. The fact that these well-respected resources already use these tools does a great deal to add credibility to the CRIM framework, showing that there is a consistency in how designers consume communication. The added value of being similar also allows for content generated by CRIM to smoothly compliment this research while not conflicting with the other content produced in this way.

When this framework is compared to these methods of communication the first similarity that stands out is the use of subjective, comparison, and contextual. The language used is very similar to that language used in these communication methods. Early research independently showed that this is the most effective way to communicate with designers and as such it adds credibility to the research to see it in use by these established tools. In addition, the inclusion of swatches in both add credibility to the importance of physical samples which are seen as indispensable part of material communication.

However, the CRIM framework does diverge strongly from the goals of these more established methods, in the fact that it does not aim to bring a standardised language to the communication process. The CRIM framework is meant to be used on a much wider variety of materials than either any of the tools intended to be covered by these materials experience approaches. In addition, the materials are vastly different in their capabilities, so it not surprising or unexpected that this should be a difference.

An argument could be made that the CRIM framework should seek to provide a consistent language as part of its remit, creating objective measurements of material properties in the same way as the more established methods. Objective language helps communicate outside of design, is consistent and reduces personal biases. The reason this objective language is not the target of the CRIM framework is due to its focus on communicating new things with old methods. The CRIM framework is effective as it uses language and examples that designers recognise to communicate something they don't, the inverse of these other methods which aim to shape language of known things. None of the research conducted shows that creating new language would have improved the communication of radical materials and in fact objective language was used, this is in addition to the challenge of creating or finding objective language that could cover the full scope of the material properties that the CRIM framework must handle.

Instead of creating a new standard language or connecting properties with existing objective language the CRIM framework instead brings a standardised method of communication. This method offers the flexibility to communicate practically any radically innovative material. This does diverge from the larger academic push to bring formal language to the design process. As covered above, applying a rigid language structure would not be effective due to the scope of the framework and the need to communicate new concepts with familiar language. What may be part of the value of this research is to highlight that formalising the structure of language offers a different and valid solution to communication in design sphere, offering a solution to communicating difficult or broad content.

In addition to offering a different method to communicate the CRIM framework also helps fill a gap and support these resources. These established methods could benefit from the ability to also clearly define these new capabilities. Something that their current processes lack. Where this research does not expand on is Karana (2010) and Silve's (2016) work, the work outlined here does not specifically help designers communicate more effectively with users or clients, key tenants of these pieces of research. It is possible that this research could aid in this area of communication however more would need to be done to help make the communication here demonstrably improve communication outside of the material communicator/designer relationship.

9.3 LIMITATION OF THE STUDY AND FUTURE RESEARCH

The limitations of this study from a methodological standpoint are covered throughout the thesis. Looking at the scope of testing and research, it is important to note limits placed upon the work. The studies focus is entirely on how written or verbal communication can be used to communicate materials accurately and did not investigate how materials could be communicated through other means, such as sketching, 3d tools, images, or other technology. This was deliberate because the investigation of how communication could be effective was already a large prospect when the focus was entirely on verbal, written/communication. Other methods could prove to be more productive or add significant benefits to communication strategy.

The research also didn't overly involve material researchers. Their insights into materials could further inform how to communicate materials given their greater understanding of the medium. This also led to constraints on what materials were reviewed. The scope of materials that were reviewed was limited by those materials the author and their connected network was aware of. As new innovations are emerging consistently, there will be innovations not reflected in this research. In addition, as many materials developed may only be discussed within specific fields (outside of design) it is possible that types of radical innovation were missed. Many expert sources were pulled on to help negate this situation, but it is impossible to say that this report covers all forms of radical material innovation. It is, however, possible to say it reflects all radical material innovations that are aimed at designers.

The core application of the CRIM framework is the communication of radically innovative materials to designers by material communicators. At this it has a proven value. There is a potential though for a wider application of the research in a way that can help different groups. As a primary example, the output of the CRIM framework has potential to help anyone who is trying to understand radically innovative materials, not just designers. The ability to communicate new concepts more effectively could benefit design education by adding a new option for teachers to employ it. In addition, it could also benefit those who seek to explore STEM learning. For those involved in Design and STEM education a system proven to improve understanding of radical innovations could offer a springboard for additional research to see if the CRIM framework could have wider applications. In managerial sectors the need to understand new concepts is also a key aspect of staying informed of the options available to them, sharing this framework with those who focus on corporate communication could also provide an opportunity to explore its application in this sector.

Any future research will look to target how communication could be enabled through various other means outside of verbal and written communication. In addition, there is the potential to spread the communication tools to focus to include innovation types outside of the radical sphere. Incremental innovations were not tested as part of this research, apart from to establish if there was a difference between them and radical innovations. It would be exciting to understand if the failure of communication is present in this form of innovation as well. Further, it would be interesting to see if the tools outlined in this research, could potentially be of use to effectively communicate incrementally and what tools might need to be changed to reflect the different form of innovation.

Future research should also include seeing if the CRIM framework has a wider application, as outlined above there is great potential in the educational sphere and in managerial sphere. To fully explore this, tests similar to the workshops completed in this thesis can be undertaken with these groups, seeing if the communication radically innovative materials changes through use of the CRIM framework. If it does a case could be made to further explore how the CRIM framework could be applied to a much wider audience and potentially see if CRIM could be used to communicate more than just radically innovative materials.

9.4 RECOGNITION IN THE INDUSTRY

Over the duration of this research the researcher has had their work and expertise recognized in number of different ways.

- For their knowledge of the sector the Materials and Design Exchange, which works in connection with the Knowledge Transfer Network, offered the researcher a role as an advisor. In this role the researcher helped support their efforts to improve the communication of materials between designers and material's scientists.
- As part of their work in the Light Touch Matters project which looked to bring design driven innovation into materials production cycle the researcher was appointed secretary for the communication group. The researched was expected in this role to co-ordinate academics, material's experts and senior designer's looking to improve the communication in the project.
- Through the Light Touch Matters project the researcher also gave insight on their learnings to the white book by Roberto Verganti and others. The researcher wrote a short chapter outlining their thoughts on how best to improve communication which appears in the published document.
- Over the duration of the research the researcher has spoken about materials at the Royal College of Art, Kingston University, Bristol UWE, Politechno Di Milano and others.
- The researcher worked with the staff at the University College of London's Institute of Making to lead a workshop on how to communicate radically innovative materials.

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11 APPENDIX A WORKSHOP SERIES CONTENT

11.1 RECORD OF FIRST WORKSHOP SERIES

Workshop 1	
Designer type: Design Students with professional experience	Number attending: 14
	Ideas produced: 6
Workshop 2	
Designer type: Design students	Number attending: 20
	Ideas produced: 8
Workshop 3	
Designer type: Design Students with professional experience	Number attending: 18
	Ideas produced: 5
Workshop 4	
Designer type: Professional designers	Number attending: 12
	Ideas produced:7
Workshop 5	
Designer type: Design students	Number attending: 19
	Ideas produced: 6
Workshop 6	
Designer type: Professional designers	Number attending: 8
	Ideas produced: 3
Workshop 7	
Designer type: Design students	Number attending: 15
	Ideas produced: 7
Workshop 8	
Designer type: Professional designers	Number attending: 7
	Ideas produced: 3
Workshop 9	
Designer type: Professional designers	Number attending: 6
	Ideas produced: 2
Workshop 10	
Designer type: Professional designers	Number attending: 8
	Ideas produced:4

11.2 RECORD OF SECOND WORKSHOP SERIES

Workshop 1	
Designer type: Design Students with professional experience	Number attending: 10
	Ideas produced: 6
Workshop 2	
Designer type: Design students	Number attending: 16
	Ideas produced: 9
Workshop 3	
Designer type: Design Students with professional experience	Number attending: 8
	Ideas produced: 5
Workshop 4	
Designer type: Professional designers	Number attending: 7
	Ideas produced:6

Workshop 5	
Designer type: Design students with professional experience	Number attending: 8
	Ideas produced: 4
Workshop 6	
Designer type: Professional designers	Number attending: 8
	Ideas produced: 6
Workshop 7	
Designer type: Design Students with professional experience	Number attending: 8
	Ideas produced: 6
Workshop 8	
Designer type: Professional designers	Number attending: 9
	Ideas produced: 5
Workshop 9	
Designer type: Design students	Number attending: 19
Material's focused on	Ideas produced: 10
Workshop 10	
Designer type: Design students	Number attending: 15
	Ideas produced: 6
Workshop 11	
Designer type: Professional Designers	Number attending: 7
	Ideas produced: 4
Workshop 12	
Designer type: Professional Designers	Number attending: 8
	Ideas produced: 5

11.3 IDEAS GENERATED IN BOTH WORKSHOP SERIES

N	Designer	Material used	Concept	Feasibility	What is/are the innovative properties used?	Which limitations, if any are, exceeded?	Logic behind assessment	Additional notes
A1	Design student only	Nitinol	Micro Solenoids for use in small electronics.	3	Changes shape when exposed to high temperatures or electric currents that cause high temps in the metal	none	Analogous to current use in actuators	Used as controllable switches through electric current
A10	Professional designer	Mycelium	Coffin for quick decomp	3	Biodegradable, can be grown to shape	none	Current use of the material	Designer proposed making a thick coffin out mycelium and working in seeds of the deceased favourite tree
A11	Design student only	Mycelium	Exhibition stands that are one use only	3	Biodegradable, can be grown to shape	none	Current use of the material	Material can be grown into sheets and shapes for short term stands
A12	Designer student plus some practical	Mycelium	Helmet lining	2	Biodegradable, can be grown to shape	Physical strength and ability to endure liquids	While the material has been used in helmets the designer described the use of the helmet as a replacement for 'all the plastic'. However, the material is prone to break down in water, either from sweat or rain. It is also not hard enough to serve the roll as the external layer of plastic. The mycelium could potentially function in this way if wrapped in something waterproof.	Designer wanted to replace all the plastic in a bicycle helmet with mycelium to make an alternative eco-friendly helmet. When questioned they did clarify that they meant both the polystyrene and harder outer shell.

A13	Design student only	FIBRE OPTIC FABRIC	For the coupe folding fabric in cars	2	Use of flexibility and light up qualities	ability to handle scratches and creases	The need to have the coupe fabric fold back and away is likely to break the Fibre optic fabric	The designer wanted a way to have the fabric of a coupe light up and wanted to have the normal fabric augmented with Fibre optic fabric.
A14	Professional designer	Fibre optic fabric	flexible Fibre optic ropes	2	Use of flexibility and light up qualities	overestimate ability to bend	as fibre optic cables are part of Fibre optic fabric the is no way that a rope could achieve this. However, the fabric could still assume a rope shape but not one that is highly flexible.	Designer imagined weaving the Fabric together to make very flexible ropes which they described 'as more flexible than fibre optic cables'
A15	Design student only	Fibre optic fabric	Built into wall of car tires	0	light up capability	none	The materials light up capability was imagined being built into the rubber of car tires. This didn't use the fabric or the innovative nature of the material. While embedding fibre optics into a wheel is possible the idea has no recognition of what was communicated about the material	The designer wanted to thread fibre optic cable into the surface of tires to make the wheels light up.
A16	professional designers	Fibre optic fabric	bags for high end shopping	3	Use of flexibility and light up qualities	none	This matches other uses in clothing and bags	The designer wanted to use the material to light up the outside of tote bags and embed the tech in the handle
A17	Professional designer	Ferrofluid	Obscuring lights that are on to create shadows	2	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	how magnetism affects the material	The designer was confused about how the magnetism would affect the change believe a stronger current would cause the material to grow around the light. Adding an electromagnet along the length of the light would solve the issue	Designer wanted to have a light that was surrounded by water and ferro fluid. As the light got brighter the ferrofluid would be drawn up the light to obscure it, creating an interesting affect

A18	Designer student plus some practical	Ferrofluid	real life visualizations of structures	2	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	how accurately the material can adopt shapes	The ability to create accurate structures in ferro fluid is very hard. The designer showed a knowledge thought different magnet pulses could be used to illustrated different areas, so this was noted as partially feasible as the designer understood the material but not it's limitations	Designer wanted to have a surface with magnets underneath and ferro-fluid on top that would allow the accurate simulation of different cities skylines, parks and other features,
A19	Design student only	Ferrofluid	Braille machine	3	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	none	Current use of the material	The designers imagined the material being underneath a silicone wrap and able to change shape to replicate the feel of dots and dashes.
A2	Design student only	nitinol	Switches that cut out at high temperatures stopping use. By physically resisting use and disengaging circuit.	3	Changes shape when exposed to high temperatures	none	Analogous to current use in actuators	Material would be contract shutting off a switch when exposed to heat, or making the switch harder to use for safety
A20	Professional designer	Ferrofluid	Shape changing material, allowing for multiple shapes of a product	2	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	Level of viscosity possible	The designer imagined having the ferrofluid as a way to contour the handles of screw drivers to different needs. While they understood the materials limitations around energy and need to be in a silicone wrapping, they overestimated how vicious the material would get, imagining that it would be capable of enduring tight grips and still holding form.	Designer wanted to embed ferrofluid under a silicon sheath that would allow the handles of screwdrivers and other tools to change shape based on the electromagnetic tuning from within.

A21	Professional designer	Faraday	Game systems	3	clear conductive coating	none	the use of the material to make invisible connections between visible components is more than possible and has been done by others	Designer liked the idea of having games printed onto glass allowing two people to see through it at each other while still allowing for small LEDS to light up and sensors to be connected to these lights
A22	Design student only	Faraday	warning lights that discrete before illumination	3	clear conductive coating	none	the use of the material to make invisible connections between visible components is more than possible and has been done by others	Designers wanted to have ability to build warning patterns on glass or plastic structures that at a distance wouldn't be visible unless illuminated
A23	Designer student plus some practical	Faraday	Light built into glasses, warning	3	clear conductive coating	none	the use of the material to make invisible connections between visible components is more than possible and has been done by others	Designer wanted to build an LED into glasses that wouldn't interfere with using them.
A24	Professional designer	Faraday	Stick on adverts	2	clear conductive coating	expect that material functions without power source	As the designer explained the concept, they didn't show an understanding that they would need to be a power source or a connection to one to enable the material to function.	Designer described the concept as being a sheet of invisible plastic that could be stuck onto glass and would light up instantly. They specifically mentioned it wouldn't need a power source.

A25	Professional designer	Faraday	Flexible light up leaflets	2	clear conductive coating	ability to handle scratches and creases and ability to bind to non-plastic/non glass surfaces	As the designer wanted to add the coating to paper to make the circuit, this would likely break very quickly if it worked at all. A different base, like a plastic would allow this concept to function	designer wanted to coat paper leaflets with the coating and then embed electronics in them.
A26	Professional designer	PCM fabric	Clothing	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer imagined using this in clothes that are in constant contact with the body
A27	Design student only	PCM fabric	Helping regulate plant temperatures	2	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	scale of ability to absorb and release heat	The designer imagined putting the material into plant pots to help keep their leaves at the right temperature, the problem is that the material cannot affect air any great distance and as such won't be able to regulate temperature away from the plant pot. Changing the design might allow for some heat retention and balancing properties so the material was given this feasibility rating.	the designer imagined a plant pot that could act as its own greenhouse keeping the plant at the right departure.
A28	Professional designer	PCM fabric	children's cribs	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	designer imagined putting the material into children's bedding to help keep them cool

A29	Professional designer	PCM fabric	sleeping bags	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer imagined lining sleeping bags with the material
A3	Design student only	Self-healing plastic	Puncture gear for bicycle tires	2	Material can permanently adhere to itself with nothing but gentle pressure	belief that the material can bond to other materials	The material was expected to be put directly onto the wheel and stick. The concept could work if wrapped tightly round a puncture as it is used purposes similar to this in plumbing.	The designer described an instinct patch that could be applied to a spot around a puncture in a bike tire. They were clear that this was a spot fix not a wraparound bandage
A30	Design student only	PCM fabric	blankets for food to keep it refrigerated	2	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	ability to reduce temperatures to below a certain temperature	The temperature that the PCM fabric can reduce food to is not the same as a fridge.	Designer wanted to have a covering that could be pulled over food to keep it at fridge temperatures once out of the fridge
A31	Design student only	PCM fabric	oven gloves	2	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	scale of ability to absorb and release heat	The material cannot absorb temperatures that much. The limit is several degrees above body temperature.	The designer imagined embedding the material into oven gloves to make the material feel nicer to the touch and enable the material to be thinner as they believe the PCM would absorb oven temps
A32	Design student only	D3O	Phone cases	3	ability to be absorb impacts extremely well	none	Current use of the material	Described lining the edge of a case with the material to help reduce shocks

A33	Design student only	D3O	bullet proof inserts for clothing	2	ability to be flexible but rigid when impacted ability to be absorb impacts extremely well	ability to absorb impacts and handle penetrative/cutting forces	The D3O material can help absorb impacts but is still limited in its abilities. Layering the material with other materials has been shown in real world examples to be effective in stopping bullets.	The designer imagined this as something that could be put into pockets in clothing to add a bulletproof element to the clothing
A34	Design student only	D3O	Luggage lining for flexible bags	3	ability to be flexible but rigid when impacted ability to be absorb impacts extremely well	none	Many bags benefit from the ability to be flexible; this would add a layer of protection the contents without compromising flexible.	the designer wanted to use the material on the inside to reduce the impacts to the goods
A35	Professional designer	PCM fabric	Clothing	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer imagined putting the material into sports clothing
A36	Professional designer	PCM fabric	Refrigerating food	2	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	ability to reduce temperatures to below a certain temperature	The temperature that the PCM fabric can reduce food to is not the same as a fridge.	Designer wanted to have a box that could be used to chill food as an alternative to the fridge
A37	professional designer	PCM fabric	bedding	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer wanted to put the material into bedding

A38	Design student only	Fibre optic fabric	Decorations (using flexibility to allow movement in wind)	3	Use of flexibility and light up qualities	none	This is possible for the material	The design group wanted to use the material as banners that would light up and move in the wind
A39	Design student only	Fibre optic fabric	tables of restaurants	3	Use of flexibility and light up qualities	none	Current use of the material	The design group imagined this as a light up tablecloth
A4	Design student only	Self-healing plastic	Bandage weaves	2	Material can permanently adhere to itself with nothing but gentle pressure	limited adhesion in small connections	By knitting the material into the bandage many other fibres are likely to interfere with the self-annealing process forming very poor connections.	Designer imagined combining the fabric with other fabrics to create a self-bonding bandage. They described using small amounts to achieve this so as to not compromise the bandages normal function.
A40	professional designer	PCM fabric	Cooling bandages	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer wanted to work the material into bandages for sensitive wounds like burns
A41	Design student only	PCM fabric	Insulating gloves	2	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	scale of ability to absorb and release heat	The material cannot absorb temperatures that much. The limit is several degrees above body temperature.	The designer imagined embedding the material into barbeque gloves to make the material feel nicer to the touch and enable the material to be

								thinner as they believe the PCM would absorb oven temps
A42	Designer student plus some practical	PCM fabric	bed sheet	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer wanted to make bed sheets that could help regulate body temperatures
A43	Designer student plus some practical	PCM fabric	cover sheet, cool coating for a book that elicits a response when touched.	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	The material can be used to create tactile responses on flat surfaces	Designer wanted to make a material texture that would feel unnaturally cool on a book
A44	Design student only	Ferrofluid	Oil barrier in water	1	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	material floats, belief it will impart magnetic properties to other oil	The designer believed the oil would float and could be used to mop up oil spills by mixing with them and then picking all the oil up with magnets. The oil does not float nor do its magnetic properties automatically spread to oil it comes into contact with	The designer imagined putting a large amount of ferrofluid on top of existing oil spills and then after the oils had mixed picking it all up with a magnet
A45	Design student only	Ferrofluid	Floating joint	1	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	belief the material has magnetic attractive forces and will float	The designer envisioned a material that could float on water and create joints between different floating objects. The material does not float nor is in itself magnetically charged	The designer imagined two pontoons linked by a stream of ferrofluid that could be teased into different shapes to move the two objects

A46	Design student only	Microsuction	Puzzle seat that can be attempted many ways	2	Reusable, non-glue-based adhesion	strength of adhesion	The hold strength for micro-suction tape is too low to support body weight if it was combined with some other method of joinery though it would help create useful hold.	The designer wanted to build a seat that could be assembled in different ways and pulled apart and tried again using only the tape as the joinery
A47	professional designer	Microsuction	Adaptable system of shapes for a table that can be altered	2	Reusable, non-glue-based adhesion	strength of adhesion	The hold strength for micro-suction tape is too low to support weight or the forces tables are subject to if it was combined with some other method of joinery though it would help create useful hold.	The designer wanted to build a table that could be assembled in different ways to suit different people using only the tape as the joinery
A48	Design student only	Microsuction	replacement for screw fittings	2	Reusable, non-glue-based adhesion	overestimate holding force	Microsuction tape does not have the strength of a screw, it can support some weight though and could be replacement for some limited joinery options.	The designer imagined this as a tool in kitchens for ways to mount shelves without the need to drill into tiling.
A49	professional designer	Bright green	Accessories for never dyeing plants.	3	Doesn't need to be tended or watered	none	didn't have the material being disturbed and specifically mentioned that it was a low maintenance option	Designers explored that it would be great for those who can't easily keep plants alive adding some extra greens to plants like succulents.
A5	Professional designer	Self-healing plastic	Industrial wrapping for large containers.	3	Material can permanently adhere to itself with nothing but gentle pressure	none	analogous to use as a sealing tool	

A50	Professional designer	Faraday	Large touch screen, plus addition of clear solar cells.	1	clear conductive coating	belief the material functions as a touch sensor	Designer believed that the coating made the surface touch sensitive which is not how the material works.	Designer imagined a cheap way to replace technology in iPad screens.
A51	Design student only	Ferrofluid	Lava Lamp sequel design	3	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	none	Current use of the material	The designers imagined a glass like a lava lamp where the amount of electromagnetic changed from time to time.
A6	Design student only	self-healing plastic	Insulator tape a replacement for heat shrink for wires.	2	Material can permanently adhere to itself with nothing but gentle pressure	temperature	The material is not rated to high temperatures that wires will encounter	The designer wanted to use the material to wrap up electronics and insulate wires. The material has not got sufficient ratings to enable that.
A7	Professional designer	PCM fabric	Food temp-regulator for fridges	2	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	temperature	The material cannot reduce temperature that much. The limit is several degrees below body temperature.	designer wanted to make a large sheet that could be thrown over food in fridges to help it keep it cool
A8	Design student only	PCM fabric	PCB heat regulator for energy spikes.	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	While the material is not rated to stop exceptional temperature change it could help with smaller variances in temperatures	designer imagined this as an addition to thermal paste in computers

A9	professional designer	Mycelium	Drone parts, for eco drones that degrade if lost.	2	Biodegradable, can be grown to shape	expectations of physical rigidity	The designer described using the mycelium for both the body and the rotors, this would place a high stress on the material limiting its ability to work with mycelium examples of mycelium bodied drones do exist though	The mycelium could be used to make all the non-electric parts of the drone and allow it to biodegrade once those parts are removed or the drone is lost
B1	Design student only	D3O	A bullet proof lining for a hoodie	2	ability to be flexible but rigid when impacted ability to be absorb impacts extremely well	ability to absorb impacts and handle penetrative/cutting forces	The D3O material can help absorb impacts but is still limited in its abilities. Layering the material with other materials has been shown in real world examples to be effective in stopping bullets.	Designer wanted to work D3O under the surface of hoodies to make them bullet proof
B10	Student + prof experience	PCM fabric	Car seat lining	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Analogous to current uses in pillows	The designers wanted to make car seats cooler and better and controlling body temp
B11	Professional designer	Cellular metal	Chair shaped in any dimensions through sintering process	3	ability to make shapes through sintering. High strength	none	Current use of the material	Designers wanted to make more ergonomic forms than traditional metal working would allow.
B12	Design student only	Faraday film	Clear Rain sensing ceiling	3	clear conductive coating	none	Current use of the material	Each of the sections would be divvied by breaks, when rain rolled over them it would complete the circuit causing the material to light up.

B13	Professional designer	Dry inside	clothes for lifeguards on cold beaches	3	wick away moisture	none	This concept built up the idea of using the clothes to help dry and keep warm those who might need that kind of support.	Designer explained that these would be clothes taken off before swimming and put back on after, accelerating the drying process and getting cold water away from skin
B14	Professional designer	PCM fabric	Clothing	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer imagined using the material as clothes to keep you cool
B15	Professional designer	PCM fabric	coating for fake marble to give real coolness	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	The material can be used to create tactile responses on flat surfaces	Designers wanted to dust the PCM material over the surface of fake marble to give it a cool feel. (The did not intend to use the fabric)
B16	Design student only	Faraday film	Coating to glossy wood to make surface conductive	3	clear conductive coating	none	possible with wood that has a smooth enough surface or has been already treated	Designer wanted to be able to embed electronics in the surface of wood.
B17	Design student only	Faraday film	Conductive mirror	3	clear conductive coating	none	the use of the material to make invisible connections between visible components is more than possible and has been done by others	Designer wanted a way to build LEDs into the surface of a mirror to improve illumination

B18	Professional designer	Bare Conductive Paint	Could be used to replace wires in printed circuit boards	3	Paint on wiring	none	This is a current use of the material	Designers discussed making a special tool to spray the bare conductive or modify printers to be able to take the ink
B19	Professional designer	Ferro fluid	digital clock	3	use of attraction to magnets and ability to flow through water	none	Current use of the material	Designer imagined a clock that had electromagnets to indicate time in the digital format.
B2	Design student only	Self-healing	A temporary strip to patch damaged clothing	3	Material can permanently adhere to itself with nothing but gentle pressure	none	If layered on both sides of a hole the material would seal	Designer wanted a quick repair tool for waterproofs when out in the field, while they acknowledged this wouldn't repair a hole, they did imagine it being able to seal up a tear in clothing, enough to get home and make improvements
B20	Professional designer	PCM fabric	Fever towel	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designers wanted to create a material that would help keep you cool when in a fever and warm you up when it breaks.

B21	Professional designer	Intumescent foam	Foam that blocks airways which would feed a fire	3	Ability to grow when exposed to heat. High flame retardant nature	none	Current use of the material	Designer imagined lining doors, air vents and chimneys with the material to cut down on airflow
B22	Student + prof experience	PCM fabric	Food chiller	2	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	Temperatures that the material can cool things too	The material cannot reduce temperature that much. The limit is several degrees below body temperature. It could however help keep food colder for longer, so this concept has been rated a 2 on feasibility	The designer imagined making a box that would allow for the PCM to act as a fridge actively chilling the food and keeping it cold for longer
B23	Student + prof experience	Nitinol	Food thermometer that changes shape	3	Changes shape when exposed to high temperatures	none	Analogous to current use in novelty spoons	Material would change shape once a specific temperature was reached.
B24	Student + prof experience	Bare conductive	For temporary patches on circuits	3	Paint on wiring	none	Could be used for PCBs due to their limited need to flex and low exposure to moisture	designer described a system by which someone could paint over small breaks that might be scratched in PCBs
B25	Professional designer	Bright green	Greening areas with no natural light	3	fact it stays green without sunlight or water	none	Current use of the material	Designers liked the idea of using it in bathrooms which typically don't get lots of light

B26	Design student only	Life cork	ECO Handlebars for a traditional style bicycle	3	Soft texture - eco-friendly nature	none	Current use of the material	Designer wanted to see an eco-friendlier alternative to rubber bicycle handles
B27	Student + prof experience	Dry inside	Hat for somewhat rainy days	3	wick away moisture	none	The material would enable the limited amount of rain to be repelled and any that did get through would be able to dry faster	The idea proposed by the designers was to have a hat that could stop small amounts of water getting in or helping dry on days when a fully waterproof option wasn't needed
B28	Design student only	Nitinol	Heat reactive locks, sealing important doors or structures	3	Changes shape when exposed to high temperatures	none	Analogous to current use in actuators	Designer specified the material could be used to unlock fire doors if they got to hot or lock doors which needed to stay closed as het could cause the lock to open or close by changing the wires shape
B29	Professional designer	PCM fabric	Hidden messages told through heat	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	The material can be used to create tactile responses on flat surfaces	Designers wanted to see the material (the dust not fabric) put into different surfaces to create hidden experiences that could only be found through integration with the materials
B3	Design student only	Phase change fabric	Add to weighted blankets to keep cool	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Analogous to use in bedding	Designer wanted to make the feel of weighted blankets more pleasant

B30	Student + prof experience	Mycelium	Insulation in a temporary accommodation	3	Biodegradable, can be grown to shape	none	The material could function as temporary insulation, though the fire rating and actual heat retention is unknown	The designer wanted to line walls with sheets of mycelium to add a layer of insulation against heat and sound
B31	Design student only	Ferro fluid	Jewellery that changes shape	3	use of attraction to magnets and ability to flow through water	none	The fact that the designers both explained how the material was to be contained and how it could be activated by different electromagnets	designer described a necklace of silicone pockets which could have different charges put through them to move the ferrofluid
B32	Student + prof experience	Shape Memory Polymer	lamp shade that changes shape base on how long the light has been on/off	1	Shape changing	Assumed that this was a two-way change, when it is only one way	The material only has a one-way change state and the material also needs to reach significant temperatures across the whole material. This change is also limited in scope	The designer imagined a lamp shade that could open when on and close when off powered only by the heat of the light.
B33	Professional designer	FIBRE OPTIC FABRIC	Light up Dress	3	Use of flexibility and light up qualities	none	Current use of the material	Designers imagined a light up dress that could fit for celebrities
B34	Professional designer	FIBRE OPTIC FABRIC	Light up sign	3	Use of flexibility and light up qualities	none	This fits the materials durability and physical abilities	Designers imagined a hanging a sign which lit up showing important information on the road

B35	Professional designer	Intumescent foam	Lining round a cooker	2	Ability to grow when exposed to heat. High flame retardant nature	how much the material grows	The amount by which the foam expands does not match up with the expansion needed to create the larger container like walls the designer described.	Designer described this as for a scenario that if a fire starts the foam will create a barrier between the cooker, encapsulating it and protecting the rest of the kitchen
B36	Professional designer	Fiberline	Low weight replacement for steel in non-essential body parts of cars	3	Use of low weight and high strength of material	none	The material is already used to structurally support architecture so the use in cars for non-essential parts is possible	Designer imagined using the material in folding rooves of the car or on the bike racks/luggage supports.
B37	Professional designer	Cellular metal	Luggage that can survive damage without adding weight	3	ability to make shapes through sintering. High strength-low weight	none	The use of wall of cellular metal could help absorb impacts and the designer prescribed a thick enough wall for the material to function	designer described an inch-thick wall protecting expensive luggage (like aircraft crates) to help absorb damage
B38	Professional designer	EL panel	make a light up travel tent	1	Illumination with flexibility	too great a degree of flexibility expected	designer expected to be able to fold up the tent into a travel bag, an amount of bending that would be impossible for and EL panel to tolerate.	Designer explained that the tent could me made exclusively from the material and then packed down and set up so you wouldn't be ignored be rescuers
B39	Professional designer	Dry Inside	Make a self-powered hose	1	wick away moisture	Limited pressure	The material cannot push water quickly while it will allow water to slowly wick up it will be very slow if at all effective at all and could be not much better than a rope as eventually the weight of the water will overcome the force of the hydrophobic coating.	designer expected the material to be able be put in hose and push water through quickly without the need for a pump

B4	Student + prof experience	Micro suction tape	Allow car add ones like spoilers to be temporary	2	Reusable, non-glue-based adhesion	strength of adhesion	The hold strength for micro-suction tape is too low for car spoilers and the material is likely to shake loose over time	The designer wanted a way to mount a spoiler to their car or potentially a bike rack.
B40	Design student only	UPM Formi	Make bouncy dice	0	None	none	The designer proposed a selection of 'bouncy' dice, this tactile feel was not the innovation	Designer wanted to make dice that he felt had a pleasant tactile feel and proposed it as a good use of the material.
B41	Professional designer	bright green	Make decorations on hard to access places	3	Doesn't need to be tended or watered	none	Current use of the material	Designers liked that is was relatively low weight
B42	Design student only	Fiberline	make easier to move furniture for always moving millennials	3	Use of low weight and high strength of material	none	The material can support enough to be used in bridges so will likely be suitable for furniture	Designer wanted to replace the steel frame of beds and items like desks and tables with Fiberline
B43	Student + prof experience	Cellular metal	Make light weight combat body armour	2	High strength/ low weight	durability	The material is not highly durable especially when thin enough to be considered wearable. It can absorb impacts well and could be used in other armour like applications if used in scenarios that allowed it to be thicker	The designer imagined adding the material as a layer in thin body armour that could be worn under clothing

B44	Design student only	Faraday film	facilitating buttons on glass surfaces	3	clear conductive coating	none	the use of the material to make invisible connections between visible components is more than possible and has been done by others	Designer wanted way to allow for buttons to be installed on glass doors without the need for wires trailing from them
B45	Design student only	Bare conductive	method to make temporary electrified signs that can be washed off	3	Paint on wiring/water soluble	none	The designer clearly identified that bare conductive would be part of a system that could be washed away not the only element	Designer said that combining with water-soluble glue and waterproof electronics you could create signs that could be washed away with water
B46	Design student only	Luminoso	Minimalist light source for interiors which want privacy	3	Permit light through wood	none	The material can let though light and act as a source of gentle light	Designer wanted to replace the concept of large wood walls that are lit by small lad's behind the wood so when not turned on there is no sign of the light
B47	Professional designer	PCM fabric	Motorcycle gear	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Analogous to use of material in sports gear	Designers wanted to see the material worked into motorcycle gear due to its thickness and insulating properties
B48	Professional designer	Microsuction tape	mount lights on glass	3	Reusable, non-glue-based adhesion	none	Current use of the material - used to mount light weight electronics to glass	Imagined placing lights on the glass so they could be moved and placed with ease

B49	Professional designer	Ferro fluid	Pipe cleaning tool for non-drinking water	3	Magnetism- ability to gain/loss viscosity	none	The concept allows for the ferro fluid to be squirted while liquid into a pipe and then using a magnet gain viscosity that may allow for other particles within to be shifted	Described being able to drag a magnet down the outside of a pipe to pull ferro fluid through the pipe
B5	Student + prof experience	Ferro-fluid	Allow the finding of magnetic particles in water	3	use of attraction to magnets and ability to flow through water	none	Current use of the material	The designers imagined putting the ferro fluid in water where magnetic particles would become clumped up in ferrofluid. Which could then be extracted
B50	Student + prof experience	Thermochromic sheet	build it into a pan to know exact temp	1	Heat detection	Too much heat	the material is a crystal display it has a limitation on how hot it can get before losing function, not to mention the plastic it is embedded into would melt.	the designer imagined putting the thermochromic sheet in pans wall so the temperature of the food could be seen
B51	Student + prof experience	Mycelium	replace traditional Styrofoam	3	Biodegradable, can be grown to shape	none	Current use of the material	The designer imagined replacing Styrofoam with mycelium
B52	Design student only	Intumescent foam	seal things like computers or microwaves which only have small opening to reduce oxygen supply	3	Ability to grow when exposed to heat. High flame retardant nature	none	The material is currently used in similar but not identical situations and is likely to work in this manner	Designer wanted to have a grid of foam that could seal shut near air vents, effectively sealing in the fire

B53	Professional designer	Cellular metal	Shoe heels for light but tall shoes (new rocks (bulky platform soles)	3	High strength/ low weight	none	Having the large shoe base take the weight shows the designers understand the need for a wide spread of material rather than a high heel which would fail	Designers specifically called out the design of new rock shoes, saying the cellular metal could get rid of lots of heavy rubber while still being strong enough to support.
B54	Professional designer	PCM fabric	Sportswear	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	Designer imagined the material being worked into sports gear worn by athletes
B55	Student + prof experience	Nitinol wire	switches that activate alarms when dangerous temperatures are reached	3	Changes shape when exposed to high temperatures	none	Analogous to current use in actuators	the designer wanted to create a non-electricity dependant alarm, imagining this as a switch that would then allow a clock work or other system to activate.
B56	Student + prof experience	nitinol	Switches are activated by high temperatures	3	Changes shape when exposed to high temperatures	none	Analogous to current use in actuators	Material would be change shape when heated to a certain temperature causing a switch to be activated
B57	Professional designer	Micro suction tape	Tablet case holder, sticks direct to tablet backing	3	Reusable, non-glue-based adhesion	none	Current use of the material	Designer imagined that micro-suction tape could be used to make cases stick to phones better

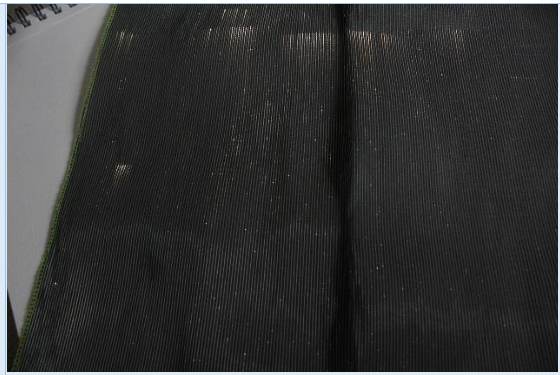
B58	Student + prof experience	Mycelium	Temporary plant pots	3	Biodegradable, can be grown to shape	none	Current use of the material	the designer imagined the ability to plant flowers in the pots without needing to remove them from the mycelium
B59	Student + prof experience	Thermo chromic sheet	thermometer for measuring the body temp of animals without need to catch them	3	Can change colour based on temperature	none	analogous to use as thermometers for babies	The material can be stuck to an animal, behind a cone or other device to stop it being bitten off so an idea of body temp can be gained.
B6	Design student only	Nitinol wire	An automatic control for vents in case of fire	3	Changes shape when exposed to high temperatures	none	Analogous to current use in actuators	Designer wanted a hinge or other shape that would shut the vents of rooms with fires in them, as the wire got hot it would pull the vent shut
B60	Design student only	PCM fabric	Gloves that keeps your hands warm	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Analogous to use of material in sports gear	Designer made it clear that this idea was not help keep your hands at the right temperature
B61	Design student only	Ferro fluid	Transportation of goods in a gel coating, can be turned off on arrival	3	use of attraction to magnets and ability to flow through water	none	The use of ferrofluid as a shock absorber that can be controlled by electric current is well documented.	Designer outlined a plan to wrap goods in wiring and seal them. Pouring ferrofluid around them and then putting a current through the wire would make the ferrofluid become viscous and keep the object suspended

B62	Design student only	Mycelium	Use for one off structures during big events	3	Biodegradable, can be grown to shape	none	similar to the current use of the material for chairs at festivals	Idea to make large drywall like structure for events, while designer knew it would need structural support the designer felt this might be more sustainable
B63	Design student only	Fibre-optic fabric	Used as a light up tie whose whole length is lit.	2	Use of low weight and high strength of material	flexibility of material and ability to handle creasing	This was described as a normal tie and designer included discussion doing different knots with it. As the material cannot endure being knotted it was ranked lower on feasibility. Simple change to a clip-on tie t would make it feasible	Designer wanted to create a tie that could be used like a normal tie, and tied in different ways
B64	Professional designer	Luminoso	Used as a screen	3	Permit light through wood	none	Current use of the material	designer imagined using the material to be projected on allowing some small amount of the picture through to the other side.
B65	Design student only	EL Panel	Used for light up signs in countries with extreme temperatures	3	function at low temperatures - illuminated	none	Current use of the material	Designer wanted to use the material to create signs that could be outside in low temperatures
B66	Design student only	Faraday Film	Used in car windscreens to defrost ice	3	clear conductive coating by passing large charge it builds up heat	none	Current use of the material	Designers wanted way to have a deice on the windscreen with no loss of visibility

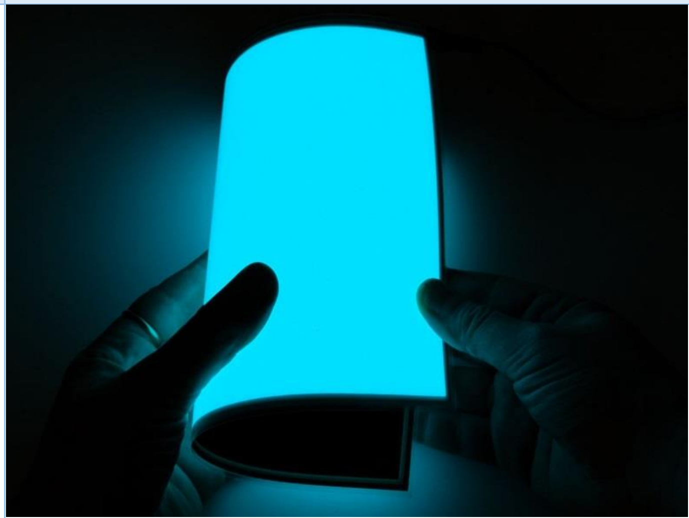
B67	Professional designer	D3O	Used to make back packs more shock resistant	3	ability to be flexible but rigid when impacted ability to absorb impacts	none	Many back packs benefit from the ability to change shape and be flexible, this would add a layer of protection the contents	Designer described using the backpack on hiking or bicycles and the impacts it can take. Explained D3O might be able to reduce the damage.
B68	Student + prof experience	Photochromic pigments	UV ray assessment tool to know how long to sunbathe	2	Can react to UV light	Ability to change UV light over an extended period of time	The material is more of a binary state going from not exposed to exposed. While this might take up to 30 seconds to kick in it's not enough to have a long-term record of UV exposure. Photochromic pigments have been seeding on suntan creams before, so this idea got a 2	The designer wanted to add a strip onto suntan cream that would slowly change colour over a few hours to indicate how much UV light it had been exposed to motivate people to use suntan
B69	Student + prof experience	Ferro fluid	Visual warning for the deaf.	3	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	none	The ability of the material to be agitated by a current in specific circumstances is well documented.	The designers proposed a fixture that would go from having a smooth pattern to having a raised spiked one to indicate a warning
B7	Student + prof experience	PCM fabric	baby clothes to maintain body heat	3	Can absorb high temperatures, feeling cooling, when outside temp drops heat is released back.	none	Current use of the material	The designs explored putting the material into baby clothes, so they don't overheat or overcool
B70	Student + prof experience	Ferro fluid	Visualize sound waves of instruments for the deaf.	3	use of attraction to magnets and ability to flow through water. Ability to change shape when exposed to magnetic fields	none	The ability of the material to be agitated by a current in specific circumstances is well documented.	The designers proposed a fixture that would have a pattern that could react to the bass level of the music turning the fluid from smooth to raised when the bass hit.

B71	Professional designer	Life cork	Wine cooler for eco-friendly wine brands	3	Insulation	none	Current use of the material	Designer imagined an eco-friendlier wine cooler
B72	Professional designer	D3O	Padding for motorbike gloves	3	ability to be flexible but rigid when impacted ability to absorb impacts	none	Current use of the material	Designer imagined this as a topping on the gloves to absorb impact
B8	Design student only	LifoCork	Bicycle seat for eco-friendly bikers	3	Soft texture - eco-friendly nature	none	The material is sturdy enough to hold this form and absorb punishment having been used in shoes	Designer wanted to see an eco-friendlier alternative to rubber or plastic bicycle seats
B9	Student + prof experience	Self-healing	Bondage gear, functioning as duct tape that doesn't stick to the person	3	Material can permanently adhere to itself with nothing but gentle pressure	none	Current use of the material	The material would be used as a tool to tape up consenting adults without worry of it sticking to hair or skin

11.4 SUMMARY OF MATERIALS PROVIDED IN THE WORKSHOP SERIES –

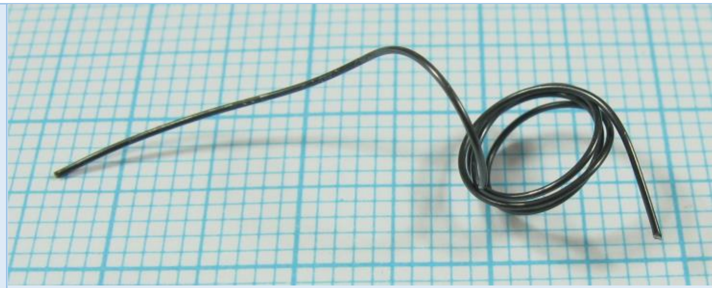
Material	Short summary of the material	Images of material
Fibre-optic fabric	Fabric impregnated with fibre optic strands, appears like a normal fabric but lights up when led is shone into the fibres. This fabric looks like a grey shiny synthetic and has a rough scratchy texture with the pattern of the fibre optic cables both visible and easy to feel. However, when a light is shone through it lights up in an organic manner.	
Bare Conductive Paint	Electronically conductive ink. Functions like a wiring when dry and can be painted on flat surfaces for quick results. Bare conductive was a recent start up that has gone from strength to strength. The has been a recent wave of conductive inks/paints and bare is one of the better solutions. In its dried form the paint can cold solder, draw circuit diagrams and be a touch interface. It's quite cool but often sees little use outside of home electronics kits and art projects. It looks like a normal black paint. Dries with a matte finish that's pleasant to touch.	

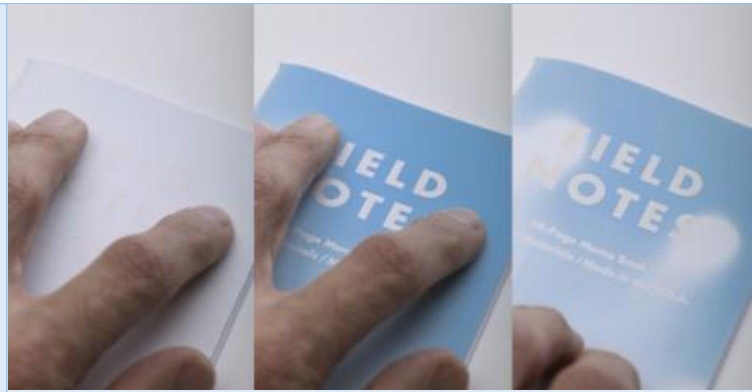
Faraday Film	Faraday film is a clear plastic film that has a conductive coating that can be made into circuits by scratching the surface. This film is completely clear with a very light tint providing a way to create completely clear circuits. Printed on a stiff plastic like cellulose it can house small low power circuits and components.	
Ferro-fluid	Oil impregnated with tiny iron fillings, reacts to the presence of electrical currents by attaching to the magnetic field and becoming more viscous. Ferro-fluid has been around for a while and you can find a lot of videos of the odd patterns and shapes the liquid can produce. However, the practical uses of this material have been so far limited to engineering applications. While its limited use in design is understandable as touching Ferro-fluid is a good way to get stains all over your hands it has some unique properties that make it different to anything else on the market.	

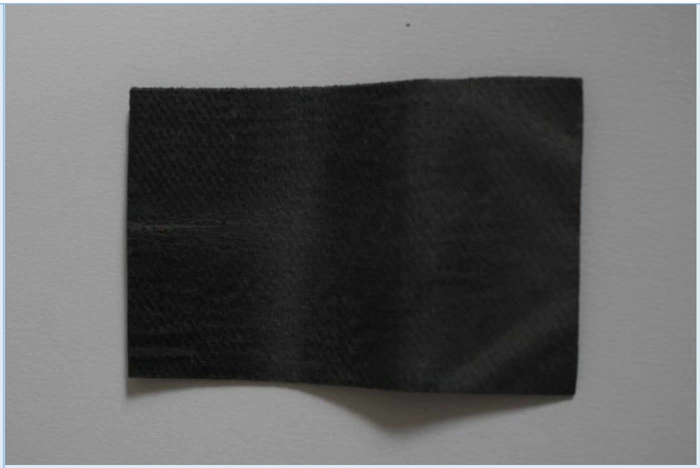
UPM Formi	Polypropylene filled with 30-50% natural fibre, making stronger and stiffer than most plastics UPM is a satisfying plastic to hold it has smooth satin finish that is quite nice to hold and a warm stiff feel to it. Looking at it there is very little to indicate that up to half its content is from cellulose fibre it's for all appearance a less flexible polypropylene. This material can reduce the impact from the plastic by 30%-60% and as polypropylene is one of the most common plastics in consumer products it may be really good option.	
EL Panel	These are panels of plastic with a thin layer of electro luminescent coating that emits light when electrically charged. Often seen as a bit of a Tron look El panels are flexible thin laminates which glow when they have power running through them. The material feels like a thick card and is encased in something like cellulose. The light it gives off is pretty good, but they are power hungry and large panels requires a power supply to get the full brightness. They can be worked on with conventional materials however they are sensitive to damage and can be easily broken if creased or cut in the wrong way.	

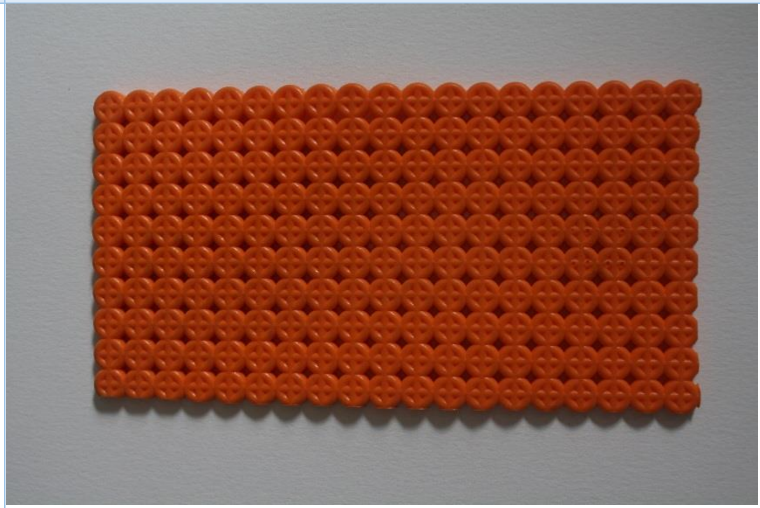
Cellular metal	Small spheres of sintered metal, with a very high strength weight ratio. Cellular metals are a distinctly odd material to hold, they feel light and gritty, but you can sense their strength if you try and compress them. Even taking a single bead which weighs next to nothing you can't compress with your fingers alone. Commonly found in crumple zones in cars to help absorb damage this lightweight material may have many more uses	
LifoCork	LifoCork is a plastic that contains shredded cork to gives it a nice cork texture and reduces the use of plastic. Cork is a great renewable resource, harvesting cork doesn't kill the tree that it is grown on, and it can be seen almost as a crop. The downside is that cork on its own is quite soft and not suited to heavy use. LifoCork takes the renewable cork side of things and wraps different plastics around cork granules to produce a wholly new material.	

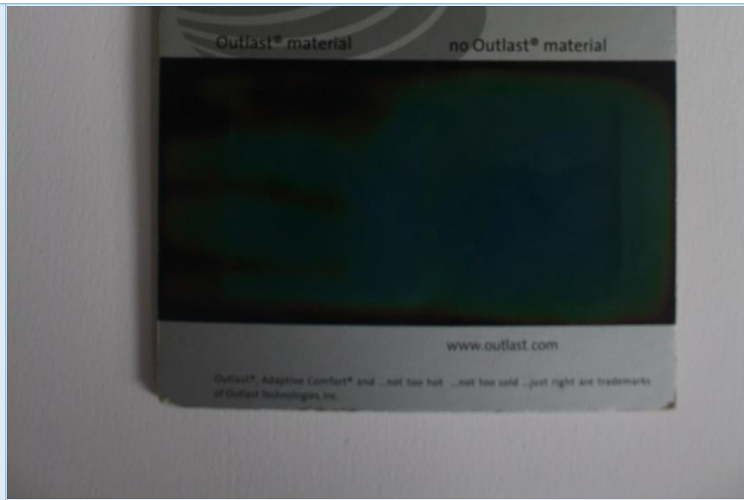
Intumescent foam	Foam that expands when exposed to high heat and after exposure chars stopping heat conduction. This foam is primarily used to protect buildings from fires as it allows for airflow in normal conditions but during fire expands sealing gaps and stopping oxygen flow. The foam is surprisingly spongy and cool to the touch, small bits of graphite can be seen in the material which is otherwise a dull ruddy brown.	
Phase change fabric	Phase change materials can manipulate heat in really special way. They slowly absorb heat feeling unnaturally cool on the skin and then slowly release that heat as it cools down. The material is available in a few forms, but we are going to look at a great sample of Outlast cloth we have in the office. This is designed to be added to other clothing either in direct skin contact or in-between layers and feels unnaturally cool to the touch but given the nice weather it's quite pleasant.	

Nitinol wire	Nitinol wire is a shape memory alloys (SMAs) are a smart material that can 'remember' a shape. SMAs will try a return to a remembered shape when heated. The effect of nitinol wire has to be seen to be believed, the odd metal will happily change shape and unknot itself. The shape change also exerts some force when doing so allowing it to be used as an actuator. The material gets some use in engineering and medical applications but considering its unique properties it should have some more uses by now. Mostly it can be purchased with a memory of being straight or as a spring, but other samples do exist.	
Bright green	Bright Green is an awesome preserved moss where all the water has been replaced with glycine, so it does not decompose. It's feels like a cross between a living organism and a rubber plant, but it thinks that's mainly the dryness. As for colour I've had it on my table for couple of months now and it's showing no sign of degradation. The moss is very pleasing to look at and anyone who wants a perfect green sign to look no further.	

Photochromic pigments	Pigments that react to light by changing colour on exposure. The pigments can be mixed into plastics or varnishes and change colour after while exposed to UV light. The colour changes are gradual but fairly swift with about 30 seconds in direct sunlight being enough to change from one colour to another, though that depends on the exact type of pigment and the material they are embedded in. The colour tends towards the more pastel with vivid colours either impossible or hard to obtain.	
Fiberline	Polyester reinforced with layers of carefully aligned glass fibre. This plastic is stronger, harder and more durable than other plastics and can perform well in tasks that other plastics would not be able to stand up to. It should be noted it is different to fibre glass which is glass fibres in a resin. Instead this is where the plastic and fibre are carefully aligned to a specific geometry for the application though some cheaper version exist which merely use the glass as an additive.	

Shape Memory Polymer	Plastic that can remember its prior shape after remoulding at low temperature, will return to this shape if heated again. Suitable for moulding with thermoforming methods like injection moulding the plastic can have come in different shapes. After forming unlike shape memory alloy, it cannot be reprogrammed short of completely melting and reforming the plastic. However, after heating past 70° the plastic can be deformed and cooled to now have a new shape. Bringing this new deformed shape up again to 70° will cause the plastic to return to its original shape.	
Microsuction tape	Micro-suction tape offers an alternative to most adhesive products like glue and tape by using a layer of microscopic suction cups, each a tiny bubble cut in half that when pressure is applied act together to grip with a lot of force. The black tape looks like a piece of bog-standard black rubber but it's holding force is amazing, 5 square centimetres and it will be difficult to remove any thing small if you don't have a good grip.	

Dry Inside	Dry-Inside has an apparently unique property, water can only move through it in one direction. Dry-inside works because it is treated to be hydrophobic on only one surface, this makes a gradient that pushes water away from that side to the other side by wicking along the material fibres. The resulting effect means that the water will be pulled through the material leaving the hydrophobic side dry. This allows it to move liquid water rather than just water vapor effectively making the hydrophobic side waterproof in one direction.	
D3O	D3O is a material with a rare feature when impacted upon it becomes harder and more rigid while being flexible in its normal state. It has surged into the forefront of the protective clothing industry as a result. It comes in only orange, but the rubbery plastic allows for thin flexible shapes to be made which massively increase the impact absorbing qualities of any product they are incorporated into.	

Thermochromic sheet	Thermochromic pigment is a smart material which changes colour in reaction to differences in heat. You will most likely to have encountered it as a novelty item often on mugs that rely on the most prevalent type which becomes transparent when heated revealing a message. The colour change actually comes from the microscopic change in the material composition when heated that causes the crystal structure to realign. The accuracy varies between different products some are so accurate they can be used as thermometers while others require boiling water to make changes happen.	
Self-annealing plastic	This plastic sticks to itself forming chemical bonds that bind it strongly. This allows cuts to be created and then resealed afterwards as well as to use the material as a tape that only binds to itself. The material is otherwise not sticky to other materials.	

12 APPENDIX B INTERVIEW AND THEMATIC REVIEW

A.

12.1 SUMMARY OF INTERVIEWS BOTH INCREMENTAL AND RADICAL

Interview	*Incremental phrasing*	*Incremental notes*	*Radical phrasing*	*Radical notes*
1	Like Aluminium, Strong aluminium feel, "Probably has a high durability".	Focus on comparison to aluminium is understandable but description failed to mention the difference in rigidity.	"Feels odd", "I don't know how to describe it", like cling film, rubbery	Participant struggled for some time to have a description they were satisfied with. They not only pulled up analogies which were incorrect but also failed to mention the self-adhesive property.
2	good strength (describing rigidity not strength) More reflective	The student was very brief in his descriptions and was fixated on the samples themselves, he failed to mention the lightweight nature.	"It's like a polythene bag that can stick to itself" (offered no other description than elaborating on this comparison.)	The analogy to the plastic bag is incorrect on pretty much every way other than they are both plastics, when asked why it was the first thing that came to mind was the response.
3	Light, compared it regular steel and focused on what material properties it might have using technical terms.	-	Strong, can stick to itself, "stretches a lot" wasn't sure what to say beyond that.	This was slightly confusing as the participant seemed to have a clear idea what the material was going to be like before they touched it.
4	"Metal equivalent of corrugated cardboard" and noted that's what	-	"Like Velcro" (in reference to ability to stick) Added the material was hard to	The analogy to Velcro appears multiple times,

	made it lighter, noted exposed fibres on edges, guessed it would have a lower cost due to lower material use. Was interested in using it in luggage or for 'vanity things'		describe, stronger than expected (they did not know what they based this expectation off) Self-adhesive in nature, Imagined an application for resalable food bags.	it is incorrect as the adhesion is not removable apart from with considerable effort. The strength that surprised them was in the quality of bonding which they expected to be low for an unknown reason.
5	Light weight (did not elaborate as a comparison explained it was light compared to expected weight) Imagined an application as a tray, good impact resistance, "It's more like aluminium than steel."	They said it was light when asked why it was clear that the visual and tactile feel built an expectation that the weight should be. They inaccurately described it as having good impact resistance, seemingly confusing this with rigidity. When mentioning the aluminium comparison, it seemed apparent they were referring to the weight alone.	Feels like vinyl, Rubbery texture, struggled to discuss further.	The description was very limited, the material seemed to confuse them, and they failed to mention its self-adhesive property
6	The material is hard and tough to bend, I imagine it is conductive		The material reminds me of sticky tape but without the getting stuck to it part. Sorry that's not very helpful, to be honest I'm not sure what else I should say.	
7	Like plywood (explaining it was like layers of plywood and	The plywood description applied both to the lightness	Struggled to describe the material – mentioned it reminded them of a	This was a very difficult discussion the participant

	needed edges covered) Also noted similarity to cardboard. Reminded them of carbon fibre. Could be used in high performance cars to cut down weight	and strength apparently and encompassed the need to hide the edges. They also mentioned that the internal sandwich reminded them of carbon fibre fibres	rubber dolphin they owned as a child, said they would need a sample to describe it. Mentioned it was like glue but failed to mention self-adhesive specifically.	seemed uncomfortable being asked to describe the material. The mentioned it "stuck to things" but failed to separate this into the self-adhesive property.
8	Lightweight steel, silvery finish, easy to polish, "seems firm" (remarking on rigid nature), "probably durable", "feels nice" "feels soft without being soft" (due to the weight the material brought connotations of softness)	-	Struggled to describe, feeling between a jelly and a polymer, self-adhesive like glue in nature, "excellent" shearing strength (unknown what was compared to.)	The mention of shearing strength marks the first time an engineering term has been used.
9	Appears to be steel, Laminated sheets of steel sandwiching metal fibres, "light". Asked if it was magnetic and if so to what degree?	-	Pretty good strength, semi-transparent, rubber feel, tacky feeling, like adhesive when overlapped.	Mentioned the self-adhesion put added a qualifier probably dictated by interaction with material.
10	Almost a soft feel, feels like plastic due to weight and rigid, smoother than mild steel, wanted to know how much impact it could take, and how much force this might require.	-	Imagined some applications as resealing bags, "flexible", "Sticky to touch", "resistant to damage" (unspecified what damage they meant), self-healing ability, "tactile touch invites touching", "grippy but smooth as well".	The "resistant to damage" was an odd description as it was unclear if they meant it could heal itself after damaging or that it was intrinsically durable.
11	Surprising lightness, two thin layers with fibres in-between, very light, different noise when knocked on, "like card"	-	Plastic that stretches and sticks to itself in a way that can't be removed. Don't know how	Very short description took a lot longer to discuss than the sort sentence makes out kept asking

				the interviewer questions as if unsure.
12	Like Steel and like aluminium, doesn't feel right as it's too light, feels too fragile to bend.	-	Plastic feel, feels "tacky", works like Velcro or a gecko's foot, clear, like flimsy Perspex.	Mentions Velcro again fails to directly mention self-adhesive properties.
13	Like steel, imagined it in used on suitcases, Aluminium weight but steel properties. Pleasant to touch, polished look	When asked what they meant by pleasant to touch stated they meant that it had a good presence like regular steel and the participant disliked the feel of aluminium.	Plastic, elastomer based, transparent, sticks to itself, strong (unknown what compared to), "twists and bends easily" (didn't say flexible) smooth feel but also rubbery.	Interestingly this participant failed to mention the word flexibility despite describing flexible attributes, also mimed motion with hands.
14	Feels like a plastic, sounds like a wood when knocked, light, edges like plywood	Mentioned plywood again, this was apparently not in reference to edges but the presumed construction of layers of steel.	Hassle free (comparing to the ability to stick without additives), Problematic once stuck to unstick, stretchy, strength unchanged by damages.	Failed to directly mention self-adhesion but had an interesting discussion on the ability to stick together.
15	Like foil on the outside, lighter, shiner than mild steel or aluminium, feels wrong (referring to the low weight and rigid nature) could be useful as a tool to keep handheld designs for phones light weight.	Description of feels wrong was interesting, when pushed they said that they felt the material was overly fragile but only because of its weight.	Stretchy elastomer, like double sided tape sticking to itself, clear, "solid connection when glued", do not feel they can trust the material to stay together (despite earlier comment).	This was an oddly conflicting interview; the double-sided tape comment was made first and then revised alter to explain that the participant meant sticking to itself. They also felt the adhesion was good but failed to trust it applications with strain.
16	Low weight, "good strength" (talking about rigidity) would suit use in a	Another person who confused strength with rigidity.	Imagined it used in waterproof clothing (commented it could be used to seal wearer inside) can	

	steel door due to light weight,		be separated by peeling edges apart like Velcro, elastic, wanted to know what kind of elasticity it had in mechanical terms	
17	Has a lesser than expected weight, but a reasonable strength it'd be good if built into ceilings or other architectural structures where trying to minimise weight		the feel is nice, would like to know exactly how elastic and how strong the bonds are in real terms (meaning objective) I think it would apply well to taping around cuts or wounds.	
18	Light compared to steel, could easily take more damage from impacts, quite rigid	The interesting thing in this description was the user presumed that the honeycomb structure would improve strength.	Reminds them of bamboo (this was hard to get the bottom of, explained it could be overlapped and repaired which is not a property of bamboo), Only has strength in one direction of extension, like a plastic.	The participant seemed to have the idea that bamboo could repair itself after damages which was odd, they also settled upon the idea strength was only in one dimension and they failed to mention its self-adhesive properties apart from saying “it heals like bamboo”
19	it's very stiff and shiny has a nice tap to it.	The designer was more focused on the sound the material made when flicked than any other property	It's clear and tacky but I can't really explain what it does, seems odd.	designer seemed uncomfortable with not knowing how the material acted
20	It's quite a pleasant heft and feel to it, it's a really satisfying difference between the weight and sturdiness	designer was interested in how the material felt and liked experimenting with bending it.	It's like a clear plastic film but it clings like sticky tape when it gets near itself	the participant didn't mention that the tape wouldn't stick to other things but tried sticking it to numerous other objects

				showing a clear understanding of its abilities
21	It reminds me of aluminium, but it's got that darker tone of steel	_	It's a satisfying stretch and strength, it's like a rubber band you can fix, I don't know how it works but it's cool. I'd like to see if you could use it like a resealable shrink wrap.	The participant worked with the material to experiment with its shape and fixing it
22	It feels smooth and light it reminds me of regular steel but without the mass. Kind of want to bend it.	The participant was most interested in the material's physical appearance	It reminds me of parcel tape but it's closer to a magnet that you can't get unstuck, apart from the attraction part	The participant kept correcting themselves in how they'd described the material
23	A shiny smooth metal, like aluminium or steel but closer in weight to aluminium, with a kind of fuzz in the middle.		It's a sticky clear plastic	
24	It's like someone took steel and made it hairy, and then stuck it to another hairy bit of steel. It's got a nice feel to it though. I wonder if with all this stuff it would still be conductive or magnetic?		The plastic reminds me of those dots of glue that hold cards to paper in the post, it's got that tacky feel to it, though I suppose it's also bit more like two different bits of epoxy. The activator and the glue, so they don't stick to anything but each other. I would expect it would be great as a stand in for normal tape when you don't want it sticking to anything.	Participant seemed to feel that the plastic was sticky to the touch but when pushed commented that they meant it was springy.
25	this would've been good for my suitcase project I was working on, it's nice light and it's much easier than steel while still looking like it.		Looks like sticky tape but I don't know how I'd explain the rest of it. Might be useful to tie stuff up securely without damaging it.	The participant seemed somewhat disinterested in the material

26	Nice look and feel would like to know if it's magnetic and the exact hardness though. Would be good for smaller stuff you want to keep light like stuff you have to carry.		The material is soft and stretchy kind of like an elastic band. The sticking is cool like it's made of glue.	
27	It's got that feel to it of aluminium I'd describe it like that, weight and feel of aluminium look of steel		Milky clear plastic with a kind of rubber band elasticity except it can hold one like Velcro to itself.	Designer focused on the Velcro concept despite being unable to pull apart the material.
28	It's smooth polished, surprisingly light, got sharp edges and is really solid (meaning rigid)		The feeling is of plastic like rubber or PVC, but it's got that sticking ability like it's welding itself together.	
29	there is a look about it of aluminium but something about it makes it seem sturdier. That and it's also got a darker colour to it that I think is more like steel.		Participants seemed enthralled with the material and just wanted to know more about its function, focusing on trying to get estimates from the facilitator as to exactly how strong it was and what temperature it was 'safe' up until.	
30	it's like two thin sheets of aluminium with black threads in the middle		Could be any normal plastic tape, but I like that it's stretchy as well. Looks like this would be good for holding stuff up without damaging the wall.	
31	It's a sheet of steel that weighs to little it stiffer than it looks.		I mean I get it's like some kind of special tape and that it's sticky to itself, but I don't really know how I would explain that to someone else.	
32	Kind of makes me think of the fur in the middle with thin polished steel		the stretchy plastic feel is nice, it invites playing, the look of it though is more like	

	sheets on the outside		clear PVC or something. I think the sticking is fun though, I'd describe it as kind of like friction welding with no heat	
33	It's like any old aluminium but it's a bit different as it's got that layer of steel in the middle that makes it lighter.	Participant was confused about the makeup of the material	Really interesting, it's stretches and sticky, kind of like selective glue built on to it.	
34	The sheet is looks sounds and feels like it's steel or aluminium, however it's much lighter. The middle seems puffed up with something, kind of like a layer of foam but replace the bubbles with whatever those strings are.		It's got a soft bounciness to it that I like, what stands out is the surface can stick to itself like it's got glue or some sort of chemical that only wants to connect with itself.	
35	The two thin layers are like regular steel, bright polished steel as well, though it has got a bit muddy with all the fingerprints, the thing is it's way lighter, I wouldn't have expected it to be so light.		The feel of it soft but it's more of an elastic feel. I would want to know exactly how elastic it is and what its strength is though.	
36	So, it's more like lighter version of steel, I don't think it's tough enough for anything like cars, but it's do great for the interior without adding the weight		I love this stuff, it's got a really nice texture, it's warm and soft but then it sticks to itself like tape does. It's a bit more complicated, it's more like some kind of chemical reaction or something like two chemicals bonding. This would be really helpful to repair anything really delicate like a fabric.	
37	The whole thing reminds me of steel but much less weight to it, still feels		This is a bit different to other isn't it? The feel is soft, and it looks kind of worn.	

	the same level of strength but the weight makes me pause and worry I'll damage it. The		Sure, this would be a good addition to any toolbox to stick bit together without getting glue everywhere.
38	Kind of like steel and aluminium at the same time, it's nice and light.		It's a really odd feel to it, like a rubber band and but less natural, sticks kind of like glue but almost like it can select what to stick, programmable glue if that makes sense.
39	I'm not sure what to say	Participant seemed unhappy with the idea of explaining, after the interview they were asked how they felt and explained that they weren't prepared and 'froze up'	It's interesting kind of soft and stretchy. Look I'm not sure what to say, I don't think I'd be much use at explaining this.
40	The weight is surprising as it feels very rigid and I almost expect it to come apart but it doesn't I think it would be useful in any scenario where you had to cut down weight, like airplanes or cars.		This is basically some kind of magic rubber that you can get to heal itself. Like it can be stuck together and heal like cells in a would coming together.

12.2 SUMMARY OF LANGUAGE USED IN INTERVIEWS

	Hybrix steel					Self-annealing plastic				
Interview	Subjective description uses in incremental	Comparison use in incremental	Objective use in incremental	Context use in incremental	Don't Know use in incremental	Subjective Descrption use in radical	Comparison use in radical description	Objective use in radical description	Context use in radical description	Don't Know use in radical description

	descri ption	descri ption	descri ption	descri ption	descri ption	descri ption				
1	x	x				x	x			x
2	x						x			
3	x		x			x				x
4	x	x		x		x	x		x	
5	x	x	x	x			x			x
6	x						x			x
7		x		x			x			
8	x	x				x	x			x
9	x		x				x			
10	x	x	x			x	x		x	
11	x	x				x	x			x
12	x	x				x	x			
13	x	x		x		x	x			
14	x	x				x	x			
15	x	x		x		x				
16	x			x		x		x	x	
17	x	x		x		x		x	x	
18	x	x		x		x	x			
19	X					x				x
20	X						x			
21	x	x				x	x		x	x
22	x	x					x			
23	x	x				x				
24	x	x	x			x	x		x	
25	x	x		x			x		x	x
26	x		x	x		x	x			
27		x				x	x			
28	x						x			
29	x	x						x		

30	x	x				x	x		x	
31	x	x				x	x			x
32	x	x				x	x			
33	x	x				x	x			
34	x	x				x	x			x
35	x	x				x		x		
36	x	x		x		x	x		x	
37	x	x		x		x			x	
38	x	x				x	x			
39					x	x				x
40	X			x			x			
Total	92.5%	60%	32.5%	37.5%	2.5%	72.5%	75%	25%	25%	30%

12.3 THEMATIC REVIEW SUMMARY

List of level 1 codes
Cloudy; cool; elastic; elastomer; Feels like the material would be useful; feels like wax; flimsy Perspex; geckos foot; good for waterproof clothing; grippy; had excellent shearing strength; hard to unstick; hardy; hassle free; I can't describe it; I don't know; I have no idea; I think this would be good for tape that doesn't leave residue; Interesting; it wouldn't be good as clothes though it would stick to itself; It's like a polythene bag that can stick to itself; It's a cool material; It's like built in glue; like a toy rubber dolphin; like bamboo; like cling film; like frosted glass; like rubber; Like vinyl; like your skin healing; plastic; plasticky (making a comparison to plastic); pliable; quick to recover; Reminds me of Velcro; resilient; Rubbery; self-adhesive; so it's chemical bonds are connecting?; somewhere between a jelly and a polymer; springy; stretchy; supple; tacky feeling; This is like an alternative to duct tape; This would be good in repair industries; Tough; twists and bends easily; very stretchy; weird; You could make self-sealing pouches of this stuff;

List of Level 2 and Level 3 codes			
Comparison			
Similarity of whole material to another material	Similarity of a specific material quality to that quality in another material.	Difference of a specific material quality to that quality in another material.	Similarity of material quality to a complex concept

aluminium like aluminium like bamboo like cardboard like cling film like plywood like rubber like steel metal mirror plastic plasticky (making a comparison to plastic) steel strong aluminium feel feels like wax	It's like built in glue looks like frosted glass feels like vinyl more reflective than normal steel	flimsy Perspex It feels more fragile than steel it's lighter than normal steel more like aluminium than steel remind them of foam core Reminds me of Velcro sheet metal weighs like a plastic weighs like aluminium	geckos' foot It's like a polythene bag that can stick to itself like your skin healing metal equivalent of corrugated cardboard somewhere between a jelly and a polymer the inside is like Velcro teeth
Subjective description			
Opinion of material quality.	opinion of a visual aspect	Opinion of a tactile aspect	Opinion of material overall.
elastic hard to unstick dense good strength inflexible high durability hollow light lightweight resilient solid sound like wood	cloudy laminated sheets of steel polished look shiny square	grippy delicate feels nice firm flimsy fragile glossy hard it's soft without being soft pliable rigid rubbery	cool Feels like the material would be useful hardy hassle free easy to polish interesting It's a cool material portable quick to recover thin weird

<table>
<tr><td>sounds like carbon fibre
stretchy
tough
very stretchy</td><td></td><td>smoother than normal steel
spongy
springy
stiff
supple
strong
tacky feeling
twists and bends easily</td><td></td></tr>
<tr><td colspan="4">Contextual</td></tr>
<tr><td>Described organisations who would benefit from using the material.</td><td>Stated intent of how they would use material</td><td>Example of how it could be processed</td><td>Questioned if an application was a poor application for the material.</td></tr>
<tr><td>Airplane industry would love this
good for airplanes
This would be good in repair industries
This would be great for high end cars</td><td>fit for luggage
good for suitcases
I think this would be good for tape that doesn't leave residue
This is like an alternative to duct tape
You could make self-sealing pouches of this stuff
good for waterproof clothing</td><td>good for pressing
suitable for shaping</td><td>it wouldn't be good as clothes though it would stick to itself
this wouldn't work on any high wear application it would get dinged up</td></tr>
<tr><td colspan="2">Objective description</td><td colspan="2">Don't know</td></tr>
<tr><td colspan="2">Used scientific terminology to assess</td><td colspan="2">Explained they didn't know how the material worked,</td></tr>
<tr><td colspan="2">Elastomer
Had excellent shearing strength
Magnetic
Probably conductive</td><td colspan="2">I can't describe it
I don't know
I have no idea</td></tr>
</table>

Self-adhesive So, its chemical bonds are connecting?	

13 APPENDIX C RADICAL MATERIALS BREAKDOWN AND ASSESSMENT

Materials	Source	Object type	Object 1	Object 2	Relation 1	Relation 2	Relation 3	Relation 4	Attribute 1	Attribute 2	Attribute 3	Attribute 3	Constraints
Faraday Film		Comparison	wires	faraday	more see through more resistance	scratches function as circuits			See through	conductive	spray		
UPM Formi		Comparison	plastic normal	plastic up									
Hybrix		Comparison	Steel norm						lighter	formable			cost, easily damaged
Bare Conductive Paint		Comparison	Wires		spreadable conductivity	liquid dry's adds to conduction			paint				
Spider Silk protein		Comparison	Textiles						stronger	human compatible			
Carburate		Comparison	Concrete						lighter	stronger			cost, carcinogen
Aerogel		Comparison	Foams						light	low thermal conduction			
areographies		Comparison	Foams						light	low thermal	hydrophobic	conductive	foam, fragil

										conduction			e, cost
EliteXC	MR 2133	comparison	Wires	Textiles					Conductive	Thread			
Graphene		comparison							Conductive	light	strong	flexible	cost, sourcing
Coolmorph		comparison	Thermoplastics						low melting point				
Thin film	MR 172	Comparison	Plastics		Programmable				Conductive	Plastic			
Power coat	MR 172	Comparison							Conductive	Film/coating	biodegradable		
Enova Aerogel	MR 182	Comparison	Paint						Insulating from heat	invisible additive to paint			cost, fragile
Bulrush panels (Naporo)	MR 70	Comparison	wood						Low weight	Organic	High strength		
S.cafe	MR 79	Comparison	Plastics						Waste material	Durable	aesthetic		
Loliware	MR 85	Comparison	Plastics						Edible	Durable	Injection moulded		low shelf life
Biodegradable electronics	MR 87	Comparison							Biodegrades	Conducts electricity			

Dichrolam	MF ID 089	Comparison							3d reflections from 2d film				
Metal foams		Comparison							Light weight	great strength to weight ratio			
Acoustic ceramics	MF ID 019	Comparison							Ceramic	Good acoustic properties			
D3O		Function	Unstruck D30	Struck D30	Hardness has increased	Reaction to being struck	More brittle less flexible	Reversible	Plastic	Rubbery	Press moulding		Reversible, limited
Ferro-fluid		Function	non-reactive	magnet exposed	more viscous under magnetism	follows magnets			liquid	nonmagnetic			Oil based, staining
EL Panel		Function	off	on					light	flat	low heat		high energy use
Intumescent foam		Function			Grows when exposed to heat	non reversible							
Phase change fabric		Function			absorbs heat	releases heat when cooled	storage is defined by quantity		powder				reusable

Nitinol wire		Function			changes shape under heat	remembers shape			highly flexible				
Photochromic pigments		Function			change colour due to light	reversible			can choose colour				
Shape Memory Polymer		Function			changes shape under heat	remembers shape			highly flexible	plastic			tight heat area
Microsuction tape		Function			acts like suction cup	repeatable action			rubber	small suction cups			
Dry Inside		Function			One water transfer	unwettable on one side			spray for alternative fabrics				
Thermochromic sheet		Function			reacts to heat	shows exact temperature							
Fibre-optic fabric		Function			allows light down tubes				flexible	fabric			damaged by creases
Poron XRD		Function	Unstruck D30	Struck D30	Hardness has increased	Reaction to being struck	More brittle less flexible	Reversible	Plastic	Rubbery	Press moulding		
Alginate	MR2	Function			changes colour as it				Setting				

	127				hardens								
Silane organisilanes	MR 2 128	Function							hydrophobic	durable			
Tiocem	MR 2 132	Function			Scrubs air as reaction to light	long duration	catalyst		Concrete				
Reverlink	MR 2 139	Function			self-healing				plastic				
Sage Glass	MR 158	Function			Transparent	Current changes transparency			Low voltage				
Ynvisible	MR 158	Function			Transparent	Current changes transparency			Low voltage				
Dichronic glass	MR 159	Function			Breaks up light based on reflective angle				Film/coating				
Luminescent bacteria	MR 167	Function			Glows	reacts to movement			living	no energy			
Prebeam	MR 112	Function			Flexible by hand	Rigid after	Can be refo						

						bending	rmed						
dissolvable plastics	MFID 187	Function			Biodegrade in water				plastic				
Self-cleaning glass	MFID 082	Function			Reacts to UV light	Breaks down deposits			Glass coating				
Oricalco	STFD 51	Function			Electrical sensitive	Contract or release			fabric				
Never wet	STFD 51	Function			Super hydrophobic	repels water			spray				
Cellular metal		Production	Tradiontal	Cellular					light	cell based	individual components	shape is defined by the sinters mould	
LifoCork		Production							Made from cork	light	eco friendly		
Bright green		Production							made from the moss				
Fiberline		Production							aligned strings	high strength	low weight		
Concrete canvas		production			sheet reacts to water	hardens			contained in sheet	suitable for storage			

Laser foamed plastics	MR 195	Production							High detail	durable	Raised markings		
Organoid forms	MR 197	Production							Biodegradable	Durable	Scrap material	spray based application	
Biogenic ceramics	MR 198	Production							Diamond hard	Wood based	Ceramic from wood		
Rice cement	MR 101	Production							Uses rice waste	Low carbon production			
Bond laminates organic sheet	MR 107	Production							Bonded organic fibres	Strong as steel			
Flexible timber (Dukta)	MR 111	Production							Flexible	wood	Can be customised		
Injection moulded metals		production							injection moulding	metal	no finishing		
Auxetic materials	MR 2146	Comparison							strength	lightness	energy absorbing		

14 APPENDIX D QUESTIONNAIRE AND FOCUS GROUPS

14.1 QUESTIONNAIRE CONTENT

1. What would you describe as your background in design?
2. How familiar are you with materials science?
3. Please look at all four messages below they are all trying to communicate an innovation in concrete to you. Which example do you feel has communicated that innovation most effectively to you?
    a. This new concrete is emitting a lot less carbon dioxide in production.
    b. Compared to regular concrete this material only produces half as much carbon dioxide
    c. This concrete would be perfect for a low emissions building project
    d. Producing a ton of this new concrete only produces half a ton of carbon dioxide
4. Considering your selection above what information did you feel you gained from this that you didn't from the other options.
5. Please look at all four messages below they are all trying to communicate an innovation in reinforced plastics. Which example do you feel has communicated that information most effectively to you?
    a. This new technique allows us to injection mould the steel into complex super thin forms.
    b. This new steel can be injection moulded like polypropylene
    c. This new steel could be injection moulded into forms like pens, springs and puzzle pieces
    d. This new steel is suitable for injection moulding.
6. Considering your selection above what information did you feel you gained from this that you didn't from the other options.
7. Please look at all four messages below they are all trying to communicate an innovation in ceramics. Which example do you feel has communicated that information most effectively to you?
    a. This new innovation allows us to make ceramics out of wood
    b. This is like produces ceramics like regular china plates but is made from specially processed wood
    c. This new ceramic could be made in areas with no access to clay
    d. This new ceramic uses wood and structures it in a ceramic matrix composite
8. Considering your selection above what information did you feel you gained from this that you didn't from the other options.
9. Please look at all four messages below they are all trying to communicate the same innovation in foaming steel. Which example do you feel has communicated that information most effectively to you?
    a. This steel foam is light and very strong.
    b. This is like normal steel but is like a sponge on the inside making it as light as aluminium.
    c. This would be great for aircraft interiors or in high speed cars where weight is an issue.
    d. This foamed steel has a density of 2800 kg/m3 and a Tensile strength of 505 MPa.
10. Considering your selection above what information did you feel you gained from this that you didn't from the other options.

11. Please look at all four messages below they are all trying to communicate the same innovation in a new silk. Which example do you feel has communicated that information most effectively to you?
    a. This new silk is slightly elastic.
    b. This new silk is like regular silk but elastic like a rubber band.
    c. This new silk would work well in bungee cord.
    d. This new silk has a Youngs modulus of 35Gpa.
12. Considering your selection above what information did you feel you gained from this that you didn't from the other options.
13. Please look at all four messages below they are all trying to communicate the same innovation in titanium. Which example do you feel has communicated that information most effectively to you?
    a. This titanium alloy keeps the surface very hard without making it too brittle.
    b. Compared to regular titanium this material is 20% less brittle.
    c. This Titanium is better suited to parts which are under changing strain.
    d. The titanium has a compressive strength of 848(S.I) and a tensile strength of 867(S.I).
14. Considering your selection above what information did you feel you gained from this that you didn't from the other options.
15. Please look at all four messages below they are all trying to communicate the same innovation in conductive ink. Which example do you feel has communicated that information most effectively to you?
    a. This new material is a conductive ink for simple circuits.
    b. This works like a wire but is a liquid and can be used like paint.
    c. This is a great tool to prototype circuits with low energy components.
    d. Once dry for every 0.20mm2 of this liquid it has an assigned maximum ampere rating of 2 Amps.
16. Considering your selection above what information did you feel you gained from this that you didn't from the other options.
17. Please look at all four messages below they are all trying to communicate the same innovation in hydrophobic fabrics. Which example do you feel has communicated that information most effectively to you?
    a. This fabric repels water really well moving it to one side of the material.
    b. When water hits this fabric it's like a hill, when water gets on the inside (top of the hill) it is forced to the outside (bottom of the hill) like it's being pushed by gravity.
    c. This fabric is great for outdoor sports where athletes might need to remain dry.
    d. The material has a super hydrophobic gradient embedded in the weave.
18. Considering your selection above what information did you feel you gained from this that you didn't from the other options.
19. Please look at all four messages below they are all trying to communicate the same innovation in titanium. Which example do you feel has communicated that information most effectively to you?
    a. D3O gets harder when it is hit hard but otherwise is a soft rubber.
    b. D3O is a rubber that reacts like water, gentle pushes and there is no resistance but slap and there will be high resistance.
    c. D3O is perfect for absorbing impacts in gravity sports armour or motorbike clothing.
    d. D3O has highly dilatant properties.
20. Considering your selection above what information did you feel you gained from this that you didn't from the other options.

21. Thanks very much for your time, you can learn more about the materials listed here on the website www.materialintuition.com

14.2 FOCUS GROUP SUMMARIES

14.2.1 **Focus group 1**

Participants:	Designers with at least two years commercial experience.
Notes from introductory questions:	What experiences have you had learning about materials/ What do you think of current ways to learn about materials?
	In this group the designers all shared that they felt they had pretty similar methods of learning about materials. A by-product of working together for an extended time. One participant said that they felt they were the 'materials guy' for the office and did the more detailed research when something new came up but otherwise the load was split evenly. Participant quotes: "I've done some online research, sometimes using a website called matteria." "We've got stacks of samples and all the marketing crap that we sometimes sift through." "In my office I'm kind of the expert on wood, I've done so many different projects with wood veneers, parts and all with different finishes so they always come to me to check what I know." "There's only so much that you can do to find out before talking to an engineer, we're lucky that on our team we've got a couple of guys who've been in the industry for years."
Notes from transfer questions:	What do you think is important to cover when explaining this material to other designers?
	The participants connected strongly with the idea that there are core bits of information that need communicating. Designers felt that the was a core element, generally seen to be the innovation that made it different from other materials it had similarities to. Designers were also very explicit about understanding what group of materials the material was innovating from within. Participant quotes: "It's important to know what we're talking about, there's a lot of information out there and I don't have time to read it all." Participant E claimed, "It's important to know what the context is why are we talking about this material." Participant A then looked to correct E saying, "There's always going to be something to chat about on the material, you could just think there's something really cool about it. Though I do agree I probably wouldn't just chat about a new variation on plastic."

	"We've got load of data sheets, but I never pay attention to them, just generally try and google the material so I can read the marketing stuff which generally brings more attention to the important bits." "The group the material belongs to is important, I like to think I know something about most materials groups so I can kind of think it through." "What will break these materials is important, I don't want to break anything." "What is actually innovative about this? (Bare Conductive) I'm sure that there's other things out there. (Participants discussed that the wasn't other things out there like this) "In that case really hit home that it's new, I kind of just thought it was part of range of options."
Notes from key questions:	What do you think is important to cover when explaining this material to other designers? / What would be the best way to explain the innovative material properties to you?
	The participants were highly varied in what they considered important to communicate. The discussion revolved around the necessity of communicating material properties they personally found interesting rather than the material as a whole. While they did discuss the innovations a great deal, they also focused more on what the material could do, having a high focus on the contextual examples of the materials. The participants also felt that the communication for each material would have to be different to reflect the variety. Two key topics that came out was the importance of how the material is introduced and that the communication shouldn't be overly technical. Participants were emphatic that the first things they learnt about the material were likely to be the most important to them. As this is what connected them to the material. Participants also wanted to avoid technical terms that could over complicate the materials description. There were a couple of discussions as to what a technical term was compared to a non-technical term with the participant who described themselves as 'the material guy' early arguing that terms like Phase Change were a useful label while other felt that this just confused them. Participant quotes: "It's important to understand if D3O is as flexible as let's say rubber." "The first thing I do is try and work out what I recognize." "What would the difference between this plastic (Ecoplastic) and silicone?" "I want to know how a material is being used, and how it makes that idea work." "Listing applications for each material would be amazing, you could have a detailed account of what the material does in each product and how it's manufactured as well." "There's a lot to understand and examples of what it can is best for me to 'get' what it's good at."

	"The ink is really cool, but it's got that too good to be true feel about it. I'd love to see some proof so I can make sure what I understand and what it does are the same." "Some of what (gestures to participants) have said is all bit more than I'd want, let me know how it feels and works as straightforward as possible." "That initial sentence is probably most important, I don't want some marketing nonsense I want to in like 10 words or less get the very basics." "Technical terms only help those who know them already. For example, I get the PCM fabric can absorb heat, but I never heard of phase change reactions before. It's just not helpful."
Notes from specific questions:	If you were comparing the material to another, how would you describe it?
	The discussion focused not just on comparisons but also suggestions as to what made a good comparison. The participants found this process surprisingly easy, working to quickly discuss the tactile and physical properties of the materials. Some of the comparisons which used analogy or looser comparisons such as the comparison around Bare Conductive took longer and caused the designers to pause more. The designer wanted to be accurate and often looked at each other to check if what they were saying was making sense. Participant quotes: "In a comparison I want to be clear on what you're talking about. It shouldn't be tough to work out what parts are being compared." "I started comparing the materials to things I knew, how it felt and looked." "A clear intro is good before getting to technical, I like how you (referring to facilitator) say that it (D3O) gets hard the harder it gets hit, I know what it does and then from there I can build on that." "The ink (bare conductive) is like some kind of paint on wire." "I'm reminded of touching a cold bottle on a hot day when I feel this (PCM fabric)" "Something tangible I know is key to explaining this, pick something I deal with every day and then modify from there, you can get creative." "You should focus on what it does better, this conductive paint is just that, like paint but conductive. (Bare conductive)" "Exactly how much is a real help, I've got some materials lock down in my head from working with them across a load of projects, if you told me it was half the weight of say polyprop, but still had the strength and manufacturing options that'd be great." "This is unlike any material I know (fibre optic fabric), It's kind of reminds me of corduroy clothes but with little LEDs run through the cords." "It's basically just super reinforced plastic, like steel plastic. (Fiberline)" "The descriptions should be as accurate as possible, just be detailed and make it understandable, I get what they're saying (participants were

	discussing comparing by changes in percentages to other materials.) but it can't be that hard to find a more interesting way to say it."
	Why did you pick this method of comparison over other ways to explain yourself?
	The participants found this question the hardest of all, with the group falling into silence a few times to think about the topic. The designers were more able to justify their use of tactile and manufacturing qualities, but they struggled with explaining their use of analogies, more describing them as a last resort, and that they had a desire to keep the comparisons as grounded in reality as possible. Participant quotes: "They (analogies) do make sense for when it's something complicated like the smart materials." "If it's going to be a bit abstract let's keep it as grounded as possible in the real world." "If I want to know what a material is like I'd prefer to know what's out there that it has the most in common with, as long as I'd hear about that one too." "Those things which are matched really closely by other materials are the best, when that's spoken about, I can really picture it and I would guess most designers can too." "Designers just want some clear reason one option is better than another so we can choose the best tool for the job, or material in this case." "It's all about picturing the words you've used, I imagined flexing a rubber band when we talked about a that earlier, as long as it's something that makes sense it should be okay." "When you compare it be clear what properties your linking, it's way different to say this (Faraday film) is like a wire when it comes to carrying a current compared to saying it's like a wire and is going to be coppery." "Having a comparison that outlines exactly what's better is the best way to explain it to me."
Other notes:	The participants often moved to use multiple methods to communicate any one material property, expecting to combine discussions about its common uses with comparisons to other materials. They saw this as the most effective way to communicate the materials rather than relying on just one tool. One of the groups especially mentioned using an introduction, a detailed explanation and then examples to communicate the material. They felt that this would be effective, once mentioned others in the group agreed with him strongly. Participant quotes: "Why limit yourself, as long as you keep them short, I don't mind the same thing being said in a couple of ways as long as there taking different tacks."

	"They do work but I feel more like I'm trying to work out a puzzle and that's a bit worrying when I've got no way to know if I'm getting the right answer." "Each chunk just does that bit more to iron out my confusion and let me know I've got it right. I wouldn't shy away from this if I were you." "I personally would introduce it really simply so we know what's the essential thing we need to pay attention to, then you can discuss it however you want but finally you should round it off with a couple of examples so I can just check that what I've understood from the rest of it is true."

14.2.2 **Focus group 2**

Participants:	At least two years design academic knowledge
Notes from introductory questions:	What experiences have you had learning about materials/ What do you think of current ways to learn about materials?
	In this group the designers focused on the different tools by which they learnt, with most focusing in on the educational tools and experiences they had. Others spoke about the online resources they accessed. The was little strong opinion of these tools as the designers had not been called upon to use them much. Participant quotes I know the university has Granta, but I've never used it Does looking through the texture options in Solidworks count? "I've looked up stuff from the library as and when I've needed it, but it's never been that helpful." "I mean I've been learning about materials since GCSE's but really I don't remember much apart from the big stuff." "I like to learn through something I can repeat, I like YouTube videos or blog posts that I can refer back to." "I use V Sauce and smarter every day on YouTube to find out about new stuff."
Notes from transfer questions:	What do you think is important to cover when explaining this material to other designers? /
	For this question the designers focused in on what was exceptional about the materials. They felt that sorting the material into a basic group was helpful, in addition they wanted the innovative property pointed out straight away so they could focus on that. The designers also described their frustration with materials as it was still something they were learning about and not something they felt overly comfortable with. Participant quotes: "I mean to me it's just a piece of plastic (Fiberline) I want to know what's special straight away otherwise it's a bit boring."

	"Unless you tell me to stick it to itself, I'm not even going to notice it." Participant E was replying to B's statement of "I think you could try and ask people to play with it to make them understand the material." "It really helps when I understand this (mycelium) is organic stuff all bound up. I can imagine what it would work like better than if you just say it's made of mushrooms." "So, the EL light, is it a plastic or something more complicated? I'd want to know because otherwise I'm scared, I'm going to break it." "Is the material durable enough, we can't be designing stuff that will just fall apart after one use." Participant B said to participant D "Look if I'm explaining something to you about this, I'm just going to focus on what I think is important. You can see it's a plastic" "This reminds me of GRP (glass reinforced plastic.) It'd be great to know if that's true and how true." "What is this like?" "I want to know if it's (Dry Inside) synthetic fabric, a natural one or if it's just some treatment I can apply so I can work out how I'd use it." "How it can be processed is essential." "People get materials wrong already when we talk about them, we just had a module where we all stuck to using ABS cause the other options all seemed too complicated, so I'm not sure where to start."
Notes from key questions:	What do you think is important to cover when explaining this material to other designers? / What would be the best way to explain the innovative material properties to you?
	The designers discussed how the most important thing was to find relatable comparisons for them to understand, this communication should be as clear and simple as possible to help them understand the material. Bringing in materials that they knew was seen as distinctly helpful to them as let them build on their limited knowledge. The group also wanted to see examples of how the materials could be used in the real world to get some guidance on possible applications. With a couple of participants in particular being very keen on using real world examples to explore the material in more detail. Participant quotes: "It's difficult to think of the new so I lock onto what I recognize." "How is this (Fibre-optic fabric) like normal fabric and how is it different?" "This is similar to OLED? (ELPanel) I want know what's the same and what's different." "Some examples of the material in action would be great, where the application isn't too complicated."

	"Examples of products using it already would be helpful, as long as it plays a key role" "A product that I recognize using the material would be the perfect solution, because then I'd know what it's like in that product." "It's the basic stuff that's really important, like is flexible and is it strong or weak. I don't need to know the exact numbers, but I do want to know how it feels and acts in clear language." "Keep it simple stupid is what we're always taught, so at least when you start talking about it you should keep it as simple as possible." "Label it, when I'm looking for some new material, I won't google material, I'll google plastic, or thermo plastic or heat resistant plastic or be even more detailed. Put it in a box for me and then I'll be more inclined to look at it." "My first though was that it looked like a big flat LED (EL PANEL), I was thinking like that till you started bending it!"
Notes from specific questions:	If you were comparing the material to another, how would you describe it?
	The designers felt that the comparisons were complicated, with many of the concepts they generated being of only limited accuracy. However, the was a strong interest in making those comparisons and despite the challenge they were keen to try. The designers bounced a lot of different ideas of each other with each picking their own material to discuss. The majority of the comparisons focused on the smart materials and the was little to no focus on the materials limitations which was notable as the group didn't even seem to think about communicating these limits, instead focusing on what the material could do. Participant quotes: "You should guide us in, tell us it's (Micro-suction tape) sticky and then says it's like a million tiny suction cups. "I liked when (Participant D) talked about the how the EL Panel is like a big bendy LED, I know it's wrong but he set it up in my head" When pushed to elaborate "I liked the whole 'it's big, flat and bendy' at the start cause I agreed and then he says LED and I get what he meant." "The fibre optic fabric is like water spilling out of hoses, except it's light not water." "The faraday film is like an invisible layer of copper, right?" "When we start talking about two materials, there's so much we could be talking about, anything from do they both floats, to is it the same colour. It helps to nail down this bit is what I'm talking about". "I want it to be obvious what we're discussing, otherwise we could get completely lost." "I want to say the nitinol wire can work like a muscle…but that can mean a lot, so you should say 'when this wire gets hot it changes shape, allowing it to pull like a muscle.' That's way clearer."

	"It seems really complex (D3O) but it's kind of makes me think of hitting a drum with you hand. If you tap it, you can kind of feel the give but if you smack it hard you just bounce back." "I get that you can program them (nitinol) to do things in certain positions, but programming a computer is so different, they're completely different systems. I just end up with more questions." "I'd prefer if it was more accurate, say something like 'Can heal from a cut and be stronger than before."
	Why did you pick this method of comparison over other ways to explain yourself?
	The designers focus was on creating communication, the group made it very clear that analogies were a last resort and that comparisons should remain as simple and direct as possible. The group showed a preference for using multiple direct comparisons to build up a picture or the material rather than using more complex comparisons which added complexity to the communication. Participant quotes "Analogies do the job when there is nothing real to compare it against." "It's (analogies) just sometimes the only option, it's not perfect but it does the job," They (comparisons) are simple and let me understand the basics without any fluff." "Comparisons work because it just a clear exchange of what I know applied to something I don't." "I find it easier to talk about attributes the material shares with others. It's easier and more obvious what you're talking about, better than trying to work out how it's different to other things." "The exact nature is a big benefit; I think I'd remember it more." "Outlining the materials properties is great. That works." "I feel like we're all trying to paint pictures of the material, and maybe (participant A) is better with reds and (participant B) with Blues but if you give us options are pictures are going to all have the same shape even if our style is a bit different." "Just make more connections, the more say it's the colour of brushed steel, looks like polystyrene, has the strength of honeycomb or whatever. Don't get bogged down on picking that one thing that doesn't describe it and then trying to cram it together." "When I say it's twice as strong as steel, I'm not really sure how strong steel is but I can imagine what it would be like to be able to use half the amount of steel to get the same strength, so I can see really skinny bridges or low weight cars."

	"I prefer this when there's only a single or simple difference that I can put a number to."
Other notes:	The designers focus on bringing multiple comparisons also led them to discuss that they saw no issue with bringing together different tools to describe the materials. They didn't see any one perfect explanation and recommended combining comparison with contextual explanations to help make the communication more effective. The group felt that by layering these insights the communication could then be effective for everyone. Participant quotes: "I can piece together some different comparisons and details without too much hassle as long as it's clear how it builds on itself." "There are like four different ways to describe this and all work so why not just list all three and then it'll be less likely we'll get confused." "I don't think there is any one perfect explanation. I'd prefer lots of different ones so I can compare them to get the best idea." "(Participant F) mentioned the whole scenarios thing. Those are great, combine it with the comparisons we've been talking about for the last 30 mins and you've got a winner."

14.2.3 **Focus group 3**

Participants:	At least two years academic design knowledge and some professional experience.
Notes from introductory questions:	What experiences have you had learning about materials/ What do you think of current ways to learn about materials?
	In this group the designers focused on the experiences they had with their placement years in industry. With most focusing on the tools they had used in that time. Some did discuss that they had built up a knowledge through their education as well. Participant quotes: "I use a service I can't remember the name of to look things up, my company pays for access to it." There are online services and my company a while back paid for some consultancy with Material Connexion. "We've got a whole module on materials and choosing the right ones." "You pick up all sorts of things when you're on design project. I learnt about some really neat plastics because of some work we were doing on eco packaging." "I'll look stuff up on the internet or chat to others who've mentioned they know about the materials I'm working on."
	What do you think is important to cover when explaining this material to other designers?

Notes from transfer questions:	In this session it's important to note that the designers became quite resistant to expanding on this topic. With the group becoming quite resistant to discussing what communications about the material would be important. The participants fed into each other with this mentality leaving the overall response to the question more focused on the challenge than actually exploring solutions. Participant quotes: "It's all about what the material can do for me!" "I'm not great at explaining simple things let alone this." "I think because it's so new I wouldn't be sure what to do." "Hell, if I know." "It's different for everyone so I'm just not sure."
Notes from key questions:	What do you think is important to cover when explaining this material to other designers? / What would be the best way to explain the innovative material properties to you?
	Potentially stymied by the initial transfer question the designers struggled to explore this question as well. They were able to explore concepts eventually. Focusing on the need for the communication to be expanded upon in detail after the specific key aspects were covered. The conversation in this space was limited though and the discussion again ground to a halt as the designers felt unsure of what to say. Participant quotes "I see the material and I'm immediately comparing it to something in my head, there's just a lot I can't work out unless you tell me." "It's all kinds of complicated. I'd prefer to see an example and see it working before I could say I understood." "I'm just not sure what to say." "What each of us round the table is thinking is going to be different that's the way with creative people." "If you let me see that paint and tell me it's black, dries quickly and can paint on different surfaces that's great. If you also say you can run a current through it then I get why it's special."
Notes from specific questions:	If you were comparing the material to another, how would you describe it?
	In this exercise it became apparent that two of the designers had working at design engineering firms, where they were expected to use material data sheets regularly as part of their work. This let them be more comfortable with them and recommended them as tools for communication, however the other designers in the group pushed back against this, saying that more 'real world' terms and examples were essential. The designers, data sheet enthusiasts or not, felt it was important to cover the basics of the material first and explore what makes it special in that space. The designer wanted to see examples with one designer recommending that all the material

	samples be replaced with products that use the material to aid understanding. One thing that stood out was that designers wanted to look at multiple sources for information on a material, with everyone agreeing that finding multiple different pieces of information helped them create an overall picture. Participant quotes: “I’m most happy with a datasheet, even if I don’t understand everything on it, I can always take it to someone else who does.” “Data sheets are useful but there more for something to compare to something else.” “We used to have stacks of data sheets, but I only understand parts of each one based on what I’ve had to look up for past projects.” “What the material is doing in the real world is essential not only can I check that what I already understand makes sense, but I can also cover how the material functions.” “This (referring to a material communication) says it gets harder under stress (D3O). Once you’ve told me that I’m intrigued, but I’m not sure how hard. If you give examples of it in use, I would have a better idea of exactly how it works.” “I just would like a summary, is it light or heavy, soft or hard, or somewhere in-between?” “Can you cover the basics first, that’s what I’d do.” “The second I know it’s just a special plastic I can think of so many ways to apply it.” “Tell me it’s a composite or a special steel foam (Cellular metal) straight up, once I get that there’s so much you don’t need to say, well as long as I actually know what you’re talking about.” “It (Nitinol) must already be being used, so how? Some examples would really help me understand what it can do.” “You could speed this process up by bringing all the materials in products rather than in samples. That would be like the ultimate intro.” “I like the memory wire (nitinol) and I kind of get the explanation but I’d want to know how it’s used so I can check I’ve understood.” “When (Participant B) said that the faraday film would be good for windscreens I realised I’d got it wrong, I thought it was the plastic, not a treatment.” “I don’t expect this to tell me everything, just to kind of frame the material so I know the basics, then I can turn to other things to improve what I know.” “No matter how detailed one source is I will always check and do more research, so you don’t have to pin it all down instantly, but it would be great to get it clear.”

	"It's the innovation and what it can do for me that's important."
	Why did you pick this method of comparison over other ways to explain yourself?
	The participants again struggled with this question compared to other focus groups. Though this group was the greatest proponent of the process of using comparisons that used numbers to alter the comparison, for instance creating statements like 'uses 60% less carbon' this was popular with those who had worked in design engineering firms but once mentioned also struck a chord with the other designers. The designers in general wanted to see these communications remain simple though and avoid specific language, those who'd worked in the design engineering firms agreed with this, and felt that it was better to have more general terms as they were more likely to be understood by everyone. Participant quotes: "Tell me what's important then compare it, like tell me it's tough and then say it's as tough as titanium, otherwise you say something is like titanium and I'm just wondering if you mean it's good in submarines." "This shouldn't be confusing this should be sharp, simple and absolute. Explain what's being covered and go from there." "It reminds me of a wound healing up (self-annealing plastic). "The nitinol wire isn't like any other material, so I'd compare it to muscles or something else you can change the shape of, if you want to see it change." "There's a lot of wasted chatter about new materials when you can just boil it down to, most of the time, the things that are just special and nothing else can bring together." "I like the plastic (UPM Formi) and 60% less CO2 compared to regular plastics makes the benefit clear." "With the cellular metal how, much lighter is it than normal steel because this could be 10% of the weight of normal steel but if it's still got even half the compressive strength that's huge." "The proportion that this material improves is important, is double the strength or just 10% stronger?" "I keep trying to think how I'd explain how light that cellular metal is. If I just say light, I don't think people will get it, but if I say it's a tenth of the weight of the same metal block, then it starts to sink in." "I feel that you don't need to find a one to one comparison, it's great when you can say things are exactly the same but as long as it's clear and you compare the properties by a percentage or say it's double or three times that works for me. Don't get into 16ths or anything to exact like 53% just round it to the closest sensible number." "Cellular metal is light like polystyrene but strong like honeycomb."

	"D3O offers everything a normal plastic does but with the added strength of oobleck built in." "It's just so much detail, so I'd split it up say, it's like a fabric (PCM fabric) that can also store heat like a thermos." "(UPM Formi) …is like silicone but doesn't need any oil to make it." "I don't really get what being more viscous looks like adding a statement like 'it doubles in viscosity' will just make me switch off." "I think there's some terms that everyone is using which I'm a little embarrassed to admit I don't know." "Analogies or metaphors can work but it's confused. Not as concrete as this thing and this thing are the same."
Other notes:	The participants didn't directly call for a three-part communication as was found in other focus groups. They did want to explore using multiple tools and didn't see this as a problem. Participant quotes: "Mix and match is my advice, as long as it's all correct and not so different I get whiplash we'll be okay." "This just needs more clarity in my mind, there's just so many ways to picture this, you need to pick things that we all have experience that we can apply and picture." "The details all add up to a picture that makes sense, each one is a bit different but that doesn't matter, just add them together." "As long as they are all right there's no reason to not explain in every way."

14.2.4 **Focus group 4**

Participants:	At least two years academic design knowledge and some professional experience.
Notes from introductory questions:	What experiences have you had learning about materials/ What do you think of current ways to learn about materials?
	In this group the designers didn't have much familiarity with finding out information about materials, with only two designers having a strong recollection about using specific tools to find out about materials. Participant quotes: "I've used the Material connexion website before, one of the other placement students put me on to it." "We had a whole block of books, just whatever we pick up during a project or if someone if the office needs it." "I used a couple of specialist books for my industry, it was helpful to get an idea of what plastics to use."

Notes from transfer questions:	What do you think is important to cover when explaining this material to other designers?
	Participant quotes: "What matters about the material is what's special, tell me that and I can work it out from there." "People send me a lot of samples and I don't have time to read all the nonsense that comes with them. So, what's important better be the first thing I read in bright bold text or I'll probably think it (D3O) looks like just another plastic. "What manufacturing options there are and how established they are, I did my placement with a pretty conservative industry and won't be able to convince investors otherwise." "The idea of what the material can do already would be helpful as it not only helps me imagine what it can do but also how it can be processed." "I've reused materials from past projects when I know they worked in those, seeing examples of the material in action would give some confidence in what it could do." "The explanation needs to be pretty simple to start off with, use small words, we're designers we can use the big words later." "What you say first is what I'm most likely to remember. I'm also more likely to pay attention then to the rest if I think it's cool." "first impressions count, especially for materials which I've gotta be honest don't really interest me, so it's better hook me right away." "I don't care if it's (Fiberline) pultruded plastic, that means nothing to me, when she (referring to another participant) said it's GRP (glass reinforced plastic) that made sense." "The dilatant thing didn't help me at all, I've no idea what that means." "What I want from materials and what others want is really different. I'm not sure I could explain it well to someone else." "I'm involved in designing for children so it's a completely different ball game, my top priority is risk and I'm not sure that's relevant to this."
Notes from key questions:	What do you think is important to cover when explaining this material to other designers? / What would be the best way to explain the innovative material properties to you?
	Participant quotes: "It's like a Velcro patch and sticks to itself but not the clothes." "Keep it simple, the plastic is basically silicone. (UPM Formi)" "Just compare it to whatever its most similar to, that's what I'd do."

	"There has got to be other materials like these out there which aren't so insane that none of us has heard of them. Pick those or get at least the closest ones." "Nail down the material first, make it super clear what I'm dealing with and then be like the magician pulling the rabbit out of the hat and reveal what's special."
Notes from specific questions:	If you were comparing the material to another, how would you describe it?
	Participant quotes: "I think it easiest if you can choose something that exists and say it's like that, tell me it's like steel or something" "There is so much out there just pick something that this is close to, you can say it's not a perfect match as long as it's not so different we get the wrong Idea." "Tell me what's improved, with the Fiberline, tell me it's GRP but then say, 'but it's as strong as steel.' That makes it clear." "Set the scene for me, let me know it's a plastic (D3o) and then tell me how much better it is at absorbing impacts." "This plastic(self-annealing) is like a rubber band that can also heal itself from cuts." "The paint (Bare conductive) is just like normal acrylic paint but also functions as a wire." The moss (Bright green) looks like real moss but lasts like plastic." "It's cool that it just (heat detecting crystals) are just waiting in black plastic form before switching to the colours." "It annoys me as heals can mean anything, if you're going to give me an example don't make it unclear. Otherwise you might as well not bother." "Some of the things you've suggested (referring to a participant) wouldn't work for me, I just want stuff to be as obvious as possible." "I know the basics of most materials but if you then tell me what it does differently, that change is what I'm interested in." "That one thing that's exceptional is what I'm here for, all the other details can be sorted out later."
	Why did you pick this method of comparison over other ways to explain yourself?
	Participant quotes: "Analogies should be really exact. I'm still not sure I'm getting mine right." "The comparisons make sense to me because they fit into how I think about everything else I work on, where I'm trying to fit what I've done before into a new challenge."

	"It works when you can make it clear what is standing out." "It makes sense to me when I can pinpoint that one innovation that makes it better than the others, then it just clicks." "The materials that I connected with are those which I can immediately know the benefit or that special option they give me, the materials where it's all a bit messy aren't so good." "The cellular metal is cool because it's just so much lighter, but I want a tangible understanding of how that affects it's features." "When you compare it to different materials it's like you filling in bits of a puzzle, each comparison gives me more pieces." "The overlap of each part works, it's like having each piece be the foundation for the next." "It should be obvious what we're talking about the is so much out there is common knowledge you shouldn't need to talk about really weird specific materials that aren't relevant." "The moss is really natural, but basically a plastic…I'd like to see it on buildings or behind glass." "I like how light the metal balls material is (cellular metal). They're kind of like metal polystyrene, I'm sure you could make some really tough stuff out of this."
Other notes:	Participant quotes: "It's a weirdly cold sheet, kind of like it's been in the fridge, I'm sure it be great for clothes in hot countries" "I like knowing what's important first, otherwise I'm just going to pay attention to what I care about."

14.2.5 **Focus group 5**

Participants:	At least two years design academic knowledge
Notes from introductory questions:	What experiences have you had learning about materials/ What do you think of current ways to learn about materials?
	In this group the designers all shared that they felt they had pretty similar methods of learning about materials. A by-product of working together for an extended time. One participant said that they felt they were the 'materials guy' for the office and did the more detailed research when something new came up but otherwise the load was split evenly. Participant quotes: "There's this blog on smart fabrics that I follow but it's defunct now, though it's got some really interesting experiments." "Sometimes I just fall down a wikihole and learn about stuff, which if I like I'll bookmark for later,"

	"There's blogs for everything, now you can generally just find what you want when you want it. Though some are better than others."
Notes from transfer questions:	What do you think is important to cover when explaining this material to other designers?
	Participant quotes: "What are its limits? Can it (D3O) take a hammer blow or a bullet?" "What kind of resistance to UV and wear has it got? I'm working on a project where we've got to make long lasting items out of plastic, and this would be perfect if it can hold up." It's not something I can see myself doing well."
Notes from key questions:	What do you think is important to cover when explaining this material to other designers? / What would be the best way to explain the innovative material properties to you?
	Participant quotes: "Giving examples helps me, there's a hundred ways I could interpret any explanation but hard tangible proof it is working in a certain way would be a bit more concrete." "It's just how I think, when I started learning about plastics, I didn't think about what their qualities where I just thought about what you could make from them." "It all gets a bit confusing so having an example is nice and clear, way better if it's something I recognize and can use as a yard stick to evaluate the material." "I've got a terrible attention span so it better be a punchy intro to get me hooked, once you've got me then you can get into the nitty gritty." "Manging all the different stuff could be complex, you should label what's important first, so we don't get lost." "Knowing it's an ecosilicone is all I really need to get it." "I didn't get why the eco-plastic was special (UPM Formi) until I tried to think of alternatives to silicone. You should really focus on that to make it clear." "There is so much out there it's really important to isolate what makes it stand out and why nothing else offers the same options." "I understand that this is an improvement over let's say rubber but exactly how much better should be top priority as otherwise I'm just wondering what makes it stand out." "I feel like I'm still learning the ropes so I'm not sure what to say." "I love a data sheet but it's only a bit of the story. I'd prefer to have a real play with a material before looking at its datasheet."
	If you were comparing the material to another, how would you describe it?

Notes from specific questions:	Participant quotes: "It's all about that added edge these materials have over everything else. "I'd personally explain this as 'best in class for eco-friendly silicone' in that one sentence I know what's special and what it's special compared to!" "It's not as complicated as you'd think. You could make a list of material properties and then compare them, for the materials we know just explain how it compares, you could say it's quarter the wright of steel, but it's got the hardness and resistance of …something else." "It's not enough to just be like it's stretchy (self-annealing plastic) say it's stretch like a rubber band or if it isn't saying it's half as stretchy as bungee cord. At least I can then google bungee cord and see how stretchy it is and work it out from there." "This stuff (Fiberline) is as strong as steel but is a fifth of the weight." It's (Mycelium) got a lot of the properties of polystyrene, can be shaped and pulled apart but it's not made of plastic." "You're (referring to another participant) talking about how airplanes work which honestly isn't my strong point can't we keep it focused onto things that we'd all recognize." "It makes the benefit clear, if it's that plastic is a quarter of the weight of steel and almost as strong, then I can see what appeals about it." "The more scientific the term the more likely I am to think this isn't aimed at me." "I'm happy to add things together, as long as it's clear what I'm talking about in each one," "You should double up on the description, then we don't have to pick the best we just read it all and the one that clicks with us clicks." "I don't like analogies. If you can do it simpler, simple explanations are always better and more likely to work for me," "It's a conductive spray, like spray on wires."
	Why did you pick this method of comparison over other ways to explain yourself?
	Participant quotes: "Pick things we've all heard about or are in the news, if it's something we encounter on a daily basis that's the best possible option, then I could literally go grab the thing you're using to compare with and have a play." "The attributes which are clearest are those which are the same as materials I use and have worked with, I've got a picture in my head and can puzzle a new picture together from the bits I know." "This is really useful for when the improvement is clear cut, saying exactly what's better immediately."

	"It's obvious what you mean when you can say it's better than something I know" "Crystal clarity is necessary on what makes the material special otherwise it's just going to get lost, I don't care how it's done but nothing is more important than that." "The discussion about being double the strength earlier made sense to me. That kind of improvement is really easy to remember and relay to someone else." "I like how you can add up different ideas to get an overall view of what the material looks like." "Adding all the bits we've discussed today into one longer explanation feels a bit clunky but it's certainly understandable, far better than just the bits and pieces on their own." "Once I know what it's like, working out what's special is easier," "Getting that clarity is all I want; the special thing stands out but there is a load of other important details I want to know."
Other notes:	Participant quotes: "I'm happy to add things together, as long as it's clear what I'm talking about in each one," "You should double up on the description, then we don't have to pick the best we just read it all and the one that clicks with us clicks." "I prefer comparing to a few things. Then you can get the benefit of each one, saying it's like this but not quite, feels less elegant,"

14.3 FOCUS GROUP GUIDE

1. Opening: • Each participant is required to introduce themselves within 30 seconds to 1 minute.

2. Introductory questions • There are about 1-2 questions of this kind. Each question should be discussed for no longer than 5 minutes. Questions of this kind aim to establish participants' connection with the discussed topic.

a) What experiences have you had learning about materials
b) What do you think of current ways to learn about materials?

3. Transfer questions: • There are about 1-2 questions of this kind, and each question should be discussed for no longer than 7-8 minutes. These questions serve as the bridge between introductory questions and key questions but are deeper than introductory questions. Introductory questions aim to introduce the discussed topic, but transfer questions are intended to realistically connect participants to the discussed topic. Participants will start to perceive opinions shared by other participants at this moment.

a) How would you explain this material to the person next to you?

4. Key questions: • There are about 2-3 questions of this kind. Each question requires a longer time for discussion, but the duration should be between 10-15 minutes. These questions are the core of focus group interview. They are usually discussed when the group discussion has proceeded halfway of the entire session. Besides, they are also the focuses of the research questions.

a) Can you describe how you would want the manufacturing properties of this material explained to you?
b) Can you describe how you would want the aesthetics & texture/feel of this material explained to you?
c) Can you describe how you would want the durability of this material explained to you?

5. Specific questions: • There are about 1-2 questions of this kind, and the total discussion time allowed for these questions should be between 10-15 minutes. Depending on the requirement of the research, researchers can request participants to discuss questions deeper than the key questions on certain points.

a) How would you want the radical property of this material explained to you and how might it differ to the other features?
b) Would you want a similar explanation using the same method of explanation for a different radical property?

6. Closing questions: • There is usually 1 question of this kind, and 3-5 minutes are allowed. This kind of question will request participants to make a conclusion and confirm the answers provided earlier.

a) If we explained the materials as we discussed do you think it would help you include the material in your design work?

7. Final question: • There is usually 1 question of this kind, and 3-5 minutes are allowed. To avoid any negligence, participants are required to provide suggestions and opinions about the discussed topic, such as "Do you think there is something we should have discussed but we did not?" This kind of question can be determined by the researcher by the realistic situations.

a) Thanks for your time is there anything that you feel should have been talked about that we did not cover?

15 APPENDIX E – ETHICS FORMS

Participant Information Sheet (Focus groups)

When our research students conduct their studies, they often need to carry out some initial research with the target market and later with stakeholder groups to evaluate the proposed design solutions or engineering innovation ideas.

• This is an invitation to you to join the study, and to let you know what this would involve.

• This project is being supervised by the supervisors, *Marco Ajovalasit* and *Eujin Pei.*

• When the project is completed, results will be added to appropriate document (e.g. Word, Excel, PowerPoint, still photo, short videos). No personal information will be identified but images of participants may be used within the final presentation if you have explicitly given your permission.

• If you want to find out more about the project, or if you need more information to help you make a decision about joining in, please contact the project supervisor (Marco Ajovalasit, Marco.Ajovalasit@brunel.ac.uk).

Your participation in the Research/Project

Why you have been asked?

You have been asked because we think you are a target user or a relevant stakeholder of the proposed project. The participation in the study is entirely voluntary; there is absolutely no obligation of any kind to join the study.

What happens if you want to change your mind?

If you decide to join the study, you can change your mind and withdraw at any time.

What would happen if you join the study?

If you agree to join the study, then we will ask you to be part of a workshop based on multiple creative activities.

Are there any risks?

We shall try to minimise any possible risks. If you did feel that there was any stress involved, you can stop at any time. Just tell the researcher that you want to stop.

What happens to the research results?

The students conducting the research are responsible for putting all the information from the study (except names and addresses, and personal identification information) into a computer programme such as Excel, Word or PowerPoint. The student then analyses the information via graphs and images presented in a research report (often these reports are not public documents). The objective is to prove and evaluate the design for a new product or service. For presentation purposes, digital imagery and video may be used at public presentations. If this is the case, then prior permission will be sought from participants.

What will I gain from taking part?

You may find the project interesting, and your opinions may inspire the researcher to innovate, but you will not receive any particular direct benefit otherwise.

How we protect your privacy

All information that is collected about you during the course of the research will be kept strictly confidential. Any information recorded about you will have your name and address removed so that you cannot be recognised from it.

If I have more questions, who can I ask?

Please feel free to ask us any question you would like about the study.

Thank you very much for taking the time to read this sheet.

Researcher's name and contact detail: James Burchill

James.Burchill@brunel.ac.uk

Supervisors` name and contact detail: Marco Ajovalasit

Marco.Ajovalasit@brunel.ac.uk

Information sheet for the focus groups

Understanding Radically New Materials from A Design Perspective

Name of Researcher: James Burchill,

This project has been approved by the ethics committee of the College of Engineering, Design and Physical Sciences, Brunel University London.

Consent Form

The participant should complete the whole of this sheet him/herself

Please tick appropriate box

	YES	NO
I have read and understood the Participant Information Sheet	☐	☐
I have had an opportunity to ask questions and discuss this study	☐	☐
I understand that I am free to withdraw from the study:		
- at any time	☐	☐
- without having to give a reason for withdrawing	☐	☐
I give permission to the researchers for recording the interview	☐	☐
I give permission to the researchers for taking photos and videos during the study	☐	☐
I agree to take part in this study	☐	☐

Signature of Participant……………………………………. Date……………………..

Name in capitals……………………………………………………………………………

Ethics form for the focus groups

Participant Information Sheet

When our research students conduct their studies, they often need to carry out some initial research with the target market and later with stakeholder groups to evaluate the proposed design solutions or engineering innovation ideas.

• This is an invitation to you to join the study, and to let you know what this would involve.

• This project is being supervised by the supervisors, *Marco Ajovalasit* and *Eujin Pei*.

• When the project is completed, results will be added to appropriate document (e.g. Word, Excel, PowerPoint, still photo, short videos). No personal information will be identified but images of participants may be used within the final presentation if you have explicitly given your permission.

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What happens to the research results?

The students conducting the research are responsible for putting all the information from the study (except names and addresses, and personal identification information) into a computer programme such as Excel, Word or PowerPoint. The student then analyses the information via graphs and images presented in a research report (often these reports are not public documents). The objective is to prove and evaluate the design for a new product or service. For presentation purposes, digital imagery and video may be used at public presentations. If this is the case, then prior permission will be sought from participants.

What will I gain from taking part?

You may find the project interesting, and your opinions may inspire the researcher to innovate, but you will not receive any particular direct benefit otherwise.

How we protect your privacy

All information that is collected about you during the course of the research will be kept strictly confidential. Any information recorded about you will have your name and address removed so that you cannot be recognised from it.

If I have more questions, who can I ask?

Please feel free to ask us any question you would like about the study.

Thank you very much for taking the time to read this sheet.

Researcher's name and contact detail: James Burchill James.Burchill@brunel.ac.uk

Supervisors` name and contact detail: Marco Ajovalasit Marco.Ajovalasit@brunel.ac.uk

Information sheet from the workshop series

Explaining materials consent form

Name of Researchers: James Burchill,

This project has been approved by the ethics committee of the College of Engineering, Design and Physical Sciences, Brunel University London.

Consent Form

The participant should complete the whole of this sheet him/herself

Please tick appropriate box

	YES	NO
I have read and understood the Participant Information Sheet	☐	☐
I have had an opportunity to ask questions and discuss this study	☐	☐
I understand that I am free to withdraw from the study: at any time	☐	☐
without having to give a reason for withdrawing	☐	☐
I give permission to the researchers for recording the interview	☐	☐
I give permission to the researchers for taking photos and videos during the study	☐	☐
I agree to take part in this study	☐	☐

Signature of Participant……………………………………. Date……………………..

Name in capitals

Ethics form for the workshop series

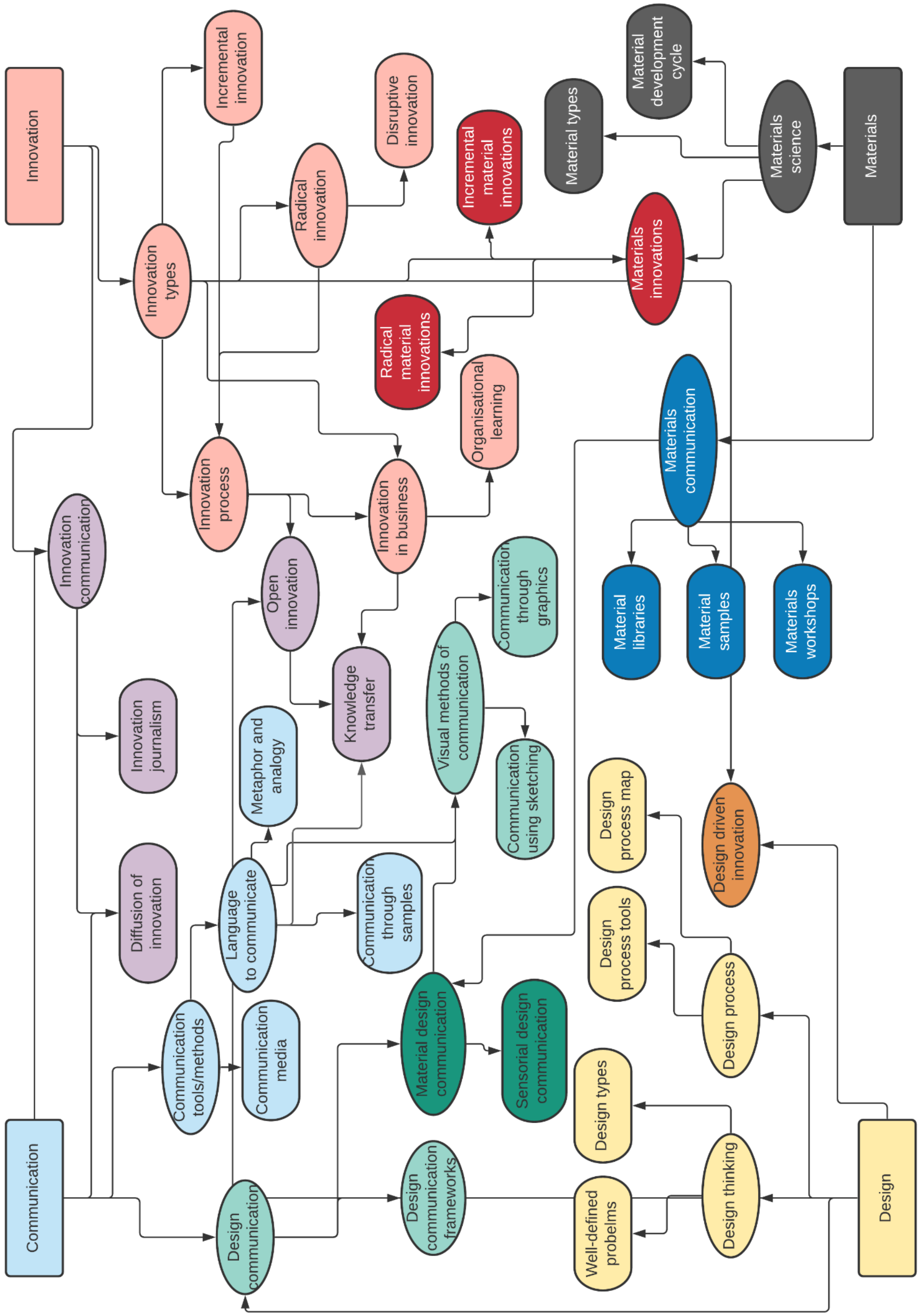
16 APPENDIX F –DEVELOPMENT LITERATURE REVIEW

In the literature review the approach of the researcher was to review a number of databases for articles these included Google scholar, Microsoft academic, and ERIC. Topics were generated first through identification of the broadest terms that could cover the content of this thesis. These were, Innovation, Design, Materials and Communication. With these identified and the topics were then combined or explored in more detail to explore the content in more detail. This is outlined in the image below.

When reviewing the articles that appeared through these searches, particular attention was paid to the reach, validity and quality of the work. This was done through reviewing those articles from reputable publications, and/or those which were highly cited. Once these were reviewed they often contributed to the progression of the topics generation or helped connect the author of with more relevant pieces of work. The publications which were given particular focus included:

- SAGE publications
- International Journal of Design Creativity and Innovation.
- International Journal of Technology and Design Education,
- Creativity and Innovation Management
- Journal of Business Research
- Journal of innovation management
- Nature materials

With this complete the literature review was created. Below is a map of how the topics developed, while this does not cover every search made it does illustrate the main paths of exploration.


Innovation
Innovation types
Incremental innovation
Radical innovation
Disruptive innovation
Incremental material innovations
Radical material innovations
Materials innovations
Material types
Material development cycle
Materials science
Materials
Innovation process
Innovation in business
Organisational learning
Materials communication
Innovation communication
Open innovation
Knowledge transfer
Communication through graphics
Visual methods of communication
Material libraries
Material samples
Materials workshops
Innovation journalism
Metaphor and analogy
Communication using sketching
Design process map
Design driven innovation
Diffusion of innovation
Language to communicate
Communication through samples
Design process tools
Communication tools/methods
Communication media
Material design communication
Sensorial design communication
Design process
Design types
Communication
Design communication
Design communication frameworks
Well-defined probelms
Design thinking
Design