Prometheus Missing

Critical Materials and Product Design

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Critical Materials are strategically important to societies, businesses and economies. They are essential to maintain and improve our quality of life. The world however faces problems of critical material supply, but these concerns are not translated into product design activity, even though current policy and history suggests that product design can play a role in finding solutions to the critical materials problems. This thesis reviews literature from the past and draws observations from historical cases, which show product design changes can help address scarcity. A 21st century critical materials literature review leads to a new definition of critical materials for product designers. In-depth interviews, conducted in 29 companies, show that most do not see links with product design and critical materials. This thesis concludes by producing a framework to help develop education on product design and critical materials. This framework also highlights policy actions within a circular economy transition.

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Prometheus Missing:
Critical Materials and Product Design

David Peck

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Propositions

accompanying the thesis:

Prometheus Missing: Critical Materials and Product Design

By David Peck

1. Modern technology could not exist without non-renewable resources, yet the availability of these resources has seldom been a matter of much concern and product designers have never been taught to regard materials as anything but commodities to be employed as necessary or convenient.
   (*Adapted from: Graedel, T., 2009.)*

2. TU Delft, with its experience in sustainability in higher education, should be engaged with the critical materials problem and should be in the process of developing strategies for resource-aware product design. (*Adapted from: Köhler A. R, et al, 2013)*

3. Critical materials are like ‘canaries in the coalmine’; they demonstrate that ‘limits to growth’ thinking is valid.

4. It is true, the past is a foreign country and they do things differently there.
   (*based on L. P. Hartley, 1953)*

5. As a result of there not being many of us, researchers in the field of critical materials and product design, can usually only drink in pairs. The inclusion of critical materials, together with circular design, closed loop, eco-design approaches, could lead to more of a party.

6. Democracy requires relative abundance in order to thrive.
   (Webster K, 2015)

7. Europe should not risk turning the lamps out because we see each other as faraway people of whom we know nothing.
   (Adapted from: Sir Edward Grey, 3 August 1914, and Neville Chamberlain, 27 September 1938)

8. The name of the ancient Greek mythological titan Prometheus means ‘forethought’ and the element Dysprosium (66) takes its name from the Greek word dysprositos (δυσπρόσιτος) which means ‘hard to access’. The ongoing search for ‘Unobtanium’ continues.
   (*Adapted from: Heflin W, 1958*)

9. The challenge of critical materials can be successfully addressed by product designers. *(this thesis)*

10. Prometheus is missing. *(this thesis)*

These propositions are regarded as opposable and defendable and have been approved as such by the promotors Prof. Dr. P. V. Kandachar and dr. C. A. Bakker.

Stellingen

bij het proefschrift

Prometheus Missing: Critical Materials and Product Design

van David Peck

1. De moderne technologie zou niet kunnen bestaan zonder niet-duurzame hulpbronnen, maar toch is de beschikbaarheid van die hulpbronnen zelden onderwerp van grote zorg en wordt productontwerpers nooit geleerd materialen te beschouwen als iets anders dan grondstoffen die worden gebruikt omdat ze nodig of gemakkelijk zijn.
(*naar Graedel, T., 2009)*

2. Vanwege zijn ervaring met duurzaamheid in het hoger onderwijs zou TU Delft zich bezig moeten houden met het probleem van kritieke materialen en zou het strategieën voor hulpbronbewust productontwerp moeten ontwikkelen. (*naar Köhler, A.R., et al, 2013)*

3. Kritieke materialen zijn als ‘kanaries in de kolenmijn’; ze tonen aan dat ‘grenzen aan de groei’ een valide idee is.

4. Het is waar dat het verleden een ander land is en dat men de zaken er anders aanpakt.
(*op basis van Hartley, L.P., 1953)*

5. Omdat we niet met velen zijn, kunnen onderzoekers op het gebied van kritieke materialen en productontwerp gewoonlijk slechts met zijn tweeën het glas heffen. De opname van kritieke materialen in circulaire en ecologische ontwerpstrategieën zou tot een groter gezelschap kunnen leiden.

6. Voor een bloeiende democratie is relatieve overvloed vereist.
(Webster, K., 2015)

7. Europa mag niet het risico lopen de lichten te moeten doven omdat we elkaar zien als mensen in de verte van wie we niets weten.
(naar Sir Edward Grey, 3 augustus 1914, en Neville Chamberlain, 27 september 1938)

8. De naam van de titaan Prometheus uit de Griekse mythologie betekent ‘de vooruitdenkende’ en het chemische element dysprosium (66) ontleent zijn naam aan het Griekse woord 'dysprositos' (δυσπρόσιτος), dat ‘moeilijk toegankelijk’ betekent. De permanente zoektocht naar ‘unobtanium’ wordt voortgezet.
(*naar Heflin, W., 1958)*

9. Het probleem van kritieke materialen kan met succes worden aangepakt door productontwerpers.
(dit proefschrift)

10. Prometheus is echt verdwenen. *(dit proefschrift)*

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren prof.dr. P.V. Kandachar en dr. C. A. Bakker.

Prometheus Missing:
Critical Materials and Product Design

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Critical Materials and Product Design

Proefschrift

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Contents

Summary

Critical Materials are important in economies, business, innovation activity and products, and they have quickly become essential to maintain and improve our quality of life. The world faces problems concerning critical material supply, but these concerns are not translated into product design activity, even though history shows that product design can play an important role in finding solutions to critical materials problems. This thesis addresses a central research question:

What has been and what should be the role of product design in addressing critical materials problems?

To address the 'what has been' part of the question, this thesis reviews literature from the past and draws observations from five Second World War (WWII) cases on scarce materials and product design. The cases cover Austerity Locomotives, Utility Schemes for Furniture, Clothing and Pottery and a proposed National Utility Vehicle. The British government imposed strict controls on product supply, through licences, permits and rationing, supplied products to those with need and encouraged society to do with less and if possible do without. The British government imposed tight product design controls which resulted in developing material substitution from British sources, less material use, increased repair & reuse through design for disassembly and re-assembly, design for product service systems including take-back and pay as you use, robust design for long life, use of higher grade materials, lower energy use and high manufacturing productivity in regional factories by lower skill workers.

To address the 'what should be'' part of the question, 21st century literature on the definition of critical materials, in particular product design perspectives, is reviewed. The range and quantity of materials used in product designs has, over recent decades, rapidly increased, supply chains have become more complex and opaque and the materials in many hi-tech products is poorly understood by product designers. At the same time governments, for example, in the EU and USA, propose that product design will be important in the effort to address critical materials problems. An example of critical materials in products is provided by the use of small amounts of Dysprosium in a Neodymium-Iron-Boron permanent magnet, which allows the magnet, used in an electric motor, to improve performance at higher operating temperatures. This produces powerful motors, in a range of products from smart phones to electric cars.

A critical materials literature review leads to a new definition of critical materials for product designers:

'Critical materials are elements from the periodic table of elements (metals / rare earths) that may be at risk of price volatility and supply restrictions. They are applied through the selection of parts and materials during the product design process and are often present in small quantities in technology products, providing unique performance characteristics,

that the product depends on and the user highly values. Physical substitution of a critical material changes a product's properties and / or performance, can entail high financial / environmental costs and can have a long lead time'.

In order to gauge the understanding and responses to critical materials in companies, this thesis presents empirical research on the topic, with in-depth interviews conducted in 29 companies with operations in the Netherlands. The results from this research show significant gaps in awareness and understanding around the topic of critical materials. The role of critical materials is seen as very important to their product design and product performance, but the topic is typically addressed by procurement / purchasing staff. The majority, over 60%, use their risk management procedures to address critical materials, but they are not clear on which materials are at highest risk or in which products they actually use critical materials. Three quarters of the companies expect their suppliers to manage the risks for them. In terms of business and critical materials, opportunities are seen by over a third of the companies, but a majority see critical materials as a threat, and only two companies see any links to product design approaches.

The main point observed in the synthesis, is that when material scarcity was a problem in WWII, product design, instigated and coordinated by government, played a key role in developing solutions. There is a parallel between the product design strategies for historical material scarcity and proposed 21st century product design strategies for critical materials. These approaches are being proposed by product design engineers and governments today, in particular by the European Union (as part of their circular economy proposals), but as the results of the company research indicates, there is a lack of urgency and activity in companies. The scale of the transition to a circular materials economy is large but so are the costs and risks of critical materials problems. In response to these challenges this thesis concludes by producing a framework to help develop product design approaches for a circular materials economy.

Samenvatting

Kritieke materialen zijn van belang in de economie, in het bedrijfsleven, bij innovatie en in producten, en ze zijn essentieel voor het in stand houden en verbeteren van onze kwaliteit van leven. De wereld kan geconfronteerd worden met problemen in de aanvoer van kritiek materiaal, maar deze mogelijke problemen vertalen zich niet in activiteiten bij het productontwerp, ondanks het feit dat de geschiedenis leert dat het productontwerp een rol kan spelen bij het oplossen van problemen met kritieke materialen. In dit proefschrift wordt daarom ingegaan op de volgende onderzoeksvraag:
Wat is tot nu toe de rol van het productontwerp geweest bij het oplossen van problemen met kritieke materialen en wat zou die rol kunnen worden?

Voor een antwoord op het 'tot nu toe'-gedeelte van de vraag wordt literatuur uit het verleden bestudeerd en worden conclusies getrokken uit vijf case's over schaarse grondstoffen en productontwerp in de Tweede Wereldoorlog. De case's betreffen de Britse overheidsprogramma's voor de Austerity-locomotief, Utility-meubilair, -kleding en -aardewerk, en het voorstel voor een National Utility Vehicle. De Britse regering zag streng toe op het aanbod van producten met een systeem van licenties, vergunningen en distributie, leverde producten aan de behoeftigen en moedigde de samenleving aan met minder, en zo mogelijk met niets, genoegen te nemen. Zij legde ook strenge regels voor het productontwerp op, die leidden tot de ontwikkeling van vervangende materialen uit binnenlandse bronnen, minder materiaalgebruik, meer reparatie en hergebruik dankzij demontage en remontage, ontwerpen van systemen voor productservice, zoals terugbrengmogelijkheden en betalen naar gebruik, robuuste ontwerpen met een lange levensduur, toepassing van hoogwaardiger materialen, een lager energieverbruik en een hogere industriële productiviteit in regionale fabrieken met laaggeschoolde arbeiders.

Voor een antwoord op het 'wat zou'-gedeelte van de vraag wordt de 21ste-eeuwse literatuur over de definitie van kritieke materialen onderzocht, met name vanuit het oogpunt van productontwerp. Het aanbod van materialen die in productontwerpen worden gebruikt is snel gegroeid, leveringsketens zijn complexer en ondoorzichtiger geworden, en productontwerpers hebben geen goed begrip van de materialen in veel hightechproducten. Tegelijkertijd stellen overheden, in het bijzonder in de EU en de VS, dat productontwerp van groot belang is bij het oplossen van de problemen met kritieke materialen. Een voorbeeld van kritieke materialen in producten is het gebruik van kleine hoeveelheden dysprosium in een permanente neodymium-ijzer-boronmagneet, waardoor de magneet, die in elektromotoren wordt gebruikt, goed werkt bij hogere bedrijfstemperaturen. Dit levert krachtige motoren op voor uiteenlopende producten, van smartphones tot elektrische auto's.
Een literatuurstudie van kritieke materialen leidt tot een nieuwe definitie van kritieke materialen voor productontwerpers:

‘Kritieke materialen zijn elementen uit het periodiek systeem (metalen/lanthaniden) waarbij er een risico is op prijsvolatiliteit en leveringsbeperkingen. Ze worden toegepast op grond van de selectie van onderdelen en materialen tijdens het productontwerpproces en zijn vaak in kleine hoeveelheden aanwezig in technologische producten, waar ze unieke prestatiekenmerken opleveren waarvan het product afhankelijk is en die de gebruiker in hoge mate waardeert. Fysieke vervanging van een kritiek materiaal verandert de eigenschappen en/of prestaties van een product, kan hoge financiële kosten en/of grote milieuschade met zich meebrengen en kan veel tijd in beslag nemen.’

Teneinde inzicht te verschaffen in de kennis van en reacties op kritieke materialen bij bedrijven wordt er in dit proefschrift empirisch onderzoek naar dit onderwerp gepresenteerd, in de vorm van diepte-interviews die zijn gevoerd bij 29 bedrijven met activiteiten in Nederland. De uitkomsten van het onderzoek brengen aanzienlijke lacunes aan het licht in het besef en het begrip van het onderwerp kritieke materialen. De rol van kritieke materialen wordt als zeer belangrijk beschouwd voor het ontwerp en de prestaties van producten, maar het onderwerp wordt gewoonlijk aan de orde gesteld door inkoopmedewerkers. De meeste bedrijven (meer dan 60%) passen hun risicomanagementprocedures wel toe op kritieke materialen, maar ze maken niet duidelijk welke materialen de grootste risico's opleveren of in welke producten de kritieke materialen eigenlijk gebruikt worden. Driekwart van de bedrijven verwacht dat de leveranciers de risico's voor hen beheersen. Wat betreft de zakelijke kansen van kritieke materialen ziet meer dan een derde van de bedrijven mogelijkheden, maar de meerderheid beschouwt kritieke materialen als een bedreiging en slechts twee bedrijven zien verbanden met de productontwerpstrategie.

Het belangrijkste punt dat in de synthese wordt gemaakt is dat toen materiaalschaarste in de Tweede Wereldoorlog een probleem was, het productontwerp, gecoördineerd door de nationale overheid, al een grote rol speelde bij het ontwikkelen van oplossingen. Er is een parallel te trekken tussen de historische productontwerpstrategieën bij materiaalschaarste en 21ste-eeuwse productontwerpstrategieën voor kritieke materialen. Deze strategieën worden nu voorgesteld door technische productontwerpers en overheden, met name de Europese Unie (in het kader van haar voorstellen voor een circulaire economie), maar de uitkomsten van het bedrijfsonderzoek laten zien dat het bedrijven ontbreekt aan een gevoel van urgentie en aan activiteit. De schaal van de transitie naar een circulaire economie is enorm, maar dat geldt ook voor de kosten en risico's van de problemen met kritieke materialen. In reactie op deze uitdagingen wordt in dit proefschrift ten slotte een kader geschetst voor de ontwikkeling van productontwerpstrategieën ten behoeve van een economie die is gebaseerd op circulaire materialen.

Preface

In 1999 the European Union introduced regulations banning the use of asbestos in products. I was leading a product design team in a company which used asbestos in certain parts of some products. We were facing a situation with a banned material, which we had to substitute but the task was not easy. Redesign is usually never easy or cheap. This experience helped me to understand that the security of the supply of materials, that many do not give much thought to, can suddenly became vital to the future of a company and that design plays an important role in managing materials supply changes.

Following the asbestos restriction experience, in 2007 I read an article by David Cohen published in the New Scientist magazine called ‘Earth's natural wealth: an audit’. The article engaged me, it was my introduction to the field of critical (scarce) materials, which though my work at TU Delft, led me to look for links with the field of product design (Cohen, 2007).

As I was considering this challenge, in 2009 attention toward the subject of critical materials began to rapidly rise, in particular around Rare Earth Elements. I came to realise that critical material problems are not, in the short term, about the threat of ‘running out’ (physical exhaustion of mineral reserves). Critical material problems do concern ensuring the security of supply, especially for the metals, and are driven by factors such as geopolitics, rising (and falling) consumption and technology developments.

All product designers must select materials and it is a core activity in their work. It is apparent that there are significant sustainability issues connected with critical materials. It also became clear there was very little publication on the combination of the fields of critical materials and product design.

My past experiences in industry, combined with an active interest in history, in particular the conflicts of the 20th century, led me to consider if there had been periods of material scarcity in the past, where product design played an essential role in securing materials supply. I found a number of examples and chose to focus on British cases from the second world war. This looking back into history helped me to find inspiration for an educational framework to help address our critical materials / product design problems today.

Prometheus missing, an explanation

Many think that because Promethium (Pm, 61) is in the lanthanide series and is a Light Rare Earth Element (LREE), that it is a critical material. According to the EU critical materials definition it is not a critical material. Promethium is missing.

This element, Promethium (original spelling; Prometheum) was named by American scientists in 1945. The name is derived from the Greek mythological Titan Prometheus. He stole fire from Mount Olympus, together with the skill of working metal, and gave them to mankind. This control of fire and metal is associated with knowledge and culture.

Prometheus is the symbol of TU Delft and a bronze statue of Prometheus stood in the campus from 1953. In January 2012 the statue of Prometheus was stolen from the university campus. Prometheus is missing.

The empty plinth which supported the original bronze statue of Prometheus and the new installation showing the 'empty space' representing the missing statue.

If Prometheus aimed to bring fire and metal working to mankind, given the lack of knowledge on critical materials and product design, Prometheus is indeed missing. This thesis attempts to address this gap and give Prometheus a place.

Introduction: Critical materials and product design

1.1 Aim of thesis

The selection of materials is a core activity for any product designer (Manzini, 1986, Ashby & Johnson 2009). With the availability of ever cheaper materials throughout most of the 20th century, designers have come to regard materials as always available when needed. Graedel has criticized this view, arguing that “unwise design” choices are being made (Graedel, 2009). In making this statement Graedel is proposing that materials complexity in products has increased considerably, and as a result, many products have been designed without the product designer having a full understanding of what materials are being used. An example of the product designer not having a full understanding of the materials involved can be seen in the development of mobile phones over the past 15 years. Whilst design engineers involved in the separate components may have an understanding of the materials involved in their part, the designer in the original equipment manufacturer, the product integrator designer, is unlikely to know of the exact sum of all materials. It is this ‘not knowing’ which, it can be proposed, Graedel refers to when he says this situation represents ‘unwise design choices’.

At the same time some governments, most notably the UK (UK Government, 2012), The Netherlands (PBL, 2011) and The European Commission (EU Manifesto for resource efficient Europe, 2012, EU KIC EIT Raw Materials, 2014, EU Circular economy package, 2015) have proposed that changes to product design have an important role in addressing materials problems. These product design changes are, however, not specified in any detail.

Materials problems, as viewed by these governments, are not about the threat of ‘running out’ (global physical exhaustion) in the timeframe of next 10 years. There are, however, problems in ensuring the security of supply for materials, especially metals, driven by changes in geopolitical and economic frameworks. Importantly, new technologies have increased the demand and diversity of metals being used. A rise in the socio-economic wealth, the so-called ‘rising middle class’, in emerging economies, has also driven up demand for all metals. Some of the emerging economies have increased their mining and processing of metals, making western, developed economies highly dependent on these emerging economies for their metals. As these metal producing emerging economies begin to mature they seek to move up the value chain. A final product is normally worth a lot more than the value of the metal contained in it. These emerging economies can use trade, taxation and investment instruments to reserve their metals for their own domestic use. This move corresponds with many product manufacturing companies developing lower cost production facilities in emerging economies. The complexity, paradoxes and contradictions surrounding critical materials is explored in this thesis.

In response to this mix of changes, governments in developed economies, in particular in the EU, Japan and USA, have been defining those materials which are most at risk of supply disruption, and which are also highly economically important, as critical materials. The EU defines critical materials in the following way:
"To qualify as critical, a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance. In such a case, the likelihood that impediments to access occur is relatively high and impacts for the whole EU economy would be relatively significant." (EU, 2010).

The critical materials considered in this thesis are; Li, Be, Mg, Sc, Cr, Co, Ga, Ge, Nb, Ru, Rh, Pd, Os, Ir, Pt, In, Sb, W, La, Ce, Pr, Nd, Sm, Y, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu. Critical materials are explained in more detail in chapter 3.

Some governments are also developing strategies that could address critical materials problems (Catinat, 2010). One of these strategies is to make changes to product designs. Product design is defined in this thesis as:

"The development of durables (mass produced products) for people, based on the integration of interests of users, industry, society and environment (Buijs, 1997)" in (Dorst, 1997)

The choice of materials is made at the product design stage. The design of the product can affect the potential to reuse or recycle the product. The product design can also affect the potential to substitute critical materials (and vice versa). The design of the product decides the length of the life of the product, which if shorter, speeds up the rate of critical material consumption, a situation made worse in a linear economy.

The linear economy is the current dominant system in the world where resources (the earth's natural capital) is extracted, processed, turned into product, used and disposed as waste. This system is mostly powered by polluting fossil fuels. An alternative sustainable approach has been termed the circular economy where materials are in closed loops in systems through activities such as reuse, repair, remanufacturing and eventually recycling. This system would be mostly powered on renewable, low carbon power. (Webster, 2015).

The list of products that use critical materials is not only limited to electrical and electronic equipment and other hi-tech products. For example, any severe supply restrictions on critical materials would mean that the deployment of most technologies and systems aimed at developing low carbon energy generation would be constrained. Furthermore, food supply, water control and availability, power supply, mobility, healthcare, communication systems and production systems could all face significant problems (Catinat, 2010; Pellegrini, 2014). The hi-tech systems and equipment that countries use for their defence, could also come under threat (Silberglitt, et al, 2013).

The aim of this thesis is therefore to explore the role product design has played and can play in addressing critical material problems.

1.2 Research questions

At an early stage in the research the central research question around the role of product design in addressing critical materials problems was established. Looking back in history is a good place to begin to look for answers to complex problems. Following this historical approach a review of definitions of critical materials was conducted, where the possibility of a gap concerning the inclusion of product design was identified. The practice of companies was developed with considering past responses.

The central research question (RQ) is:

What has been and what should be the role of product design in addressing critical materials problems?

In order to address the central research question the following sub research questions were developed:

Sub-research question 1: *What can be learnt from past product design responses to materials scarcity?* This is addressed in chapter 2

Sub-research question 2: *How can critical materials be defined within the context of product design?* This is addressed in chapter 3.

Sub-research question 3: *How are companies responding to critical materials?* This is addressed in chapter 4.

The research questions are addressed through the analysis of a set of five World War II cases, the analysis of more recent critical materials definitions, the development of a critical materials definition for product designers and empirical research on recent company responses to critical materials. The outcome of the answers to the research questions is the development of a critical materials product design framework. The critical materials product design framework is intended to facilitate the development of further research and education activity on critical materials and product design. Literature review and structured interview are the main research methods used. The details of the research methods are outlined in each chapter.

1.3 Scope of the study

This section defines and delimits the specific area of the research. The fields not dealt with in detail include energy, geoscience, material science, materials processing, geo-politics, economics, ‘conflict metals’ issues, wealth distribution, emerging economies, climate change (and other environmental impacts), water, bio-based solutions and food issues, the broader 'wicked 21st century challenges' topic and any fore-sighting of new advanced technologies.

This study will explore understanding of the state of the art of materials criticality from a company perspective. The core of this thesis will be around critical materials and product design awareness in organizations. The timeframes cover the 20th century (selected cases) and up to 2020.

1.4 Relevance of Study

This work is aimed at these involved in product design and innovation (in companies and research / education) to inform and raise awareness of critical materials and product design practice. This includes architects and urban planners.

For those in companies, education and research this thesis is aimed at highlighting the impact that critical materials problems could have on product development activities. In addition the results will contribute to a greater awareness that materials should not be just 'for the taking'. Most products are currently designed in a way which does not reflect the true value of the materials within them.

The wider relevance of this study is related to critical materials being 'warning' materials. The Earth does not have the carrying capacity for 7 billion (growing to 9 billion people) who are part of a take-make-use-dispose, linear economy. Critical materials are 'warning' materials: they indicate that we have reached planetary limits. Critical materials provide a rationale for societies, companies and governments to seek different, sustainable approaches. Critical materials are essential for a range of low carbon technologies, such as renewable energy, electric mobility, smart grids and smart cities. Without critical materials, these potentially more sustainable approaches to energy may become very difficult to realise.

The subject of critical materials has the ability to gain the attention of companies, governments and product designers, and solutions can be realized via existing sustainability strategies. Critical materials and energy are two sides of the same coin. Critical materials can also engage those who remain skeptical towards issues and debates concerning sustainability and provides an excellent rationale for a transition to a closed loop economy. Such a transition cannot take place however, without further knowledge development.

1.4.1 Structure of the thesis

Chapter 1, the introduction, is where the scene is set for this thesis. It also outlines the research design and research questions. This chapter goes on to outline the significance of the study and ends with an overview of the thesis structure.

Chapter 2 explores approaches to the critical materials and product design problem by looking back to events in the 20th century. This chapter examines five selected cases, called Utility and Austerity design (Locomotives, a car, pottery, clothing and furniture) implemented by the British, during the Second World War and in the immediate post war period. This chapter concludes with a review of the main lessons learnt from the cases.

Chapter 3 covers the contemporary field of critical materials. The chapter does this by examining 21st century critical material definitions and reviews these definitions from the perspective of product design. The chapter concludes by producing a new definition for critical materials for product design.

Chapter 4 details the empirical research conducted for this thesis. This research concerns companies who use critical materials, who were interviewed on the topic of critical materials. The goal of this research is to assess the effects critical materials has had on technological companies in the Netherlands, what kind of implications that could have for product design and addresses the question of how companies are currently responding to critical materials risks. A total of 29 companies participated. The interviews, developed from the literature review in chapter 3, explored the wider company critical materials knowledge, the role of critical materials, risk management strategies, business opportunities and future support needs.

Chapter 5 conducts a synthesis on chapters 2, 3, and 4 by conducting a reflection of historical and company responses to critical materials through product design. This allows for a product design – critical materials framework to be developed to help address critical materials problems.

Chapter 6 addresses the research questions raised in the thesis and draws conclusions and recommendations for further work.

The diagram shown in figure 1 shows the outline of the thesis and the associated research questions.

Chapter 1: Introduction
Critical materials and Product Design Introduction to critical materials, ccritical materials problem description, scope of study and research questions.

Central research question
What has been and what should be the role of product design in addressing critical material problems?

Chapter 2: Lessons from history; product design responses to materials scarcity
Background literature study . Five product design for material scarcity case studies reviewed. Austerity and Utility design cases. Successful in managing material supply.

Sub research question 1
What can be learnt from product design responses to materials scarcity?

Chapter 3: Defining critical materials for product design
Literature study on recent critical materials definitions. The literature shows there is no critical materials definition written for product designers. Development of a definition written for product designers.

Sub research question 2
How can critical materials be defined within the context of product design?

Chapter 4: Critical material awareness and responses in companies
The research and results from interviews with 29 companies with an operation in the Netherlands. Awareness but no product design activity to address critical materials problems

Sub research question 3
How are companies responding to critical materials?

Chapter 5: The potential role of product design in addressing critical materials problems.
Bringing together chapters 2, 3 & 4 to develop new framework for education and research development for product design to address critical materials problems. Circular product design chosen.

Central research question
What has been and what should be the role of product design in addressing critical material problems?

Chapter 6 : Conclusions recommendations Answer RQ's
References / Appendices

Figure 1 Outline of thesis and associated research questions

2 Lessons from history: product design responses to materials scarcity

2.1 Introduction

Material shortages has been a problem for societies across all of human history (Tilton, 2003, Ashby, 2013, Ashby et al, 2016). It is only the contexts, technologies and materials that change in each case. This chapter selects a period of extreme material scarcity in history, Britain in the Second World War (WWII). Through the selection of five British WW II cases, the aim of this chapter is to explore the role of product design in dealing with the material scarcity of the period. The chapter shows that product design changes played an important role in mitigating the materials scarcity problem.

This chapter addresses research question two: *What can be learnt from past product design responses to materials scarcity?*

A number of writers have linked product design practice and the use of materials, and examples include Victor Papanek (1972), Clive Dilnot (1982) and Victor Margolin (1988, 1989, 1997). In the recent, specific field of critical materials (material scarcity) and product design, there are however, no published works exploring historic responses and relating those past responses to current and future scenarios. The majority of publications on the topic of critical materials assess current situations and project proposals forward in time. Very few look back for lessons from past responses.

In order to address the research question, this chapter examines, through historical cases, product design changes which were undertaken, assesses if these changes did help manage materials scarcity and states what lessons the past product design approaches can provide for critical materials problems today.
Five British WWII product design cases are examined; Austerity Locomotives, a 'National Motor Vehicle' design, Utility Clothing, Utility Pottery and Utility Furniture. The chapter concludes with a review of the main lessons learnt from these cases and these are taken forwards into chapter five, the critical materials and product design synthesis.
This chapter does not seek to propose that events and actions, in a wartime material shortage situation from 70+ years ago, will provide an exact blueprint for product design actions required in the 21st century. For example many of the critical materials of today were not in industrial use in WWII and also many of the technologies of today did not exist then. What is highlighted is that, given a particular set of materials challenges, the British found a product design response that 'worked' in resolving material scarcity problems. Re-visiting their response may help in the search for solutions today. It can also highlight strategies to avoid or which may prove paradoxical.

2.2 Methodology

This section explains the methodology deployed to answering the research question: What can be learnt from past product design responses to materials scarcity?

First, it is important to make an observation on the terminology and definitions. The term 'materials scarcity' was in widespread use, prior to the more recent, 21st century development of the term 'critical materials'. In the 20th century the term 'scarce' was used to describe materials shortages. The definition of scarce is given as 'insufficient for the demand' (Oxford dictionaries, 2016).

This chapter does not use the term critical materials, the current lists of critical materials (as shown in chapter 1), nor the criteria used to generate such lists. The definition of scarcity is not clearly stated in the WWII product design literature. The terms used were varied and outline a progression of terms such as 'new materials requirements', 'war reserves of materials', 'Important materials for war production', 'essential commodities', 'shortage materials' as well as 'scarce materials'. The list of materials was confined to the technological requirements of the time and was much shorter that the material requirements of technologies today. The metal requirements were covered what today would be termed the 'commodity metals' and would not include the rare earths for example. Metals such as the 'super alloys' were not in widespread use. There was some references made to the economic needs of the nation.

It is important to note the time period covered for the definition of 'material scarcity' goes from an economy in peacetime preparing for war, to a wartime economy. In the period 'scarcity' was happening. In the peacetime pre-war period scarcity was present because the demands of building up military equipment quickly meant there were choices that had to be made concerning the supplies available. In the wartime period there was the double factors of loss of traditional sources of materials combined with shipping losses, coupled with increased military equipment production. The definition of scarcity was therefore a limitation of supply against the demand. This led to, even in pre-war peacetime, governmental control on the allocation of materials. The government decided, in collaboration with industry, who got what and when they got it.

This evolution of the definition show that as events unfold the definitions change and adapt. The definition field is, like product design itself, dynamic and responsive.

Definitions and the subsequent lists of 21st century critical materials change with time and context and therefore the lists of critical materials today have little direct relevance in past cases. Added to that some of the critical materials of today were not in widespread use in the historical timeframes used (or in some cases even discovered). This applies, in particular, to the rare earth elements. The technologies which use them, in particular electronics or advanced materials, also did not exist (Ashby 2016).

Ashby highlights this increasing diversity of elements used in materials and products over the period from WWII to the 21st century in table 1 below.

Table 1 The increasing diversity of elements used in materials over the period from WWII to 2016. Table adapted from Ashby 2016. Note: Data from the composition fields of records in the CES EduPack ’14 Level 3 database, Granta Design, 2014, (Ashby, 2016).

Materials	Changing demand for elements from WWII to 2016	
	WWII	2016
Iron based alloys	Fe, C	Al, Co, Cr, Fe, Mn, Mo, Nb, Ni, Si, Ta, Ti, V, W
Aluminum Alloys	Al, Cu, Si	Al, Be, Ce, Cr, Cu, Fe, Li, Mg, Mn, Si, I, V, Zn, Zr
Nickel Alloys	Ni, Cr	Al, B, Be, C, Co, Cr, Cu, Fe,Mo, Ni, Si, Ta, Ti, W, Zr
Copper alloys	Cu, Sn, Zn	Al, Be, Cd, Co, Cu, Fe, Mn, Nb, R Pb, Si, Sn, Zn
Magnetic materials	Fe, Ni, Si	Al, B, Co, Cr, Cu, Dy, Fe, Nd, Ni, Pt, Si, Sm, V, W

It is not the response to any specific critical material and associated technology per se, that is highlighted in this chapter. It is the generic responses to materials scarcity, in a very different context, and the role of product design in particular, which is highlighted and in chapter 5, synthesised.

2.2.1 Case analysis: Synchronic and Diachronic

A literature review was undertaken into British material shortage publications around World War II. To ensure no literature was missed the literature covered the historical period 1917 to 1952. The time frame for date of publication is 1914 to 2015. Analysis of the literature produced five suitable British WWII cases for analysis; Austerity steam locomotives, ‘National Motor Vehicle’ design, utility clothing, utility pottery and utility furniture.

This use of multiple cases adheres to the design of the use of cases by Yin:
“… that most multiple-case designs are likely to be stronger than single-case designs. Trying to use even a "two-case" design is therefore a worthy objective compared to doing a single-case study.” (Yin, 2009)

The cases are analysed by the use of Synchronic and Diachronic analysis techniques as proposed by John Walker in his 1989 book *Design history and the history of design* (Walker, 1989).

The oldest form of history writing is the chronicle and as its name suggests it is typically a chronological arrangement of chosen facts and events in a temporal sequence. The problem of this approach, is that much can be lost in terms of ‘*context and rationale’*, in other words events may seem to have *‘no causes, meaning or connections’*. The terms Synchronic and Diachronic were first developed for the field of linguistics and published by Ferdinand de Saussure (posthumously) in 1916 (Walker, 1989). The figure 2 below shows the principle of the two approaches.

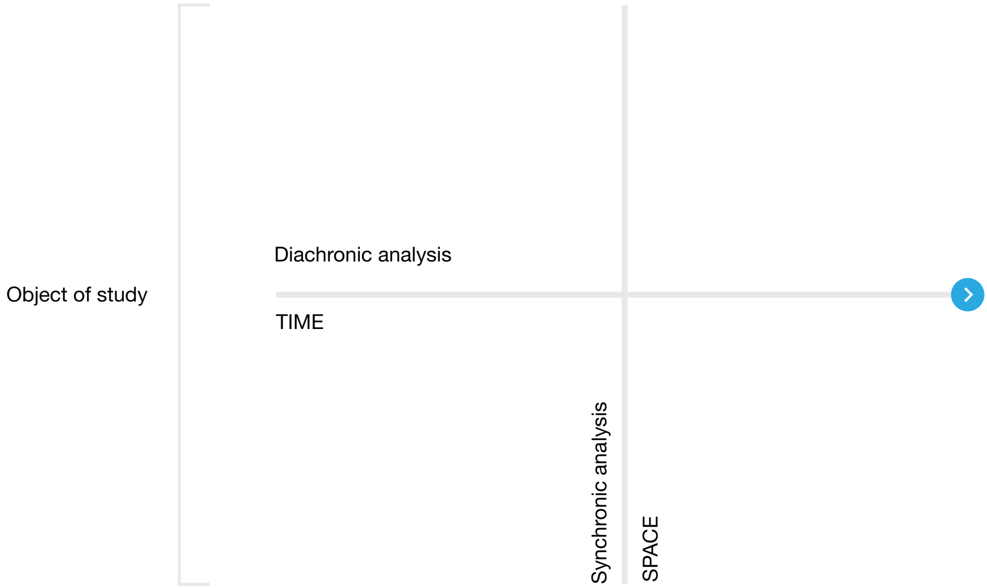


Figure 2 Synchronic and diachronic analysis (Walker, 1989)

It is important that both Synchronic and Diachronic analysis should not be used in an overlapping fashion. Of importance is how Walker terms the synchronic analysis as a *‘synchronic analysis space’*. Peter Osbourne explores this aspect in his 1995 publication *‘The politics of time; modernity and avant-garde’* (Osbourne, 1995 pp 26-28) as does Mark Bevir in ‘The logic of the history of ideas’, published in 2000 (Bevir, 2000). As Walker states:
“Scientific rigour would be lost if the two approaches were conflated or confused” (Walker, 1989).
In accordance with the observations of Walker, Osbourne and Bevir, this chapter firstly analyses the literature deploying a synchronic approach by the use of case analysis (Yin, 1989). The diagram shown in figure 3 below shows the synchronic analysis and the selected cases from Britain.

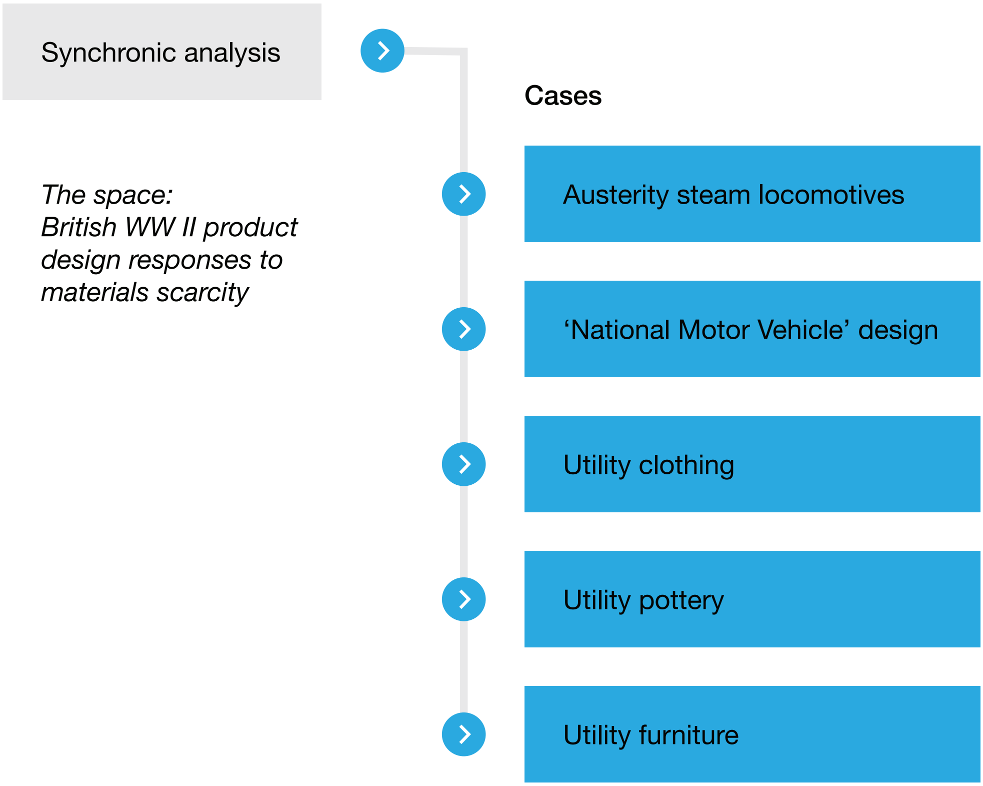


Figure 3 Synchronic analysis using five cases from Britain in WWII

In order to cover the context of the five cases (the development of events before and the immediate period after) a diachronic analysis approach was also undertaken. To facilitate this process, the literature was sub-divided into 4 chronological phases which reflect key planning and actions around British responses to material scarcity and provides the context for the five cases. This is shown in figure 4 below.

Diachronic analysis

I 1918 - 1935

Development from experience in the First World War.

II 1936 - 1939

A new focus, planning for war.

III 1939 - 1944

War and making the plan work.

IV 1945 - 1952

End of war and transition to peacetime.

Figure 4. The Diachronic analysis showing four phases, reflecting key planning and actions around British responses to material scarcity risks.

The Utility Furniture Scheme case is the main case of the five and has a separate section of further analysis. This is due to a number of reasons; firstly the wood used for the Utility Furniture products has detailed data available. Secondly the design of Utility Furniture has a discrete set of literature dedicated to it. Thirdly the regulatory requirements of Utility Furniture were severe, there was for a number of years only one range of furniture available. The other four cases are comparison cases to look for patterns in design approach, and to be sure Utility Furniture design approaches were not an anomaly.

2.2.2 Criteria for the selection of cases

The 20th century was selected as the time frame for seeking a suitable cases. A combination of clear materials scarcity and a distinct product design change, were sought. Cases which were considered include later 20th century conflicts / sanctions / restrictions (Balkans, Iraq, Israel, North Korea, communist European eastern bloc responses – especially the DDR-East Germany and the Soviet Union) but none had the scope and scale of cases during both of the world wars. In the case of World War One (WWI) much of the more sophisticated approaches to materials shortages did not come until the final year (1918) of WWI. The Great War was a period of learning to cope with materials shortages and this did not come to the fore until 1918. (A.J.P Taylor, 1966; Brown, 1999; Hart; 2009). Any product design aspects as a response to materials scarcity, have not been well documented.

WWII provides a wider choice of suitable cases. Importantly product design (including industrial design approaches) had developed and played a clear role in solving scarcity problems.

Nazi Germany in WWII (1939 – 1945), in many ways, provides the stronger cases. Material shortages in Germany became ever more acute as the conflict progressed and innovative product design solutions were deployed to overcome severe shortages. There was a series of post-war analysis carried out, mainly by American reviewers, on Nazi Germany and their response to resource constraints (Mason, 1949). This was done as part of a WWII lessons learning exercise for the USA and other NATO allies in response to the threat of feared material scarcity brought about by a potential new global 'hot' war with the Soviet Union / Communist China in the early cold war years (1949 – 59).

Nazi Germany was not selected as a case for this thesis because solutions were distorted by slave / forced labour and by the theft of resources from occupied territories. This was an ethical choice by the author.

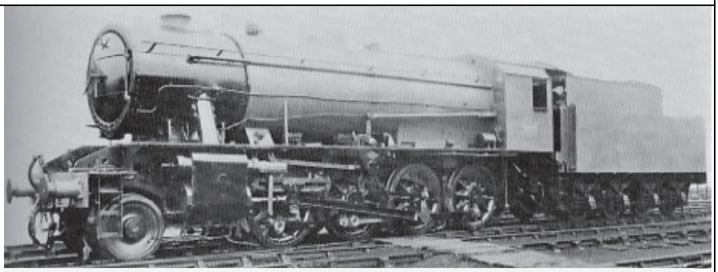
Britain in WWII was selected because severe reductions in supply of materials were experienced (Postan, 1952, Edgerton, 2011; Reimer & Pinch, 2013; Broadberry & Howlett, 2014). In addition materials and product controls were more far reaching and adhered to much more rigorously in Britain, than in the other democratic allied nations (Broadberry & Howlett, 2014). Finally the cases were selected because the British developed a clear, distinct, product design based response to their materials scarcity problem. The products were changed to help address materials scarcity.

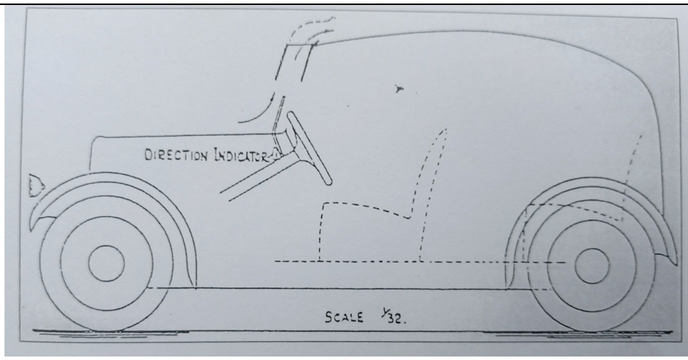
The five cases were chosen as they were the sum total of cases found in the literature. The cases represent non-military product designed in the first instance during the war years.

2.3 Synchronic analysis of the literature – the five cases

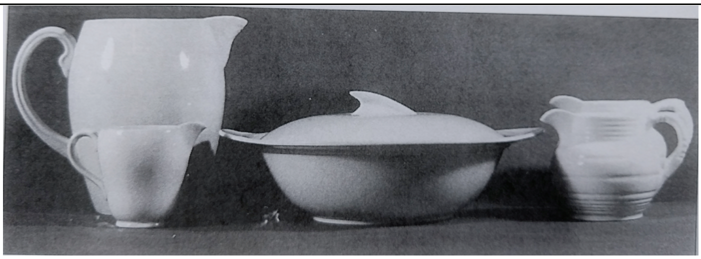
The five cases were analysed in the synchronic framework using the approach of mapping the literature as outlined by Hart [Hart, 2011]. The results of this mapping can be seen in Table 2, which was developed to provide an overview of the cases. No particular weighting was given to any heading. The aim of the analysis is to develop a case description and use cross case analysis. The key aspect was; *linkages of materials scarcity problems and product design* and this is shown in table 2 below:

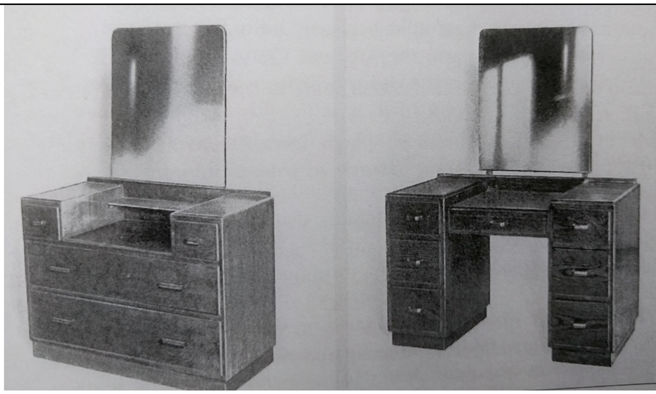
Table 2. Mapping of the five Austerity and Utility product design cases.

Case & Literature	Linkage of materials scarcity problems and product design
1. British Austerity steam locomotives 1. Peck, D.P.; Bakker, C.A.; Diederen, A. Innovation and complex governance at times of scarcity of resources: A lesson from history Knowledge Collaboration & Learning for Sustainable Innovation: ERSCP-EMSU Conference, Delft, The Netherlands, 25-29 October 2010 2. Rowledge J.W.P. Heavy goods engines of the War Department, Vols 1 - 3 Springmead railway books 1977.	 WD Austerity (Class O7) No. 7177 at Doncaster in 1945 prepared for dispatch http://www.lner.info/locos/O/o7.php This case concerns two sequential sub-types of austerity type locomotives that are examples of designs of wartime locomotives. The aim was to produce these British locomotives using as little energy, labour and materials as possible. The designs were governmental approved and the numbers built were also approved. Materials were controlled, resulting in less material being used and reducing waste. Less was needed to make the locomotives and the design allowed higher productivity. Location of manufacture was controlled and distributed. 1. The War Department (WD) "Austerity" 2-8-0, heavy freight steam locomotive for war service. Chief designer R.A. (Robin) Riddles. 935 built, 1943-45, most-produced class of British steam locomotive. Built by North British Locomotive Company. Designed to have interchangeable parts. Adjustable gauge (British and European). Lasted in post-war British Railways (BR) service until 1967. 2. The War Department (WD) "Austerity" 2-10-0, heavy freight steam locomotive for war service. Chief designer R.A. (Robin) Riddles. 150 built, 1943-45, similar to 2-8-0 above but

	with 2 more driving wheels meaning a lighter rail loading. Chief designer R.A. (Robin) Riddles. A derivative was the last British steam locomotive built in 1960. Used by the 'new' post-war Dutch Railways (NS) 1946-52.
2. British 'National Motor Vehicle' design Bell, Johnathan; The design of utility vehicles in wartime Britain. Published in: Utility reassessed. The role of ethics in the practice of design. Edited by Judy Attfield. Manchester University Press, Manchester, UK. Also St Martins Press Inc. New York USA. Also UBC Press, Vancouver, BC, Canada. All in 1999.	 Side view sketch from the proposed NMV 1944. Bell 1999 This case covers a British motor vehicle designed during the WWII for post-war manufacture. Was never made. The design informed the later 'generic utility vehicle; the Land-Rover. The original speculative 1942 proposal was for a 'National Motor Vehicle' (NMV) of 'utilitarian design'. Designer Leslie Hounsfield. Based on 'emergency design' principles of modernist principles. Links with the government 'Utility Scheme'. The design would have been produced by the 'big five' (Morris, Austin, Vauxhall, Ford and Standard). The design was for a small, 5 seat, economical petrol engine car. The aim was for personal mass transportation – a form of public transport held in private hands. There would be one government approved design. The design was to be simple, few unnecessary accessories. Examples include no springs but 'balloon tyres and a single tail light. This would allow low cost as well as low materials and labour use. Target user was middle low income 'man' looking for 'fairlue' = 'fair value for money'. The vehicle would be 'subsidised' or shared ownership, sponsored by government. It used a 'pay as you go' system of revenue and included insurance. A mileage recorder in the vehicle allowed the use of a coin operated payment system. The maintenance would be done by the manufacturer as their part of the package. The design would also therefore avoid the waste of scrapping vehicles off at end of life as the vehicle would be reused over and over again. To facilitate this standardised and recyclable parts would be used throughout. There was a speed limiter of 35 mph (60 km/h) to improve safety, economy and durability. The purchase tax

	would be low and flat. The design styling was basic and contemporary. The panels would be plastic (due to steel restrictions and to avoid corrosion), seats removable for flexibility. Streamlining was avoided as it was seen as a 'designer and salesman' feature, and as 'American vulgarity'. In 1948 the Rover car company adapted the 'emergency design' and 'fitness for purpose' aspects into the Land-Rover vehicle. The Land-Rover was light (Al-Al body panels), cheap, strong and less wasteful. Government controls on materials helped drive the land-Rover design.
3. British utility clothing. Reynolds, Helen. *The Utility Garment: its design and effect on the mass market 1942-45.* And Kirkham, Pat. *Fashion, femininity and 'frivolous' consumption in World War Two Britain.* Both published in: *Utility reassessed. The role of ethics in the practice of design.* Edited by Judy Attfield. Manchester University Press, Manchester, UK. Also St Martins Press Inc. New York USA. Also UBC Press, Vancouver, BC, Canada. 1999 Attfield, Judy and Kirkham, Pat. Editors. *A view from the interior: women and design.* Womens Press Ltd. 2ed 1995	 CC41 logo on a Utility dress. Reynolds 1999. This case concerns British clothing and cloth controls via the Utility Clothing Scheme which regulated scarce materials and labour in WWII Britain, through rationing and statutory designs. The British Board of trade introduced the Utility Clothing Scheme in 1941. The aim was to produce the nation's new clothing using as little power, labour and material as possible. The scheme was direct governmental intervention to control the clothing market in order to control quality, prices and supply shortages. A labelling scheme using the CC41 logo (see image above) was used on all garments. By 1945, the last year of operation, the scheme covered 90% of all clothing sold. Prices were fixed low, and purchase tax exempt, to allow all income groups to obtain clothing. Profits for producers and retailers were fixed. All stages of the supply chain were recorded and audited. Production required a licence and attempts were made to concentrate production in designated geographic locations. Production line (conveyor belt) methods were used where division of labour was deployed. All designs has a unique

	government approved specification number. Large runs were encouraged. Durability and ease of repair were important Coupons were issued to everyone allowing a limited amount to be purchased in any given period. To limit wastage market research was conducted on what styles people wanted. The group conducting this research and approving designs later became the Council of Industrial Design. The designs did not have any features which 'wasted' material of 'unneeded' style such as shirt/blouse/trouser pleats, trouser turn-ups, or longer shirts for tucking in. Following customer complaints well known fashion designers were asked in 1942 to design women's clothing which was termed the 'courtier scheme'. One outcome of the whole scheme was to develop London as a centre for fashion design. Whilst the public did not like 'being told what to wear', the scheme was a success in making the best use of scarce resources whilst clothing the nation as fairly, efficiently and economically as possible.
4. British utility pottery McLaren, Graham. Utility forgot: shaping the future of the British pottery industry 1941-45. Published in: Utility reassessed. The role of ethics in the practice of design. Judy Attfield. Editor Manchester University Press, Manchester, UK. Also St Martins Press Inc. New York USA. Also UBC Press, Vancouver, BC, Canada. 1999 McLaren, Graham. Moving forwards but looking backwards: the dynamics of design change in the early post-war pottery industry. Published in: Design and cultural politics in post-war Britain; The Britian can	 Image: Utility pottery examples. McLaren, 1999. This case concerns British Utility Ceramics Scheme which regulated scarce materials and labour in WWII Britain, through rationing and statutory designs. The British Board of trade introduced the Utility Ceramics Scheme in 1941. The aim was to produce the nation's new table-wear using as little power, labour and material as possible. The scheme was direct governmental intervention to control the ceramic table-wear market in order to control quality, prices and supply shortages. Prices were fixed low to allow all income groups to obtain table-wear. Profits for producers and retailers were fixed and tax exempt. All stages of the supply chain were recorded and audited. Production required a licence and attempts were made to

make it exhibition of 1946. Edited by; Maguire, Patrick. J and Woodham, Johnathan. M. 1997	concentrate production in designated geographic locations. Production line (conveyor belt) methods were used where division of labour was deployed. Large runs were encouraged. Durability was important. Coupons were issued to everyone allowing a limited amount to be purchased in any given period. The designs did not have any features which 'wasted' material of 'unneeded' style such as colour (all were white), glazes or decoration.
5. British utility furniture Harriet Dover, Home Front Furniture. British Utility Design 1941-1951. Scolar Press, Aldershot, England, UK pp103 1991 Judy Attfield. Editor Utility reassessed. The role of ethics in the practice of design. pp268 Manchester University Press, Manchester, UK. Also St Martins Press Inc. New York USA. Also UBC Press, Vancouver, BC, Canada. 1999 Suzanne Reimer and Philip Pinch Geographies of the British government's wartime Utility furniture scheme, 1940-1945 Journal of Historical Geography 39 (2013) 99-112 2013 Suzanne Reimer and Philip Pinch. Nationalising local sustainability: Lessons from the British wartime Utility furniture scheme Geoforum 65 (2015) 86–95 2015	 Image: Dressing table designs from the second Utility Furniture Catalogue published in 1947. Attfield, 1999. This case concerns British furniture controls via the Utility Furniture Scheme which regulated scarce materials and labour in WWII Britain, through rationing and statutory designs. The British Board of trade introduced Standard Emergency Furniture in 1941 followed by the Utility Furniture Scheme in 1943. The utility furniture scheme closed in 1952. The aim was to produce new furniture using as little power, labour and material as possible, only to be supplied to those who needed it most. The scheme was direct governmental intervention to control the furniture market in order to control quality, prices and address supply shortages. A labelling scheme to show the product conformed to the scheme, using the CC41 logo, was applied to all items of furniture. Prices were fixed low to allow all income groups to obtain furniture. The products were purchase tax exempt. Profits for producers and retailers were fixed. All stages of the supply chain were recorded and audited. Production required a licence and production was allocated in designated geographic locations to limit transportation distances. Batch production methods were used, the design 'de-skilled' the production and division of labour was deployed. All designs has a unique government approved

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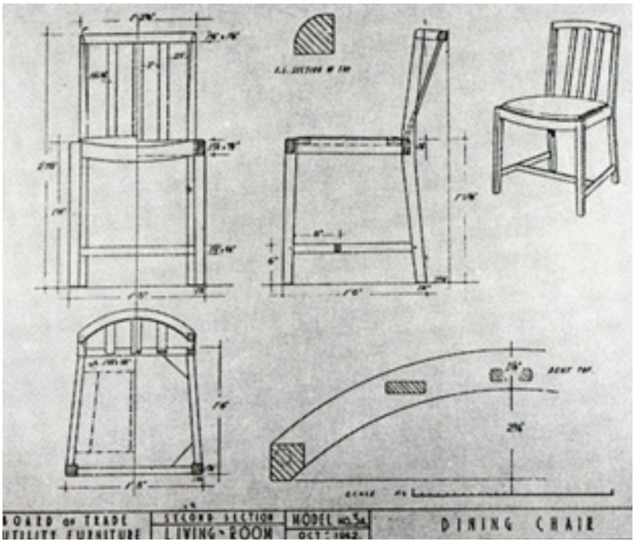
specification number. Large runs were encouraged. Durability and ease of repair were important. A buying permit giving access to limited coupons were issued to those who could prove a furniture need (bombed out, just married, new baby, etc.) allowing a limited amount to be purchased in any given period.

The group conducting the furniture research and approving designs later became the Council of Industrial Design. The designs did not have any features which ‘wasted’ material of ‘unneeded’ style such as carvings or mouldings. The designs conformed to a British style of modernism. In general the public had mixed views on utility furniture. The scheme was a success in making the best use of scarce resources whilst providing furniture to those who had need, across the nation as efficiently and economically as possible.



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2.4 Diachronic analysis of the five cases, with a specific focus on utility furniture

A key point in time when the level of materials scarcity increased sharply, was the declaration of war, heard by the British population in a radio broadcast, on 3rd September 1939. Planning for such an eventuality had, however, been going on for some years prior to that day.

The Prime Minister explained in his 1939 radio announcement, how the decision to declare war had come about and what the British people needed to do. He said:

"When I have finished speaking certain detailed announcements will be made on behalf of the Government. Give these your closest attention. The Government have made plans under which it will be possible to carry on the work of the nation in the days of stress and strain that may be ahead. But these plans need your help"

The plans he mentioned included plans for securing the supply of essential materials.

2.4.1 Diachronic analysis, a timeline of events and activity in concerning material scarcity

As the international situation worsened in the mid to late 1930's, carefully developed plans for a new conflict were being firmed up, and by mid-1939 they had become sufficiently detailed to offer a framework for the strategic organisation of wartime production (Postan, 1952, Hancock and Gowing, 1949).

The following section outlines in more detail the events and activity from a British perspective, divided up into 4 time periods. These periods reflect key phases relating to the cases. The periods are shown in figure 5, below

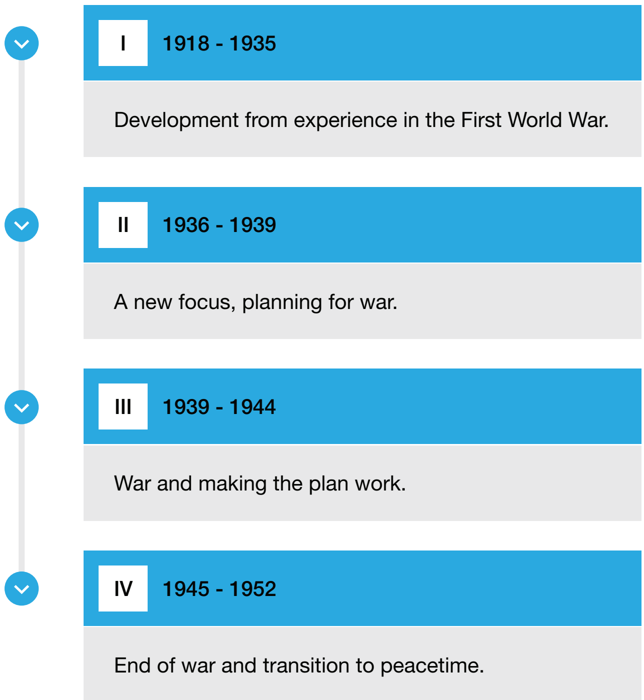


Figure 5. The Diachronic analysis showing four phases, reflecting key planning and actions around British responses to material scarcity risks.

2.4.2 Period 1; 1918-1935 – development from experience in the First World War

This period reflects the British experience of securing material supply in World War I. This is explored in David Stevenson's book 'With our backs to the wall – victory and defeat in 1918' where Stevenson argues that the allies overwhelming supply of materials in 1918 was a key factor in the central powers defeat (Stevenson, 2015). This aspect has, until recently, been largely overlooked by historians, who have had a focus on the military and political aspects of the conflict (A.J.P Taylor, 1966; Brown, 1999; Hart; 2009). With the knowledge of the importance of material supply in mind, but with little real threat of a new conflict in sight in the 1918-1935 period, Britain allocated, in a theoretical way, the industrial resources of the country for any foreseeable wartime uses (Postan, 1952, Hancock and Gowing, 1949).

Committees were set up to prepare plans to ensure the supply of materials essential to any foreseen war effort. They would determine and monitor stocks of raw materials and maintain a list of contractors that could be used in war manufacturing. These committees determined which materials would have to be controlled if a war broke out and the manufacturing capacity, again all building on the experiences of WWI (Postan, 1952).

Between the late 1920's and into the early 1930's a special section of the War Office was set up. This special section made an appointment of an official whose task was the direct planning of war potential with respect to material supplies.

The Nazi party took power in Germany at the start of 1933. The European political situation steadily worsened. As a precautionary planning measure, at the end of 1933, Britain appointed an advisory group of leading people from industry. This advisory group produced an assessment of the resources that manufacturing needed for the production of armaments and set out the general guidelines for the development of a 'shadow' armaments industry. Later, in 1939, the advisory groups' views were also sought by the British Cabinet on other aspects of industrial mobilisation, including areas such as furniture supply. These arrangements made available to the Government expert company views, at a time when government plans could not be disclosed to the whole of industry (Postan, 1952, Hancock and Gowing, 1949).

2.4.3 Period II. 1936 – 39 – A new focus, planning for war

As the international threats increased through the 1930's, British governmental thinking changed to reflect the new material requirements of a modern war. In this second period more detailed plans for raw materials supply requirements were made. Preparations included the final detailed planning for future actions to secure strategic materials.

A radical change in the Government's actions towards the build-up and security of materials began in 1936. A Minister for Co-ordination of Defence was appointed in February 1936, who was in charge of all aspects of rearmament. The requirements of the armed forces had grown and manufacturers were expected to speed up the transition to ‘war’ production. The demands for materials in the early phases of a possible war, were expected to be very high. In addition, allowance had to be made for considerable dislocation in European supplies. Consideration was made of the possibility that the policy of American neutrality might prevent the supply of raw materials from that country. The Government decided that to address this risk they would build up reserve stocks to be ready for any outbreak of war (Postan, 1952, Hancock and Gowing, 1949).

Postan, 1952, outlines how through 1936 and into 1937 planning officers were appointed to conduct a detailed planning of production, firm by firm. This work included gaining a detailed understanding of the company material requirements. During this time it was realized it would be difficult for the re-armament programme to be completed, in the planned timescale of 1940, if the Government did not allow rearmament to interfere with normal material supplies (business as usual) to companies.

By March of 1938, Postan explains how the British Cabinet had decided that the policy of ‘normal trade not impeded’ (business as usual) should be ended. The raw materials supply for military production could overrule the materials supply to other companies. In other words military production had priority, even if that diverted material supply away from another company producing a non-military product, such as civilian furniture or civilian clothing.

Postan explains how though 'business as usual' was now over, 'life as usual' still went on. With respect to supply and production of defence equipment over civilian production, the cabinet did not establish anything more than a generic system of priorities. This encouraged manufacturers to take on armament orders at the expense of their non-military business. They did not do so for reasons of profit, as there was no advantage to be had, but out of a sense of patriotism and duty. There was at this time no action to restrict material supply to non-essential (civilian) businesses and civilian material requirements continued to compete with military material requirements.

By the spring of 1939 the Secretary of State for War expressed a desire for a new Ministry of Supply. Postan explains that the British cabinet was now politically and psychologically less afraid of interfering with the normal peacetime process of industry. A sense of urgency was rising with a sense of not ‘if’ war would come, but ‘when’. It became clear that the Ministry of Supply would not be formed in the style of previous ministries and committees. As Postan outlines the new Ministry of Supply would be so overarching that it could take over total responsibility for raw materials. By July 1939 the planning for a new Ministry of Supply had been finalised. Before it came into being, the government authorised the Board of Trade to purchase ‘war reserves of materials’, an action which would today be termed as ‘stockpiling’ for defence purposes.

The new Ministry of Supply started operations in August 1939, one month before hostilities broke out, and took over the ‘Production, Contracts and Inspectorate’ branches of the War Office. This aspect means that product ‘Research and Design’ came under the ministry of supply. Amongst the plans worked out in the last year of peace, were various schemes for reorganising materials supply to match the expected changes in international materials supply, to develop domestic (home produced) supplies of timber and iron ore, to plan carefully the use of scarce materials and to develop their substitution by other materials. Production would be based on a system of priorities (Postan, 1952) with the higher the war production priority, the greater allocation of material. At this stage, the production of domestic furniture was very low down the list of priorities.

2.4.4 Period III 1939 – 1944 – War and making the plan work

When the war broke out, 56% of Britain’s hardwood came from continental Europe, a source which was soon to be lost (Mills, 2008). As a result of stockpiling, several other important materials, such as bauxite (aluminium), zinc, wool, flax and natural rubber, were available in volumes sufficient for nearly six months of the estimated British wartime requirements. Importantly, the main feature of the pre-war plans was their avoidance of any single approach and therefore the plans had high flexibility. This flexible approach set the tone for the future of raw materials supply through the war.

In the beginning no attempt was made to establish an overarching single materials control organisation. The planners assumed that the challenges arising for the supply of different materials, would, form the controlling organisation, and that the changing supply position would be responded to accordingly.

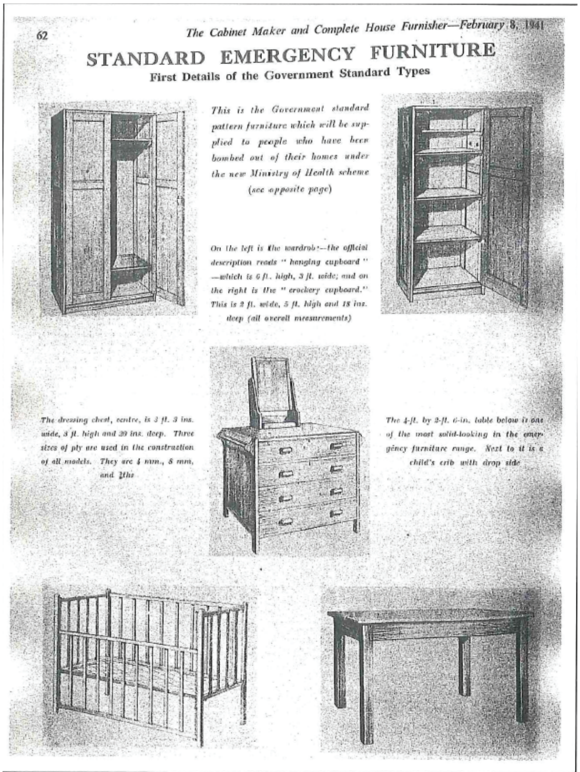
One of the control mechanisms deployed was statutory (legal) powers to control prices and to lay down conditions of material purchase, product sale and product use. This action can be seen in the utility clothing, pottery and furniture cases. Compulsory government controls were imposed on some materials, but if a material, though essential, was not expected to be critical, e.g. natural rubber, asbestos or silk, the control would be on a company voluntary basis. This voluntary control would normally be done by a trade association, under the supervision of the Raw Materials Department of the Ministry of Supply. The instrument of policy (governmental control) was a company licensing system and <u>not</u> (at this stage) through material allocations.

To a greater extent prices and costs were of low importance. Britain would pay if a material could be supplied. The effect of material supply on the economic performance of Britain was of interest only in that it effected the war effort. Economics as usual (peacetime / transition to war, economics) were suspended.

As the first six months of the war (the so-called ‘phony war’ -1939 into early 1940) were concluding, a large proportion of materials were still being used in producing ‘non-essential products’. In military production, materials were not being distributed in the quantities and order, which were needed. A number of 'essential' commodities—iron and steel, some non-ferrous metals (especially aluminium), wool, leather, timber, hemp, flax, jute and paper were deemed scarce (or becoming scarce) and they were placed under controls. Another group of commodities, including rubber and mica, continued to be under the voluntary control of trade associations, and still another group, including plastics and other non-ferrous metals, were left uncontrolled (Taylor, 1966).

In 1940 the unrestricted allocation of timber for civilian furniture, which was deemed a non-essential product, was discontinued. A Timber Supplies Committee was set up to explore the problem of replacing furniture, damaged through the increasing incidence of bombing. This Committee made a small timber allocation for the manufacture of specified products. This was in response to the upwardly spiralling prices of second hand furniture, which was quickly being bought by bombed out families (National Archives). Such spiralling prices fuelled a growing black market and the authorities were keen to show they were in control of all aspects of the ‘home front’.

The specified furniture products were ‘extremely basic and totally undistinguished’, it was called Standard Emergency Furniture and was introduced in February 1941, see figure 6. There was no variation in the design which was strictly specified. The design style was influenced by British - modernist thinking. The range of items was very limited. The product was over 80% plywood and was lent out for a period of 3 months at which point the user could either buy it or return it. The scheme was run by the Ministry of Health (Mills, 2008).


62 The Cabinet Maker and Complete House Furnisher—February 8, 1941

STANDARD EMERGENCY FURNITURE

First Details of the Government Standard Types

This is the Government standard pattern furniture which will be supplied to people who have been bombed out of their homes under the new Ministry of Health scheme (see opposite page)

On the left is the wardrobe—the official description reads "hanging cupboard"—which is 6 ft. high, 3 ft. wide; and on the right is the "crockery cupboard." This is 2 ft. wide, 5 ft. high and 18 ins. deep (all overall measurements)

The dressing chest, centre, is 3 ft. 3 ins. wide, 3 ft. high and 20 ins. deep. Three sizes of ply are used in the construction of all models. They are 4 mm., 6 mm, and [illegible]

The 4-ft. by 2-ft. 6-in. table below is one of the most solid-looking in the emergency furniture range. Next to it is a child's crib with drop side

Figure 6. Standard Emergency Furniture, 1941 (Dover, 1991)

The loose system of material priorities and product manufacture, described above (government controls and voluntary controls), could not be continued as it was essentially not working. The system was highly inefficient and led to conflicts of material requirements. As a result, the final sorting out of 'who got what' was often random or as a result of company actions.

As a response to the situation, a full governmental 'system of allocations' was introduced. Under this system of allocations each material requirement could be assessed according to the 'fundamental importance to war production'. Materials were now allocated to each government department on a quota basis. The time-period for which the allocations were made was reduced from a year to six or even three months, and the government departments had to ensure that the allocations they were given did not contradict those determined by the Materials Priority Sub-Committee. In the later stages of the war, with the general tightening of the system, all materials were brought under such control.

The growing shortage of raw materials by late 1940 was not, wholly due to the restriction of traditional sources of supply, and would in any case have developed with the dramatically increased requirements of a full blown war industry (Eggerton, 2013). The

Ministry of Supply was tasked with addressing a range of material shortages, some of which were immediate and unexpected, others expected. The Ministry of Supply extended the domestic (British) material sources. Development of home sources inevitably created changes and problems for the manufacturers. For example the iron ore mined in Britain was of inferior grade and especially of lower iron content than imported ores. This situation leads to a greater demand for coking coal in steel manufacture.

In the example of timber, home-grown hardwood was not always a good substitute for imported softwoods, as some furniture was designed to use softwood. Nevertheless, by the end of 1941 companies were adapting and coping with the changes, and in this way the country became more material self-sufficient.

With the reduction of ships, due to U-boat sinkings in the Atlantic, the Government had to meet materials supply problems, not only by larger orders from abroad and domestic supply, but also by various measures of economy or simply using less. By October 1941 it was estimated that only one-sixth of the total supply of timber (which was a fraction of the pre-war total anyway) was being used for manufacture in the civilian sector (non-military use). The reduction in timber supply drove the need for not only greater economy in the use of raw materials but also for more efficient distribution of available supplies.

By the end of 1941 there was a ‘short moment of satisfaction’ (Postan, 1952). Assisted by better estimates both of needs and supply, the government had fully organised the distribution of materials and capacity. Allocations of materials was done in one of two ways. Allocations could be made, as in the case of steel, cotton and timber, on a departmental basis, i.e. the Materials Committee would allocate to each department a certain tonnage and leave it to the department to determine whether or not to issue the material to manufacturing contractors. The second way was where the material, such as rubber, paper and jute, would be allocated not to the required department but the 'end use', i.e. the product to be manufactured.

Once again the supply situation got worse in 1942. The conflict with Japan in the Far East, together with the diversion of American shipping and their switch to support their own military build-up, as they entered the war, caused a new strain on supplies. More importantly was the developing shipping situation. In 1942 revised Atlantic U-boat activities (co-ordinated attacks using ‘wolfpacks’ directed by Enigma encoded radio transmissions) raised the loss of Allied ships. As a result raw materials import expectations had to be significantly reduced.

The situation became so worrying that the Prime Minister, Winston Churchill, was, in December 1942, forced to intervene with a directive that material stocks should not be allowed to drop to a level which would leave Britain without any 'elbow room' (reserves) for possible unexpected contingencies. The planned materials strategies did however work and at no time during this period was munitions production interrupted, or even slowed down, by a failure in the supply of materials. This was due in part to a decline in munitions requirements, but also to the steps which the Ministry of Production took in April 1943 to restrict consumption. Equally importantly food supplies were maintained so everyone was fed with the correct calorie intake being maintained.

It was during this period of severe scarcity the Utility schemes were created. Of particular focus is the Utility Furniture Scheme. The Standard Emergency Furniture scheme (introduced in February 1941 and a temporary measure) was not working and second hand / black market furniture prices were again out of control. In addition the plywood used in the Standard Emergency Furniture design was needed in war production for military aircraft such as the successful De Havilland Mosquito. As a result of the worsening supply situation, in September 1942, the manufacture of civilian furniture was completely prohibited, unless the producer had a licence. Licences would be granted only for the production of Utility goods, one of which was the so called Utility Furniture Scheme (National Archives). The Utility Furniture Scheme was introduced by the Board of Trade at the end of 1942. Under this scheme only the poorest quality (lowest grade) wood was permitted for making civilian furniture. Other restrictions included the introduction of standard designs – the Utility Furniture Scheme Design, where the supply of timber was for the production of the designated design only. In addition there was also the zoning or regionalisation of supply, in order to reduce fuel used for transporting products. The Board of Trade selected the firms to make Utility Furniture, and allocated production volumes and timings to them, together with the raw materials.

The first range of Utility Furniture products became available in 1943 and the scheme formally ceased in 1952. For 6 years 1943 – 1948 the design of furniture was very tightly controlled and manufacturing firms had no freedom to adapt the limited range of designated designs at all. These designs ensured the least amount of material was used to provide the highest level of durability and function. The materials which could be used were specified. The designs also ensured the production labour could be lower skilled, allowing for regional distribution of manufacture and freeing higher skilled craft workers for military product production (Pinch and Reimer, 2013).

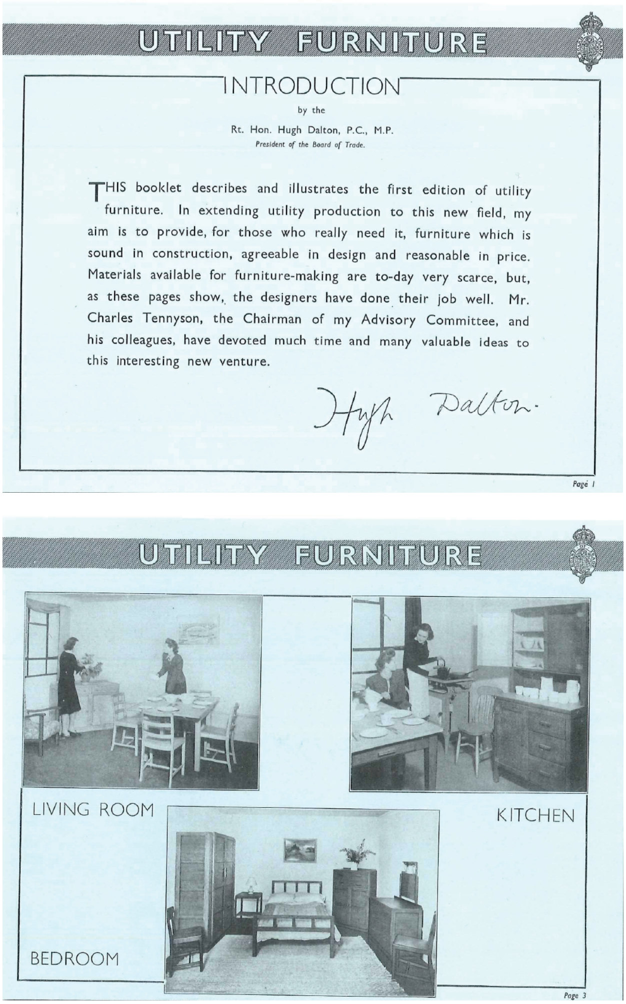
At this point the chapter will focus on the Utility Furniture Scheme during the war years. The timeline post war is developed in section 2.6.

2.5 The Utility furniture scheme

The case of Utility furniture is one where consumer products were designed and developed as a response to severe material shortage. This action is set in the context of an exceptional set of political, economic, social and cultural wartime conditions where the products were designed, manufactured, used and often reused over a long lifetime, under very stringently controlled conditions. (Dover 1991).

In July 1942 Hugh Dalton, President of the Board of Trade announced that he had appointed a Utility Furniture Advisory Committee (UFAC). This committee would advise on both design and manufacture and would be very powerful. It comprised 9 people with a mix of societal backgrounds, from research and industry. There was a call for submissions from private sector company designers to meet the utility furniture requirements.

The designers selected were Edwin Clinch and H.T. Cutler, both from the furniture design and production area of High Wycombe near London. In January 1943 the first catalogue was produced which outlined the furniture which would be on offer. This catalogue remained in place for the next 3 years, and two pages of the catalogue are shown in figure 7 below.


UTILITY FURNITURE

INTRODUCTION

by the

Rt. Hon. Hugh Dalton, P.C., M.P.

President of the Board of Trade.

THIS booklet describes and illustrates the first edition of utility furniture. In extending utility production to this new field, my aim is to provide, for those who really need it, furniture which is sound in construction, agreeable in design and reasonable in price. Materials available for furniture-making are to-day very scarce, but, as these pages show, the designers have done their job well. Mr. Charles Tennyson, the Chairman of my Advisory Committee, and his colleagues, have devoted much time and many valuable ideas to this interesting new venture.

Hugh Dalton.

Page 1

Figure 7. Pages from the first Utility Furniture Scheme catalogue, 1943 (Mills, 2008)

The Board of Trade also set up eleven regional offices to deal with all questions relating to Utility Furniture. A Utility Mark (termed today a ‘labelling scheme’), CC41, was designated for all Utility Furniture. As shown in figure 8, the CC41 logo of Utility Furniture was taken from the one developed for the utility clothing scheme: two capital letter C's and the number 41, and the CC41 stood for "Civilian Clothing 1941" and has also been termed as “Controlled Commodity” (National Archives, 2015). The utility clothing CC41 label can be seen in table 2.

Figure 8. CC41 logo as required on all Utility Furniture. Application of the CC41 logo was a stamp of authenticity. (Dover, 1991)

By February 1943 25,000 units of Utility Furniture had been sold. The Utility Furniture scheme was such a success that demand outstripped supply (Mills, 2008).

Through 1942, 1943 and 1944 the home-grown supply of timber increased. The main relief, however, came from a much reduced rate of consumption – which was imposed on the consumer by the coupon system which was in place from the beginning of the scheme (data in the *Monthly Digest of Statistics No. 1, January 1946. Central Statistical Office, London),* (Postan, 1952). For example in September 1943 the number of points (coupon value) was reduced from 60 to 30. 30 points would barely furnish one room (6 points would buy a fireside chair). By mid-1944 the coupon units went back up to 60 – but only for those previously given 30 units (Mills, 2008), see figure 9 below.

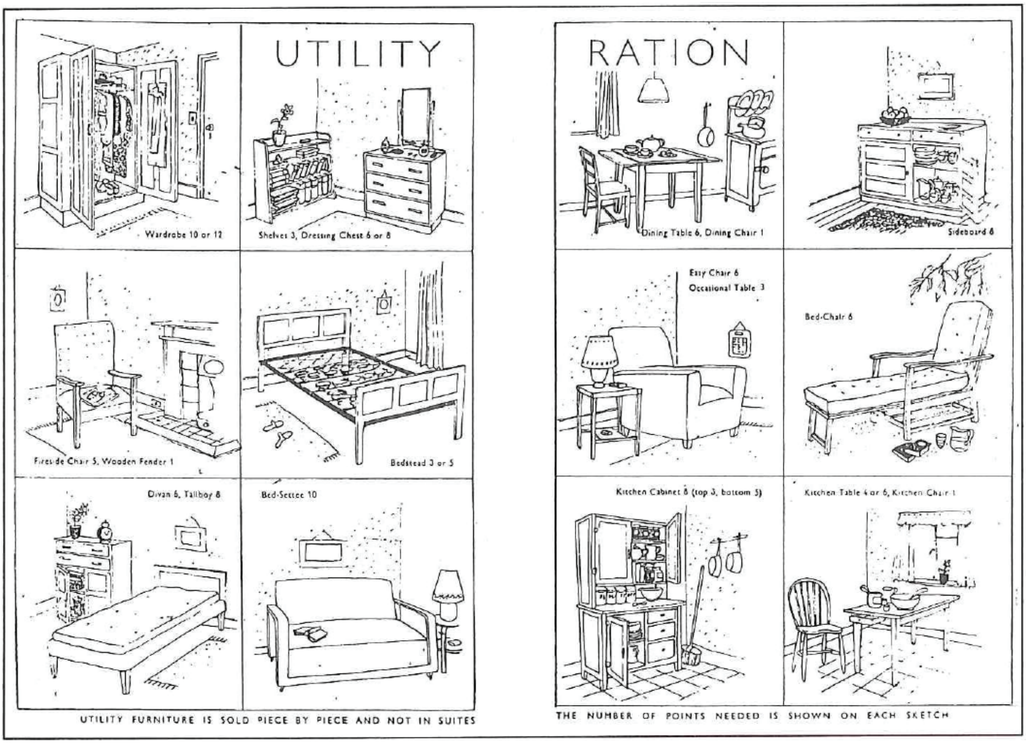


Figure 9. Utility Furniture coupon points needed for each item (Dover, 1991)

Furniture product design during the period of utility furniture (1943 – 52) has been termed ‘socialist designer ideology’ and is centred on tight controls and restrictions of the design, manufacture and sale of furniture products but with the aim of introducing accessible style and taste to the masses (Dover 1991).

Utility built upon a combination of the modernist style together with a British furniture making tradition, whose design and production called for a craft based ‘moral code’ based on simplicity and quality combined with honesty and straightforwardness, where *‘inhabitants in industrial towns should not be fobbed off with ugly things because they live in ugly surroundings’* (Russell 1968 p217 in Dover 1991 p28)

The utility furniture scheme had a complex range of influences and influencers. Industrial product design, as a distinct field had not been firmly established at the beginning of the Utility Furniture Scheme and it was the interior design branch of architecture, coupled with art and design movements, that provided the basis for the utility furniture design. Harriet Dover explores the antecedents of utility furniture around a framework of three principle trends in aesthetic thinking: Pugin on gothicism, Morris on arts and crafts and Cole who believed design could change living conditions for all of society (Dover 1991). Picking up on Cole, Dover argues that the modernist movement was the clear influencer on the style and design of utility furniture, but as these influences were either from

Germany (Bauhaus) or other occupied countries such as Austria or the Netherlands, this was not acknowledged. Dover proposes that Britain took these European influences and then delivered a typically British angle on the designs.

As can be seen from the antecedents of utility design furniture, there are clear left of centre ‘socialist’ leanings. This has been explored in some detail in papers and literature on the subject (Dover, 1991). This was crucial to the spirit of the whole utility scheme, which included clothing, pottery and furniture. The ‘war socialism’ was a mix of state control over production, power, water, food supply, nutrition, health, education, employment, pay, entertainment and the arts, construction and the utility product schemes.

The control came from the government ministries but was delivered by the private sector. This was not a free market capitalist economy as understood today. This was a war economy with private enterprise playing their part. The emphasis was on fair and equal treatment for all to allow, through war production, the country to win the war. The furniture scheme was brought in to allow workers to have a furnished home to live in, eat and rest to allow them to work to win the war. A secondary interest was to maintain the morale of the nation – again to ensure production was kept up.

2.6 Period IV 1945 – 1952 End of war and transition to peacetime

By May 1945 the war in Europe was over and whilst the supply challenges became ever greater as a war-devastated Europe, and wider World, attempted to rebuild, an exhibition to show what products of the future might look like was being planned for 1946, entitled ‘Britain can Make It’ organised by Misha Black, a designer involved in the utility furniture scheme. In that year the ranges of utility furniture expanded to three. By mid-1947 a second utility furniture catalogue was issued. This new catalogue had a low take up however as furniture was now on display in showrooms.

Having furniture back in the showrooms was the return to ‘business as normal’ and in June 1948 furniture rationing ended. At the same time ‘freedom of design’ was introduced, see figure 10. Manufacturers could produce their own designs but these would be subject to heavy taxation, whereas the in 1945 formed Council of Industrial Design (CoID) approved utility designs remained tax free (Dover, 1991). It is interesting to note that after this point the CC41 mark could still be applied to furniture by manufacturers, as a stamp of quality and durability, if wanted. This lasted until 1952 when the Utility scheme was closed.

Fig 10. The 1948 new Utility bedroom designs, called the ‘Diversified’ range, with a Scandinavian appearance. This range was not produced.

2.6.1 Development of the concept of material scarcity

The literature shows that in the period before and during WWII, the British described scarce materials in four distinct phases. These phases are shown in figure 11 below which is developed from figure 5 in this chapter.

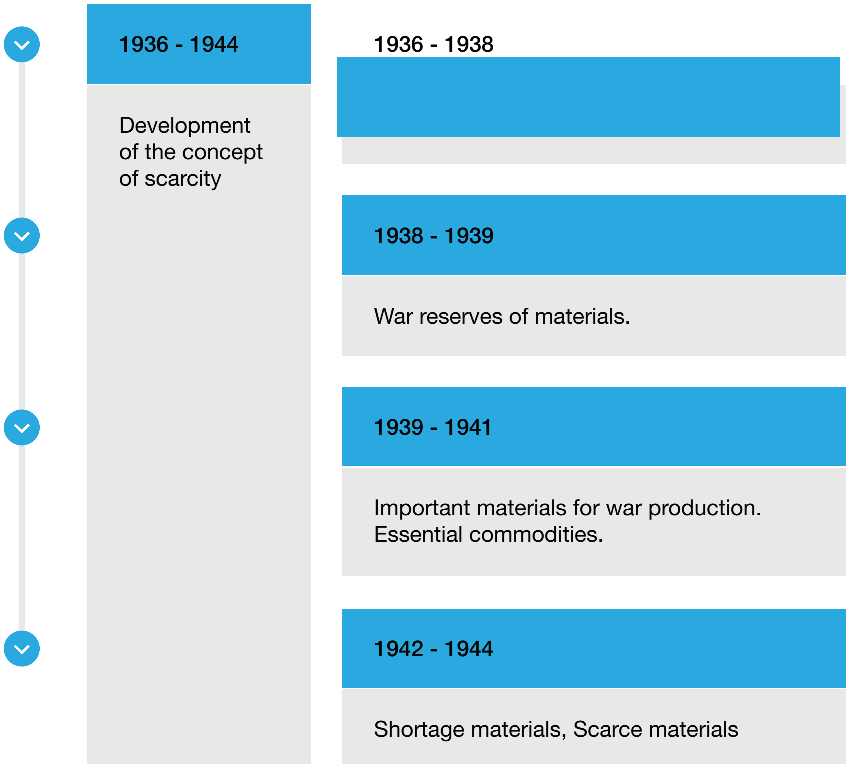


Figure 11 The Diachronic analysis showing the development of the concept of ‘scarce materials’ before and in WWII.

During the re-armament phase of 1936 to 1938, the government instigated the planning of materials requirements in the event of war. In 1938 to 1939 (to end August) it became clear that the question was not if there would be a war but when. This meant business as usual was suspended and materials were prioritised to armaments production.

The period 1939 (Sept onwards) to 1941 were the early years of war. Pre-war stockpiling meant the real stress of material scarcity was not felt at first. By mid-1940 with continental Europe lost as a material supply base and the U-boat campaign beginning to take hold, materials began to become scarce, and this could be seen by severe supply restrictions. Scarce materials were now called ‘important materials for war production’ and ‘essential commodities’. By 1942 to 1944 the shift to stating that materials are ‘scarce’ had become widespread. At this point all the five cases shown in this chapter were in place.

2.7 Discussion

This chapter addresses sub-research question two: What can be learnt from past product design responses to materials scarcity?

2.7.1 Product design strategies for dealing with material scarcity

The product design responses to material scarcity 1936 to 1944 have a focus on the five cases; Austerity steam locomotives, ‘National Motor Vehicle’ design, utility clothing, utility pottery and utility furniture. The five cases had products in production from 1941 to 1952, but not all at the same time. The exception is the ‘National Motor Vehicle’ design, which remained on the drawing board.

It is important to observe that the five cases were not interconnected and were not designed under some centralised Austerity / Utility design plan. Even the 3 Utility design schemes (Clothing, Pottery and Furniture) were not designed together. This highlights the Synchronic analysis approach is needed. The Diachronic analysis would be wrong here in trying to show one case led to another in a chronological way.

All five design cases do, however, have overarching design strategies for dealing with material scarcity, which are summarised below in table 3. These design strategies are derived from the literature across all 5 cases. More specifically this was done by reference to the literature in each case, searching for the aspects of the design which related to some aspect of material use and in particular addressing scarcity.

Table 3. A matrix showing all the utility / austerity design strategies

Design Strategies for dealing with material scarcity	Clothing	Pottery	Furniture	Vehicle	Locomotive
Standardised, legally enforced, designs.	x	x	x	x	x
The designs were produced by a government appointed committee of leading designers.	x	x	x	x	x
The designs were communicated to the producers via detailed specifications.	x	x	x	x	x
The reduction of use of material via no 'decorative or unnecessary styling features'	x	x	x	x	x
Reduction in consumption of energy during production and distribution	x	x	x	x	x
Standard parts, standard machine joints, use of jigs and fixtures, simple joining, fewer parts.	x	x	x	x	x
Mass production runs using line production and assembly - centralising production facilities	x	x	x	x	x
The design was for low cost product.	x	x	x	x	x
Design for repair via design for disassembly and reassembly	x		x	x	x
Designed for ease of maintenance, with long gaps between servicing/maintenance.	x		x	x	x
Grade of materials selected to give a longer life.			x	x	x
Reduction in weight through light-weighting design where applicable.				x	x
Robust design features to ensure longevity.	x	x	x	x	x
Coupons controlled the supply of product and required for the purchase of products.	x	x	x	x	
A buying permit was required to obtain coupons.			x		
Part of a new, more fair society, based on equality for all, allocating products.	x	x	x	x	
Designed in product flexibility (e.g. Change track width or removable seats)				x	x
Max speed lowered to improve safety, economy and durability.				x	x
'subsidised' or shared ownership, sponsored by government.			x	x	
'pay as you go' system of revenue and included insurance, coin operated payment system.				x	
New business model to ensure maintenance would be done by the manufacturer as a package				x	
Use of plastic (due to steel restrictions and avoid corrosion for long life)				x	

The product design strategies for dealing with materials scarcity can be brought together into a model to show the synchronic aspects of WWII product design across the five cases as shown in figure 12 below. These product design approaches together played a significant part in Britain managing scarcity which prevented war economy materials shortages whilst providing for the needs of the military, industry and society.

Product design for materials scarcity 1943

Application of the CC41 logo as a stamp of authenticity.

Product Design

- Less material
- Lightweight
- Robust and long lasting
- Designed for repair
- Specified materials, local where possible
- Standardised designs and parts common
- Complimentary but limited product range
- ‘Modernist’ design style, ‘good’ design
- No decoration or ornament
- Designed by single design committee Government, Industry, Academics & Society involved

Production

Governmental control of the following:

- Production location specified
- Material allocated
- Production licences required
- Labour allocated
- Energy supply controlled
- Production volumes and timings given

Customers

- Only product legally available, CC41 stamp used
- Permits required, based on need
- Coupons required
- Products in catalogues not showrooms
- Purchase or lease or sharing
- Open to all, value for money
- Low cost
- Make do and mend encouraged

Product design to address material scarcity to ensure material supplies for military production

Figure 12 A synchronic analysis of the parallels from product design approaches to address materials scarcity in 1943.

Figure 12 was developed from table 3. The descriptors for the design strategies were shortened and categorised into 3 sub-sets; product design, production and customers. All 3 sub-sets contribute to 'product design to address material scarcity to ensure material supplies for military production'. This approach of structuring the product design into sub-sets was taken as it complements the current trend of structuring actions for materials criticality, which is further explored in chapter 5.

2.7.2 The effectiveness of product design strategies as a response to material scarcity

A key point in looking at product design for scarcity is the role that product design played in helping to reduce the consumption of materials. To address this, the utility furniture case is used, firstly because the degree of product design control was tightest and secondly most of the product range in 1943 was comprised of wood. Steel screws, steel / brass hinges and steel springs, together with some fabrics were used, but the majority of the material, in all the products, was wood. This use of mainly a single material (although 126 named types of timber are approved) corresponds with the available data, which in turn, can be analysed.

As Reimer and Pinch observe, a useful source of materials data is the *Monthly Digest of Statistics No. 2, January 1946. Central Statistical Office, London. Data extracted from Table 89, Imports of miscellaneous raw materials, page 73 (*Reimer and Pinch, 2013)*.* The monthly digest, in volumes 1, 2 and 3, covers the wartime period and would have only become available after the war as such information was secret during the war. In volume 1, table 34, page 25 there is a more detailed breakdown of hard and soft wood production and consumption. In particular, there is a detailed breakdown of sales of utility furniture.

The utility furniture has supply data starting in June 1943 to November 1945 and this is shown below in figure 13. As can be seen the introduction of the utility furniture went from 250,000 units of furniture to over 1 million units by the war's end and 2 million by the end of 1945.

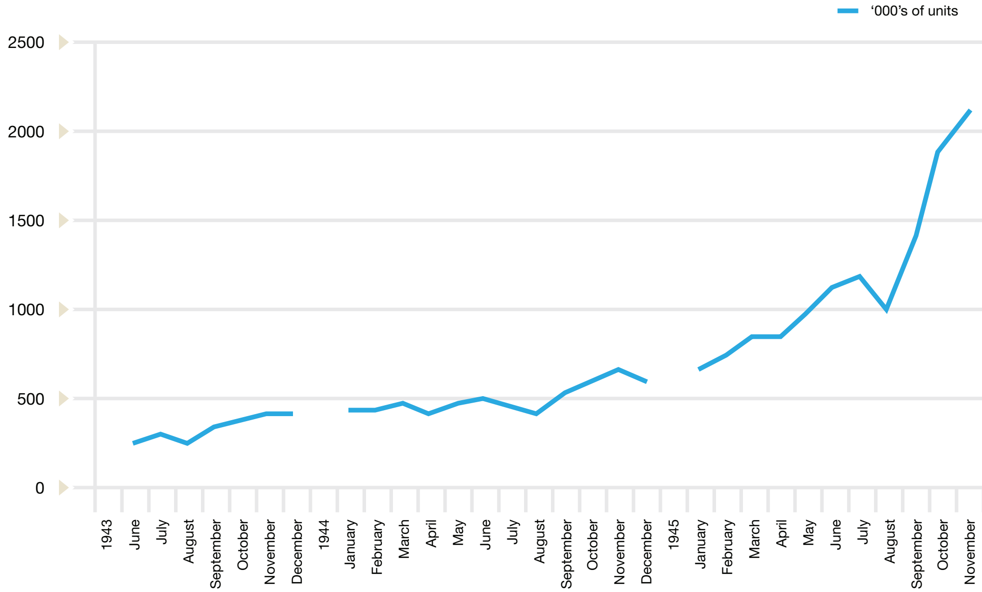
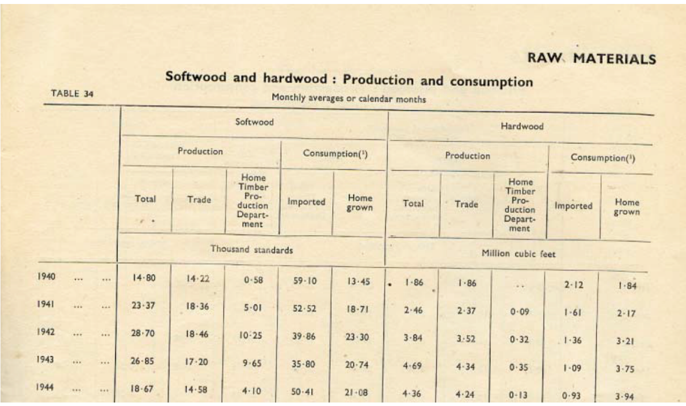


Figure 13. The supply of utility furniture in Britain (Thousands of units), 1943 to 1945.

What cannot be directly drawn out, is the data on consumption of wood and the effect of the utility furniture scheme had in solving the wood scarcity problem. The data for wood production and consumption covers all wood products and does not differentiate for that used only in utility furniture manufacture.

There is, however, one set of data which may indicate an effect of the utility furniture design approach. The data for hardwood shows the differences in consumption for imports and home grown as shown in the extract in figure 14 below.



RAW MATERIALS

TABLE 34

Softwood and hardwood : Production and consumption

Monthly averages or calendar months

	Softwood					Hardwood				
	Production			Consumption(1)		Production			Consumption(1)	
	Total	Trade	Home Timber Production Department	Imported	Home grown	Total	Trade	Home Timber Production Department	Imported	Home grown
	Thousand standards					Million cubic feet				
1940	14·80	14·22	0·58	59·10	13·45	1·86	1·86	..	2·12	1·84
1941	23·37	18·36	5·01	52·52	18·71	2·46	2·37	0·09	1·61	2·17
1942	28·70	18·46	10·25	39·86	23·30	3·84	3·52	0·32	1·36	3·21
1943	26·85	17·20	9·65	35·80	20·74	4·69	4·34	0·35	1·09	3·75
1944	18·67	14·58	4·10	50·41	21·08	4·36	4·24	0·13	0·93	3·94

Figure 14 Data example from Monthly Digest of Statistics No. 1, January 1946. Central Statistical Office, London. Table 34, page 25

The wartime utility furniture used hardwood. When the data for hardwood is presented as a graph, in figure 15, it can be seen that for most of the war home grown hardwood consumption grew, whilst imports fell. The utility furniture design facilitated this occurrence, but this is only an indication of a correlation and not a clear evidence of one. Utility furniture was only one sixth of all wood use.

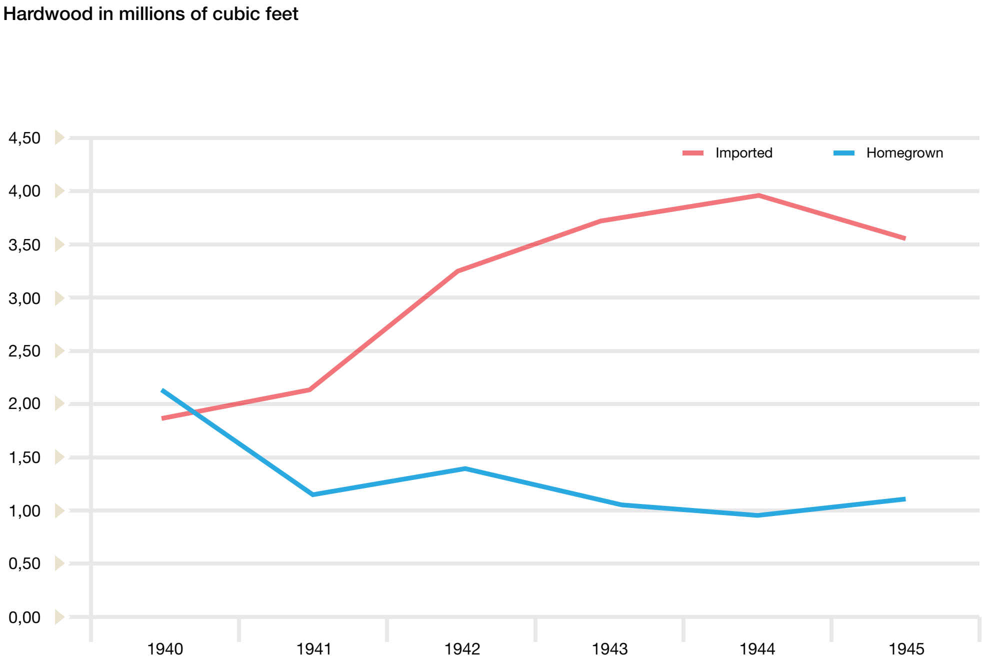


Figure 15 Data example from Monthly Digest of Statistics No. 1, January 1946. Central Statistical Office, London. Table 34, page 25 – presented graphically.

A second observation can be made when the sequence of furniture wood controls and utility design controls are shown against the hardwood graph as shown in figure 16 below.

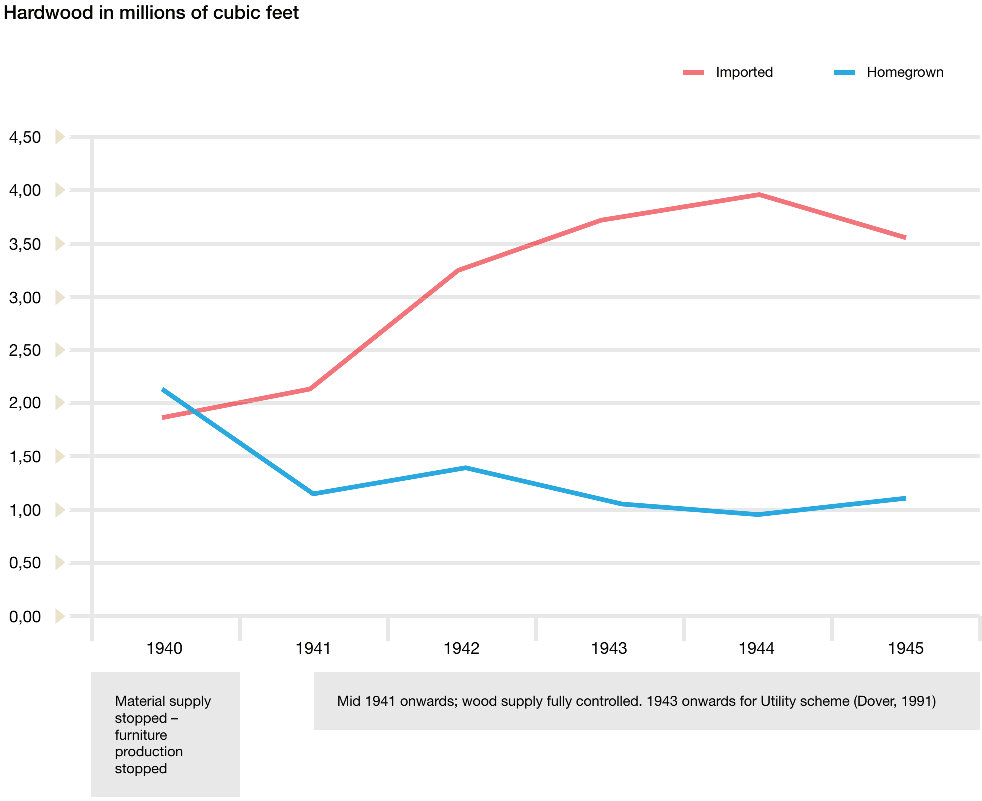


Figure 16 The effect of furniture wood controls and utility scheme product design controls shown in terms of hardwood consumption. This shows the drive to develop home-grown hardwoods through the product design actions.

This indicates that there may be an effect of the furniture design strategies and the changes in imports and home grown hardwood consumption. The change in design to utility furniture and the controls around which woods were available, resulted in imported wood being used less and local home-grown increasing. This was the effect the government desired, allowing shipping to be used for more essential goods.

This utility furniture case demonstrates how the changes to the design combined with material and production controls, together with purchase controls, allowed the management of materials to take place. The change of the design was a key feature of the whole material control scheme. A mix of pre-war designs would not have resulted in the level of control desired.

2.8 Chapter 2 conclusions

Research sub question 2: What can be learnt from product design responses to materials scarcity?

The response to material scarcity in the five WWII British cases can be sub-divided into responses around the product design itself (the development of a range of design strategies for dealing with materials scarcity), the control of materials & production (rationing, strict government controls) and the customers (who accepted lack of choice and restricted availability). It is these three measures together that constituted an effective response to materials scarcity.

When looking at product design in particular, the five Austerity and Utility design cases demonstrate what product design can do when faced with material scarcity. Key design approaches were the standardisation of designs to reduce waste, avoidance of material (for instance by avoiding unneeded features) and mass production techniques. These three approaches helped design products to address the materials scarcity context.

The five cases show the important role product can play in addressing materials scarcity where very different designs were deployed in order to address a materials crisis. This is the most important lesson from the cases; The government could have simply restricted the range and volumes of existing designs, but they did not. The government chose to instruct the companies to produce new products to a new set of requirements, which the government oversaw. They did this because it provided the most product for the least material, energy and labour, at the lowest cost.

This final point, to decide to implement a whole range of new product designs in the middle of war, is the most striking feature of this chapter. The product design approaches that were chosen (such as standardization) are not new, but it may prove surprising to some today that they were being considered so long ago. More to the point the product design approaches were in the main successful, they provided product and managed materials.

Further detailed analysis of the correlation between the design strategies, other governmental interventions and the supply of materials, is recommended.

3 Defining critical materials for product design

3.1 Introduction

The aim of this chapter is to develop a definition of critical materials for product design. This is important, because product designers appear not to realise they design products containing critical materials and therefore are unable to justify the cost and risk of any changes to product designs to help address critical materials problems. Product designers will need to know which materials are critical, what the severity of the problem is and what role these materials play in their product. Most importantly this knowledge will then allow product designers to design innovative solutions.

In developing a new definition of critical materials for product design, this chapter addresses sub- research question 2: *How can critical materials be defined within the context of product design?*

This chapter uses a literature review to conduct an analysis of 29 existing published definitions of critical materials to establish their usability for product design. The review shows that the definitions used for critical materials are variable and therefore open to misunderstandings by product designers. This leads to the development of a new definition of critical materials for product design.

3.2 Critical materials; The problem

Critical materials problems are not, over the next 10 years, about 'running out'. In other words metals, although finite, are, not currently, physically being exhausted (Catinat, 2010), (Pellegrini, 2014). Not physically 'running out' does not, however, mean there is security of supply.

Threats to the security of supply of materials have been driven by market and governmental concerns over the volatility in prices of, for example, the Rare Earth Elements. Chinese organisations control the majority of the mining and processing of rare earths (Catinat, 2010, Pellegrini, 2014). In September 2010 a Chinese fishing boat was involved in an unauthorised territorial incursion incident off a Japanese island. The ensuing diplomatic dispute led to China delaying the export of rare earths to Japan (Abraham, 2015). Rare earth export quotas were then implemented by China. The result of these events are reflected in the prices, which rose sharply in 2011, as can be seen in figure 17.

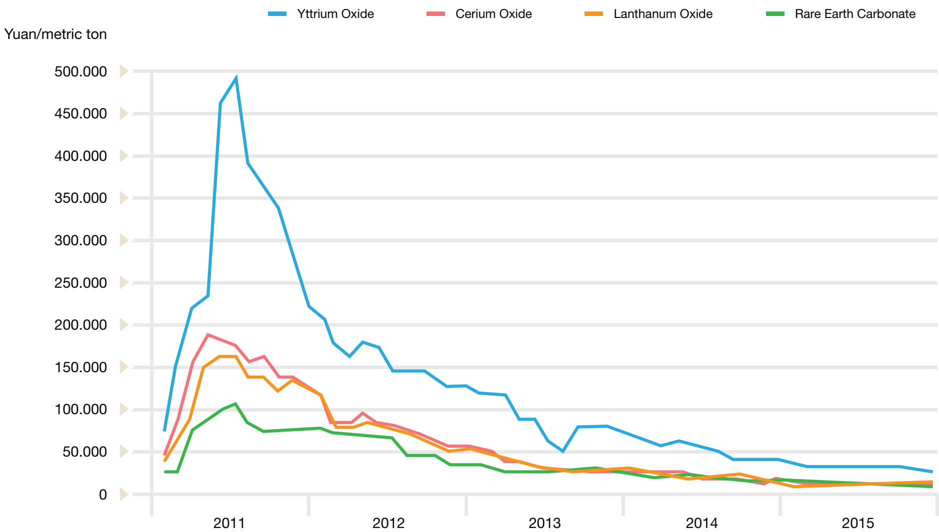


Figure 17. Rare Earth price rises and falls 2011 – 2015. (Bloomberg, 2015)

This period of high price rises for the rare earths, has been termed the 'hype' period (Kooroshy 2013). Figure 17 also shows a 'after the hype – hangover' rapid collapse in prices (Bloomberg, 2015). Investments in new mining and processing projects, that were started during the hype period, of rare earths, have come under severe strain, which in turn raises concerns over the security of supply of rare earths going forwards.

The critical materials are part of a materials value supply chain. The technologies and innovations of the 21st century have driven the pull of more materials out of the materials science lab. The critical materials value chain can be seen in figure 18 below, where examples of materials, sectors, components and products are shown.
The first problem with critical materials is their essential function in the products they are used in and secondly, that critical materials are difficult to substitute.

Geosciences

Mining

Processing

Critical Metals Elements:
Li, Be, Mg, Sc, Cr, Co, Ga, Ge, Nb, Ru, Rh, Pd, Os, Ir, Pt, In, Sb, W, La, Ce, Pr, Nd,, Sm, Y, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

Critical material containing metal materials - examples

- Steels
- Al-alloys
- Glass
- Super-alloys
- Mag-alloys

Critical material containing sectors - examples

- Energy
- Mobility
- Buildings
- Communication
- EEE
- Defence
- Water Mgt.

Critical material containing components - examples

- Motor magnet
- Capacitor
- PCB
- LED
- Lasers
- Hard discs
- Batteries
- Steels

Critical material containing products - examples

- Wind turbine
- Solar PV panel
- Smart power grid
- Mobile phone
- Personal computer
- Internet services unit
- Armoured personnel vehicle
- Fighter Aircraft
- Aircraft carrier

- Locomotive
- Aircraft
- Electric car
- Cargo ship
- Microwave oven
- Air conditioner unit
- Elec. Cooker
- Sea barrier
- Water pump
- Water purification unit

- Low energy home
- Office block
- Smart energy meter

Critical material containing products – end of life

Most critical materials – end of life:

- Landfill
- Incineration

Figure 18. The critical materials value chain

Taking wind turbines as an example from figure 26, these are important technologies for lower carbon energy generation. Their production and use is on the rise not only in developed countries but also in emerging countries like China. The product uses critical materials. This is shown in figure 19 below.

Figure 19. Examples of components and related CRM's in wind turbines. Developed from (CRM_Innonet 2013) and (CRM_InnoNet, 2015). Published in Critical Raw Materials, Circular Economy and Wind Turbines, Fromberg, et al, 2015.

The end of life box in figure 20 highlights a third problem with critical materials, which is what happens to them at the end of the life of the product. This is shown in figure 20.

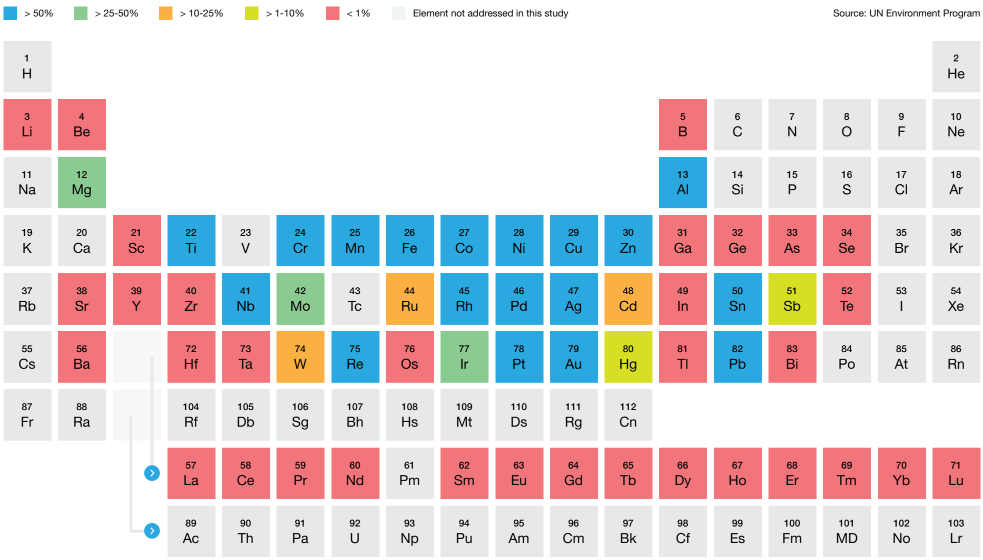


Figure 20. Recovery rates for recycling metals (United Nations Environment Program, 2011)

Figure 20 shows that for example with the Rare Earth Elements, recycling rate are very low to zero. Rare Earths are often used in very small quantities, highly mixed with other materials (as alloys for example) and difficult to separate without losing other valuable materials. The market volumes for some critical materials are not large either.

The summary of the problem of critical materials can be described as materials supply insecurity of economically important materials whose demand is driven by an increasing worldwide population (longer life expectancy), increasing wealth (in particular the rise of the 'middle class' in emerging economies), technological trends driving increased use of critical materials and the increasing complexity in the winning of new resources (Graedel 2009, Tilton 2001, Simpson et al 2004, Allwood et al 2011, Allwood & Cullen, 2015). Adding to the problem of critical materials is their low substitutability and recoverability.

A focus on products and technology trends shows the material requirements of technologies as deployed in products has become increasingly 'omnivorous' (Greenfield & Graedel, 2013, Tilton, 2001), with one large, global, engineering and technology company stating they use at least 70 of the first 83 elements listed in the Periodic Table of Elements (Duclos, 2010). This reflects the rapid technological developments over the past 30 years, often utilizing new technologies.

The design of products often contributes to the critical materials problem. The choice of the materials is made at the product design stage, and often the designer does not realise they are choosing critical materials. This situation is reflected in product design education (Köhler, et al, 2013). The materials focus in design education tends to be on aesthetic and user sensory factors (Karana, et al, 2008), with normally no consideration of what elements are in a material.

The design of the product decides the life of the product, which when the life is shorter, speeds up the rate of critical material use. The design of the product can make it harder to disassemble (and reassemble) the product which can hinder reuse, refurbishment, remanufacturing (which slows critical material use) and recycling (which returns critical materials for another product). The product design can also make it harder to use material substitution strategies.

3.3 Criteria for determining materials criticality

The term scarcity is not suitable for the complex range of factors concerning materials like rare earth elements, because scarcity, as explained in chapter 2, means 'insufficient for the demand' and as has been shown this description is too simplistic for the complexity of critical materials. The term scarcity suggests that the world may be soon running out. However, as explained above, the world is not immediately 'running out', but some materials have a higher risk of supply disruption and are correspondingly economically more important than others. From these two factors the definition of 'critical materials' was developed.

This approach was further developed in the work of Sievers et al, 2012 and is shown in shown in figure 21 below.

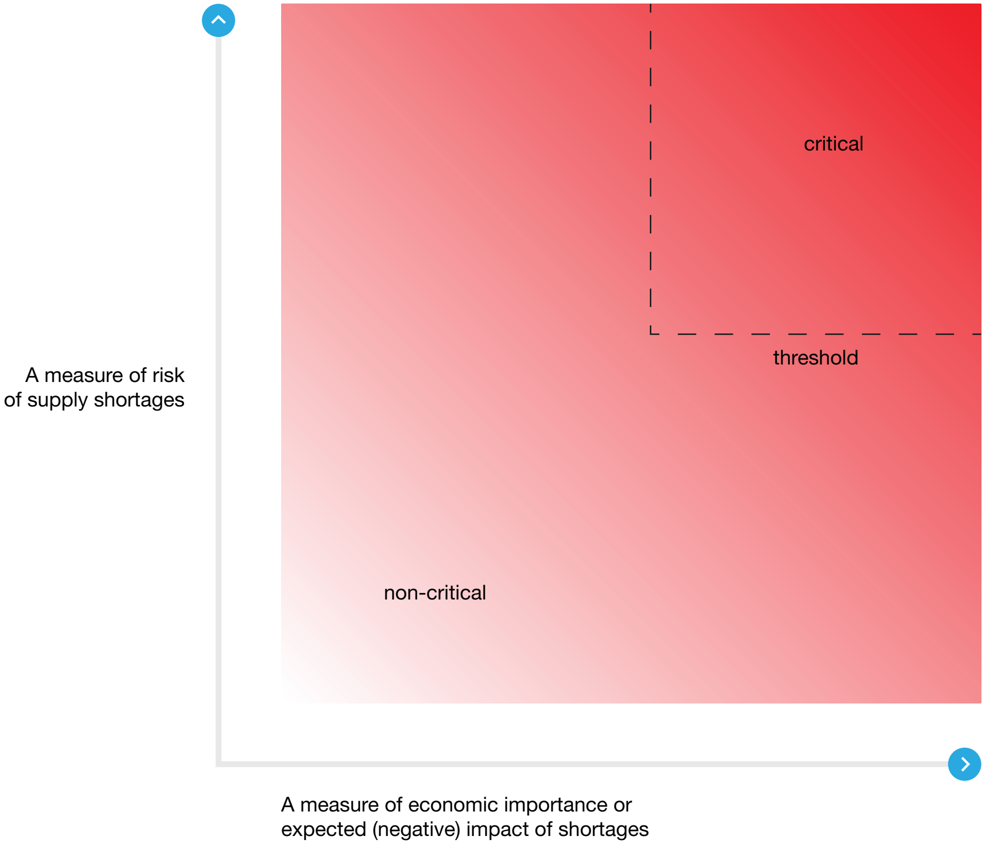


Figure 21. The two factors which determine if a material is critical; economic importance against supply risk.(Sievers et al 2012)

The figure shows how if, for any given material, two pre-determined thresholds have been crossed, then a material can be named as critical. It is therefore the supply risk and economic importance metrics, which determine where any given material is on the graph, which are important.

A generic approach to determine if a material is critical or not was developed over a similar period (2008-12) in a number of countries (EU, USA, UK, NL). This approach was used to develop, for example, the graph in the 2014 EU report, as shown in figure 22 below. This two axis basis, supply risk against economic importance, is the core of most post 2008 definitions of critical materials.

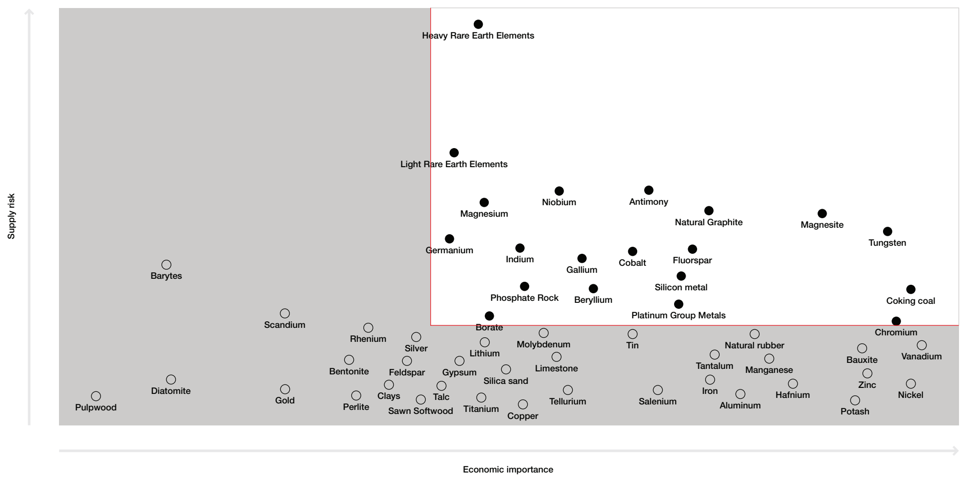


Figure 22 The two axis – economic importance against supply risk to determine criticality of a material. The EU 2014 critical list is shown (Peligrini, 2014)

In the case of the EU definition of critical materials the diagram in figure 23 shows the outline of the criticality assessment methodology for candidate materials (Pelligrini, 2014). These metrics are used to determine the supply risk and economic importance.

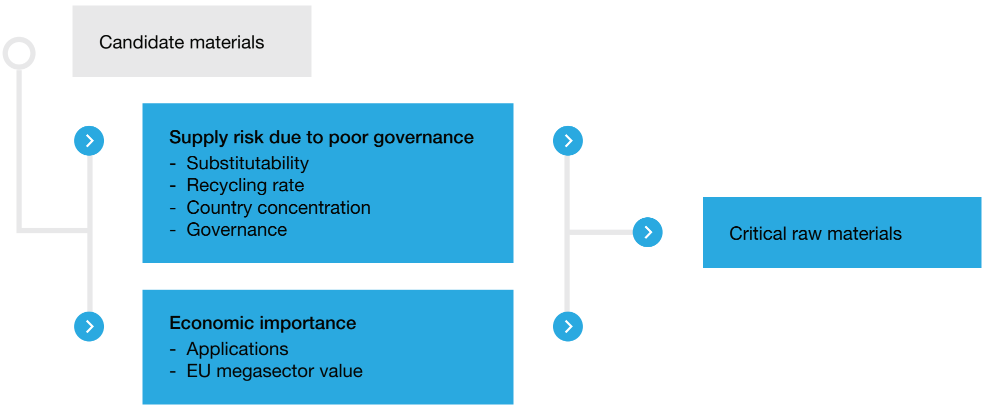


Figure 23 The outline of the criticality assessment methodology for raw materials (Pelligrini, 2014).

For any given material the supply risk is determined by four assessments being conducted and the results collated together. Firstly by assessing the substitutability of that material. This looks at how widely that material can be substituted by applying ‘substance for substance’ substitution and / or ‘process for process’ substitution and /or ‘new technology for substance’ substitution methods. Put another way substitution can involve for example removing an element from a metal alloy and replacing it with one or more other elements to result in an acceptably similar metal alloy. Alternatively the process by which the metal alloy is made can be changed to remove an element. Another way is via a new technology which can be developed which means a material no longer (or less of it) is needed.

Secondly, by assessing the rate at which that material is recycled in the EU member states for which the assessment is being made. For the heavy rare earths for example, recycling is close to zero.

Thirdly, by assessing the mining and processing concentration of a material. For the heavy rare earths the country concentration in China is very high.

And fourthly, by assessing the international governance index of the raw material supplying country. The poorer the governance of a country the higher the risk. Preference is given to EU countries which mine and process a material.

For any given material the economic importance is determined by two assessments being conducted and the results collated together. Firstly, by assessing the type of applications which depend on a given material. This allows for an assessment to be made of the importance of that material. For example materials which are needed for a form of renewable power generation are assessed as more important. Secondly the economic mega-sector value. An assessment is made on the volumes in weight and corresponding prices for the EU.

In the 2014 EU critical materials definition report the EU considered 54 candidate materials were assessed for the 28 countries in the EU. 20 were determined as critical as shown in figure 22 above. On average the report comes out every 4 years with the next not expected until 2018. In the example shown in figure 22 it is important to note that the position of a material is often the result of a 'best estimation' and is the view of the committee of experts in place at the time. The 'uncertainty rate' of data can be high.

The two axis model is not the only model available to define critical materials. Graedel, et al 2013, have developed a further cross cutting analysis in defining metals criticality in the paper entitled *'On the materials basis of modern society'* and their framework is shown on figure 24 below. In their paper the authors state that out of 62 metals they looked at not one had a an exemplary substitute available for all possible uses. Importantly the method used to derive the framework in figure 24 is given in an earlier publication (also led by Graedel); '*Methodology of metal criticality determination'*, Graedel et al, 2012. The supply risk axis remains but is complimented by two vectors showing vulnerability to supply restriction and environmental implications (Graedel, et al, 2012 & 2013). This model has, so far, not been adopted by governments to define critical materials.

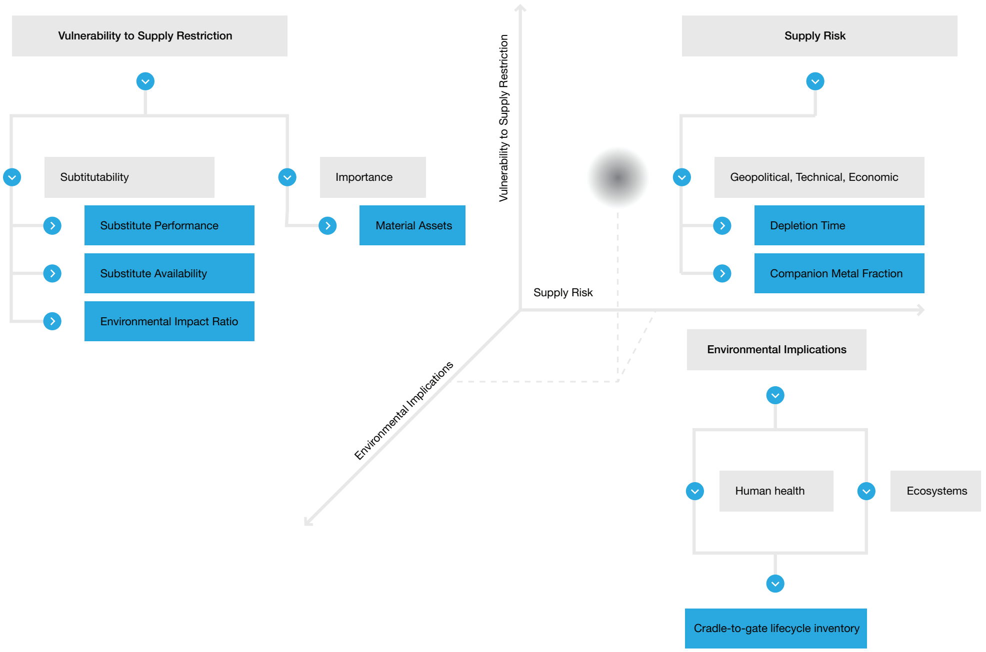


Figure 24. The Yale analytical framework for determining metal criticality at the global level (Graedel, et al, 2012 & 2013).

The methodology described in Graedel et al, 2012 covers not only the three vectors shown in figure 24 but also the criticality from corporate, national and global level. They also considered the criticality from different time perspectives. Needless to say this gave rise to a number of detailed analysis perspectives.

In the environmental implications (figure 24), societal, systemic and lifecycle aspects are considered. This however presents a challenge here. Environmental lifecycle impact calculations are a reflection of the percentage volume of a given material. Critical materials are usually only a trace percentage of the materials in a product and the annual production of some critical materials is measured in kilogrammes rather than tonnes. In these cases the environmental impact seems very small when compared to iron, aluminium or copper, for example. Conversely the environmental benefits of adding critical materials, as already discussed, can be significant. The analogy with spices in food is a useful reflection. There is often not many grams of spice in a dish but without them the meal is tasteless. In the case of metals, the material without critical materials is useless.

3.3.1 Lists of critical materials.

As shown in figure 22 the use of the two axis framework allows for a list of critical materials to be generated. Due to the geographic variations there is no agreed global list of critical materials. The materials named on the lists vary and this suggests that materials criticality is both geographic and product dependent. The lists sometimes mix up elements, materials and minerals, a distinction that has the potential (even if only one list were used) to cause some confusion with all stakeholders, including product designers. A product designer, once an awareness of critical materials had been established, would likely ask; 'So which materials are critical, do you have a list?'. As shown in table 4 below we have many lists globally, which if taken together, (never mind the mix of elements, materials and minerals) are confusing. The lists are also snap-shots in time and are often out of date very quickly. An overview of the critical material lists can be seen in table 4 below.

Table 4 Critical materials – materials of interest for a range of countries. Adapted from U.S. Department of Energy, Critical Materials Strategy, Dec 2010 [Bauer et al 2010]

Country or Region	**Critical Elements**
Japan	Ni, Mn, Co, W, Mo,V
European Union	Li, Be, Mg, Sc, Cr, Co, Ga, Ge, Y (as HREE), Nb, PGM's, In, Sb, W, Light Rare Earth's (LREE, not Pm), Heavy Rare Earth's (HREE). Non elements: Borates, Magnesite, Silicon metal, Coking coal, Fluorspar, Natural graphite & Phosphate rock.
The Netherlands	Ag, As, Au, Be, Bi, Cd, Co, Ga, Ge, Hg, In, Li, Mo, Nb, Nd, Ni, Pb, Pd, PGMs, REEs, Re, Ru, Sb, Sc, Se, Sn, Sr, Ta, Te, Tl, V, W, Y, Zn, Zr
China	Sb, Sn, W, Fe, Hg, Al, Zn, V, Mo, REEs
South Korea	As, Ti, Co, In, Mo, Mn, Ta, Ga, V, W, Li and REEs, PGMs, Si, Zr
Australia	Ta, No, V, Li and REEs
Canada	Al, Ag, Au, Fe, Ni, Cu, Pb, Mo
Germany	Ag, Be, Bi, Co, Cr, Ga, Ge, In, Mg, Nb, Pd, PGMs, Re, REEs, Sb, Sn, Ta, W
France	Au, Co, Cu, Ga, Ge, In, Li, Mg, Ni, Nb, Re, REEs, Se, Ta
Finland	Ag, Co, Cr, Cu, Fe, Li, Mn, Nb, Ni, PGMs, REEs, Ti, Zn
United States	Ce, Co, Dy, Eu, Ga, In, La, Li, Nd, Pr, Sm, Tb, Te, Y

Table 2 above highlights there are some elements which regularly feature in the lists from the different countries. In particular the Rare Earth Elements (REE) and Platinum Group Metals (PGM) appear often.

The Rare Earth Elements (also referred to as rare earth oxides – REO's and rare earth metals – REM's, rare-earth elements and yttrium – REY, or even simply rare earths), are a set of seventeen chemical elements, comprising of the fifteen in the lanthanide series plus scandium and yttrium. The REE's can be divided into light and heavy.

In 2014 the European Union list REE's following this distinction between the light and heavy rare earths, as shown below (Peck et al, Jan 2015).

LREE = light rare earth elements (La, Ce, Pr, Nd, Sm)
HREE = heavy rare earth elements (Y, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu)
Scandium is listed on its own – neither HREE nor LREE.

In addition to the REE's there are the Platinum Group Metals (PGM) which are six elements; Ru, Rh, Pd, Os, Ir and Pt. (Pelligrini, 2014) (Peck et al, Jan 2015).

3.4 The product design team involved in the selection of critical materials

Product design contributes to the critical materials problem (and the possible solutions). Product designers choose the critical materials, the amount of critical material used, the amount of potential reuse, refurbishment & remanufacturing cycles, the ease of recycling and the product designer can help or hinder the use of material substitution strategies.

In support of this view a British government report published in 2012 entitled *Resource Security action plan – making the most of valuable materials* (UK Government, 2012), states that product design could be a strategy to address critical materials concerns. Other government reports, in particular EU reports, have adopted this view (EU, REE, 2015), (EU, CE, 2016). This section looks at how materials are selected during final product design.

It is not always clear if product designers, designing for original equipment manufacturers (product 'integrators'), actually select the materials at an element level. Furthermore other employees are involved in making materials selection from fields such as marketing, supply chain / procurement (buying), manufacturing engineering, logistics / supply chain and finance. Ashby and Johnson discuss the different people involved in the design of a product and they differentiate between technical design and industrial design, (Ashby & Johnson, 2009, p 33) *(Pahl et al, 2007)* (Peck et al, Jan 2015). In the case of an existing design being adapted, upgraded or modified (which constitutes most product design activity), the materials is already there and usually as little change as possible is made. In addition products come as part of a product range and therefore common platforms are shared, which includes materials.

Product designers' prime concern is the performance of a material. Typically product designer knowledge of the elements in a material would become apparent if the name of the material made it obvious, such as 'niobium alloy structural steel', 'rare earth magnets' or 'lithium-ion batteries'.

3.4.1 The materials selection process

Material choices during the product design process follows a process of elimination, eventually selecting the most suitable material (Ashby, 2013). The product designer chooses the material based on a trade-off between functionality, quality (grade) and cost. These trade-offs are done both for engineering material requirements (Ashby, 2013) and for more subjective aspects, such as the user perceptions of material qualities and meanings (Karana, 2008).

Ashby and Johnson in Materials and Design (Ashby & Johnson, 2010, p161), propose that new materials are developed through a science driven development path which is part of company commercialisation activities. Put another way the materials scientist *'pushes'* the material towards the product designer who uses the material in the product design. This push of materials from materials lab to product appears logical, but this is not the whole story. There is, in many cases, a demand from the end users (consumers) which is translated into technical requirements, and changes in materials can make a significant difference (Buijs, 2003). In those cases there is a *'pull'*, by product designers, driven by the user wants, of new materials, out of the materials lab. This is the materials part of the field of 'user centred design'.

In either pull or push case, there has to be a commercial case for the development of new materials. This 'pull' can be driven by a user wanting a feel, sensation, look, which together can be named the 'meaning' of a material (Karana, 2008) . Equally the user can come to expect a certain performance from a product, for example the sensitivity of a touch screen on an electronic device, which also requires changes to materials, which again 'pulls' materials out of the materials development lab.

The selection and application of critical materials is normally decided by materials scientists conducting scientific materials research either in universities / research and technology organisations or in the R&D labs of a materials company. The technical product designers (engineers) working in component companies that use critical materials may also have good knowledge of critical material content, as they design components to meet the performance requirements of their upstream customers (the OEM's).

The complexity of the situation is further highlighted, when one looks at the information and communications / electrical and electronic equipment (EEE) sector. In the case of electronics, key aspects of the product design activity is carried out by the electronics design engineer, who has to make design choices, driven by consumer demand, in a highly competitive market. The market seeks designs that are smaller (thinner), lighter, higher performance, more power efficient (e.g. battery) and robust (e.g. waterproof). This has, in turn, driven the selection of components that use critical materials, which in turn increases the risk of critical materials problems. At the same time societies, companies and governments have rapidly become highly dependent on electronics and the impact of any restriction in the supply of such technologies is severe

In the 2014 publication: Report on Critical Raw Materials for the EU (Pelligrini, 2014), there is a proposal that:
"….*there should be facilitated an open discussion among experts to create a network of excellence and cross-disciplinary exchange (including product designers) in order to enhance the knowledge of the most efficient use of critical materials, including their substitution."*

If there is a risk to the supply of a material it is sensible to ask if another lower risk material can be used in its place. There are however concerns about a lack of progress on substitution as highlighted by Graedel et al. Their 2013 paper, *On the materials basis of modern society,* asks that given uncertainty over critical materials in the future, what is the potential for the substitution of materials? Put another way as we explore the whole of the periodic table of elements, switching to other elements simply makes them critical. In addition the switch from one element to another is not easy. Graedel et al. analyse the potential substitutes of 62 metals and conclude that none of the potential substitutes provide exemplary performance. As shown in this paragraph, this Graedel et al. paper is based on the position that substitution means substance for substance replacement (Graedel, et al, 2013).

The results of Graedel et al. 2013 paper on substitution would suggest that it provides little comfort to any product designer concerned over critical materials and hoping that substitution will 'fix it'. There is, however, an expansion of the term 'substitution', which has been proposed. An EU funded project, CRM_Innonet, (Critical Raw Materials Innovation Network – Towards an integrated community driving innovation in the field of critical raw material substitution for the benefit of EU industry), provides a development in the meaning of substitution. Figure 25 shows that the concept of substitution is widened, to include not only the existing substance for substance (alternative elements) and changes to processes approaches, but adds new technology (engineering) and service to replace product approaches. Such services can include reuse, repair, refurbishing and remanufacturing activities. A product which was designed to be easily remanufactured means that as it goes back into use, the raw materials needed for a new product, were not used and they were in effect 'substituted' by the service provision of the remanufacturing activity. In other words new materials were not used because the original materials were used again.

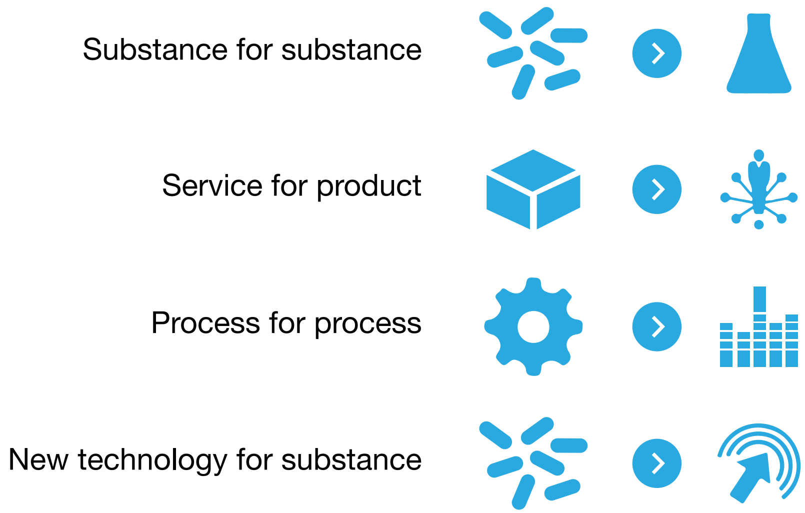


Figure 25. Substitution from CRM_Innonet (CRM_InnoNet, 2014.

To summarize, currently product designers are certainly not the only ones who make material choices, and when it comes to components, they usually choose the constituent materials only implicitly. There are four substitution strategies, where the product designer has a role to play in helping to address critical materials problems.

3.5 A critical materials definition for product design; method

As contemporary concerns over the security of supply of certain metals began to be published post 1999, this year is selected as the start date of the diachronic analysis and the timeframe selected for review runs to the end of 2014. This end date is selected to correspond with the most recent EU critical materials definition report (Peck, et al, 2015).

The concept of critical materials uses a wide variety of terms. For the literature review the following search keywords were used:
Critical materials, materials scarcity, critical raw materials, materials scarcity, material security, rare metals supply, rare earth elements, rare earths, platinum group metals, essential substances security, criticality of materials, resource security, scarcity of minerals, priority materials, shortages of precious metals and commodities, key resources, supply security, energy-critical elements, key materials, product design & critical materials, product design & scarce materials (Peck, et al, 2015).

The searches for the literature were conducted between 2010 and May 2014 and used Scopus and Google Scholar search engines (Peck, et al, 2015).

Peer reviewed Journal papers, academic textbooks and committee based governmental government reports were included. Only publications in English were selected.

Not included in the selected literature were theses / dissertations, media articles and company reports. Such publications have however been read as part of the wider research activity (Peck, et al, 2015).

The literature was analysed using the approach of *feature maps* as outlined by Hart (Hart, 2011). Table xx was copied into an excel spreadsheet and columns were inserted which allowed for headings and scoring the number of times a feature was noted. No particular weighting was given to any heading (Peck, et al, 2015). Only the following from the publication were assessed:

1. Date of publication
2. Main country / region where the publication originated
3. Words in the term used
4. Descriptors in the definition given

3.6 Results: Published definitions of critical materials

Table 5 shows the feature map that gives an overview of the publications selected for review. The columns 'Term' and 'descriptor' were derived from the publication. It should be noted that some of the publications discuss product design but this research only looks for the 'Term' and 'descriptor'. The publications are shown in chronological order (Peck, et al, 2015).

This table has been significantly developed from the masters graduation work of Fabian Watelet and Michael Vroom, both of whom Peck supervised (Watelet 2013), (Vroom, 2012). This table is a new development from this previous work and builds on the concept from Watelet and Vroom.

Table 5 Feature map showing a comparison of terms and descriptors given in the literature (Peck, et al, 2015). Adapted from (Watelet, 2013) & (Vroom, 2012).

Title	**Author**	**Term**	**Descriptor**
1. Depletion and the long-run Availability of Mineral Commodities **2001**	Tilton J E, Report published by IIED for WBCSD, Washington D.C, USA	Mineral commodities depletion	Mineral resource availability Mineral depletion Shortages and scarcity=opposite of availability Excess of demand over supply Declining availability
2 On Borrowed Time? Assessing the Threat of Mineral Depletion **2003**	Tilton J E, RFF Press, Washington, D.C. USA	Mineral depletion	Mineral resource availability Mineral depletion Shortages and scarcity=opposite of availability Excess of demand over supply Declining availability
3 Scarcity and Growth in the	R. David Simpson, Michael A. Toman, and Robert U. Ayres	Scarcity New Scarcity	Resource limits to growth

New Millennium: Summary **2004**	Discussion Paper 04-01 Resources for the Future, USA		
4 Minerals, critical minerals, and the U.S. Economy, **2008**	Eggert R G et al, Minerals, Critical Minerals, and the U.S. Economy, National Research Council, USA.	Critical minerals; Critical materials	The two dimensions of criticality are: 1. importance in use; 2. availability.
5 Methodology of Metal Criticality Determination, **2009**	Thomas E. Graedel, et al., Yale University, USA	Metal criticality	A critical metal involves three dimensions: 1. supply risk ; 2. environmental implications; 3. vulnerability to supply restriction.
6 Material Scarcity, **2009**	Wouters H and Bol D, Materials innovation institute (M2i); The Netherlands	Material scarcity; critical elements; critical materials	Supply of the material versus its demand. Balance is affected by socio-economic factors. Critical = quantities used & change in supply, has an impact on current lives, and that resources will expire in the next two to five decades
7 Critical Metals for Future Sustainable Technologies and Their Recycling Potential **2009**	Buchert M et al, UNEP, UNU, Öko-Institut e.V., Germany	Critical metals	A metal with: 1. high demand growth; 2. high supply risks; 3. recycling restrictions.
8 Critical raw materials for the EU **2010**	Ad hoc working group under the authority of the European Commission, EU	Critical raw materials	1. high access risks, i.e. high supply risks or high environmental risks; 2. high economic importance.
9 The German Government - raw materials strategy, **2010**	Federal Ministry of Economics and Technology (BMWI), Germany	Distorted raw materials supply, security materials	Uses EU def: 1. high access risks, i.e. high supply risks or high environmental risks; 2. high economic importance.
10 Critical Materials Strategy **2010**	Bauer D, et al, Department of Energy, USA Revised and updated **2011**.	Key materials, Critical materials	A material with: 1. high importance to clean energy technologies; 2. high supply risk.
11 Global Resource Depletion – Managed Austerity and The Elements of	Diederen A, Eurborn Academic Publishers, Delft, The Netherlands	Scarcity of metals	Energy scarcity = materials scarcity, peak metals curve.

Hope, **2010**			
12 Critical materials in the Dutch Economy – Preliminary Results **2010**	Statistics Netherlands, The Hague, The Netherlands	Critical materials	1. high access risks, i.e. high supply risks or high environmental risks; 2. high economic importance., EU Definition graph shown.
13 Material Efficiency: A white paper **2011**	Allwood J et al, Journal of Resources, Conservation and Recycling, United Kingdom	Scarce materials	1.High demand materials 2. Scarce selected materials 3. materials that affect security 4. Climate change impact materials
14 Strategically important metals **2011**	Science and Technology Committee - House of Commons, United Kingdom	Strategic metals	A metal that may be of importance to any user within the United Kingdom - used chemical innovation KTN and EU lists
15 Scarcity in a sea of plenty? Global resource scarcities and policies in the European Union and the Netherlands **2011**.	Netherlands Environmental Assessment Agency (PBL), NL Government The Netherlands	Resource scarcity	Minerals that have: 1. physical scarcity; demand and applications 2. political scarcity; concentration leading to abuse
16 Critical Metals in Strategic Energy Technologies, Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies **2011**	Moss et al, Joint Research Centre, European Commission Petten, The Netherlands, Oakdene Hollins Ltd, United Kingdom, and The Hague Centre for Strategic Studies, The Netherlands	Significant metals; supply-chain bottlenecks; critical metals	A material with: 1. a relatively large share of the total future supply that will be consumed by a strategic energy technology; 2. high risk of supply-chain bottlenecks.
17 Raw Materials Critical to the Scottish Economy, **2011**	Scotland & Northern Ireland Forum for Environmental Research, Scotland, United Kingdom	Resource risks; critical resources; key resources	Scores high on the following criteria: 1. combined consumption/production and scarcity/availability; 2. availability of alternatives; 3. supply distribution; 4. supply domination; 5. extent of geopolitical influences; 6. press coverage; 7. price fluctuation.

18 Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses, **2011**	Erdmann L & Graedel T E, Institute for Futures Studies and Technology Assessment IZT, Germany & Yale University, USA	Material criticality	Material criticality captures two aspects: 1. supply risks; 2. vulnerability of a system to a potential supply disruption.
19 Critical Materials for Sustainable Energy Applications **2011**	Fromer N et al, Resnick Intitute, USA	Critical materials	A material with: 1. high importance to clean energy economy, i.e. it has one or more properties that appear to be physically essential for the performance of the system; 2. some uncertainty or risk in the supply.
20 Energy Critical Elements: Securing Materials for Emerging Technologies **2011**	Jaffe R et al, American Physical Society & Materials Research Society, USA	Energy critical elements	The term 'energy-critical element' is used to describe a class of chemical elements that currently appears critical to one or more new energy-related technologies. More specifically: 1. elements that have not been widely extracted, traded, or utilized in the past; 2. Elements that could significantly inhibit large-scale deployment of the new energy-related technologies.
21 Study on Rare Earths and Their Recycling, Final Report for The Greens/EFA Group in the European Parliament, **2011**	Schüler D et al, Öko-Institut e.V., Darmstadt, Germany	Critical metals	A metal with: 1. high demand growth; 2. high supply risks; 3. recycling restrictions.
22 Methodology of Metal Criticality Determination, **2011**	Thomas E. Graedel, et al., Yale University, USA	Metal criticality	The degree of criticality of the metals of the periodic table; 1. supply risk,

			2. environmental implications, and 3. vulnerability to supply restriction
23 Material Efficiency: An economic perspective, **2012**	Söderholm P & Tilton J E, Journal of Resources, Conservation and Recycling, USA	Material Scarcity	1.Material availability 2.short-term scarcity 3.Long term resource depletion
24 Resource Security Action Plan: Making the most of valuable materials, **2012**	Department for Environment, Food and Rural Affairs, United Kingdom	Resource security; Critical resources; Resource risks; Critical materials	Risk to business – multiple and varied factors.
25 Materials and the Environment – eco-informed materials choice, 2nd ed, **2012**	Michael F. Ashby Butterworth-Heinemann, United Kingdom	Resource criticality Scarcity Strategic materials Materials-energy- carbon triangle	Material sustainability – flows of energy, biomass and materials
26 Critical materials and The Netherlands – a view from the industrial - technological sector **2012**	Bol & Bastein, M2i & TNO. Translated from Dutch by: Moerland-Masic I and Peck D, The Netherlands	Critical materials	Metals and industrial minerals, crucial to modern society, decreasing as a result of increasing demand combined with a range of geopolitical complications.
27 The omnivorous diet of modern technology, **2013**	Greenfield A & Graedel T E, Resources, Conservation and Recycling 74 2013 1– 7 [4] USA	elemental scarcity, metal criticality, material constraint	Materials & Elements: biophysical, political, increasing population, increasing wealth, declining ore deposits, minerals widely dispersed.
28 Material efficiency: rare and critical Metals, **2013**	Ayres R U, Talens Peiró L. Phil Trans R Soc A 371: 20110563.USA http://dx.doi.org/10.1098/rsta.2011.0563	Critical Materials	Metals that are: 1.Geologically scarce 2. Subject to potential supply constraints 3. Costly 4. Economically important 5. Difficult to substitute
29 Report on Critical Raw Materials for the EU. **2014**	Report of the Ad hoc Working Group on defining critical raw materials, Mattia Pellegrini (WG chair), European Commission, DG Enterprise and Industry, May 2014	Critical Materials	Critical when risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials. Assessment components: •Economic importance

			•Supply risk and environmental country risk Features: •Pragmatic approach •Indicators-based •Dynamic concept •Primary and secondary raw materials

3.6.1 Results of the literature analysis

The graph in Figure 26 shows the results of the literature review on the 29 publications shown in Table 5. The first 5 bars, coloured blue, show the country or region of main origin of the publication. The next three bars, coloured red, show the word used in the term. The final seven bars, coloured green, show the main words used in the definitions (Peck, et al, 2015).

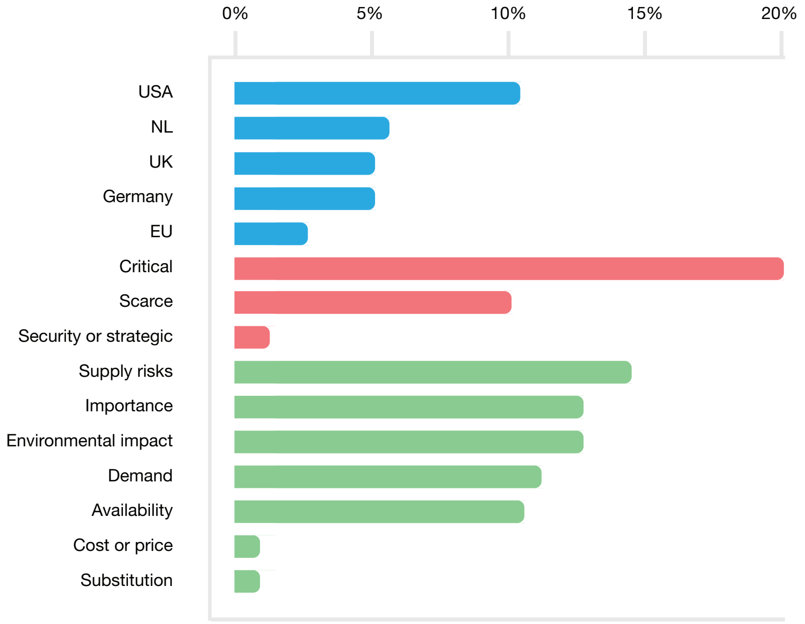


Figure 26 Graph showing the results of the literature review.

3.6.2 The country or region of publication

The USA has the highest number of publications in the selected literature, with half of the total coming out before 2009. The EU is a union of sovereign countries and no journal papers are published from EU. The publications do not cover every year with a number of years missing. An example of this is 2004 to 2008. There was a publication in these years but as the same authors published again with no change in term or definition, the publication has not been used. There were publications in every year from

2009 onwards. The number of publications (in the English language) peaked in 2011 (Peck, et al, 2015).

3.6.3 Scarce or critical – name used

Out of the 29 reports and papers reviewed, 20 used the term *critical* (metal, mineral or material). The second most used term being *scarce / scarcity* (metal, mineral or material), which was observed 10 times. In 2 cases both terms were used in the same definition. The security / strategic term was used only by the UK. The term scarce was used more in earlier publications (Peck, et al, 2015).

It should be noted that the elements, materials, metals and/or minerals being defined as either critical or scarce (or other terms) were wide and varied. So not only were the terms and definitions varied but the nature of the substance (elements, materials, metals and/or minerals) varied as well (Peck, et al, 2015).

3.6.4 The descriptor used:

The highest common factor in the definitions given is *supply risk*. This aspect was given in 14 of the publications. Following this is the use of *high economic importance* and *environmental impact* in the definition which was given in both cases, in 12 of the publications. Issues around *demand* were used 7 times. The only other issue in the definitions more widely used was around *availability* which came up 6 times (Peck, et al, 2015).

Issues around *cost, prices, substitution and alternatives* were raised in two of the publications. None of the publications used the term *product or end use* either in the term or definition. All of the publications do discuss the importance of *product* and *end use* to a greater or lesser degree in the body of text – but not in the term or definition (Peck, et al, 2015).

3.7 A definition of critical materials from a product design perspective

The review of current critical material definitions highlights the lack of involvement of product designers regarding critical materials definitions. There is a further challenge which revolves around the discussion of the term *elements* when the product designer uses the term *materials*. It is around the function of a technology and not the elements within it. The critical materials literature has mainly been developed by industrial ecologists, economists, material scientists, mining engineers, international relations experts, etc. and has seen far less contribution and involvement by product designers (Peck, et al, 2015).

From the analysis of the literature a new definition for critical materials for product design was developed. To do this the following key points are important:

Critical materials:

They are normally named as elements (from the periodic table of elements) and lists of which elements are affected are variable and regularly change. Lists of critical materials can change in different geographical contexts and different organisational contexts. Most are metals. Critical materials facilitate a unique performance to be attained. Critical materials play an important role in parts and components making them, for example, lighter, stronger, smaller, higher performance and have delivered radical new technology innovations that the product user values (Peck, et al, 2015).

Critical materials are subject to supply challenges. This can include price volatility, quality changes, supply delays (and oversupply) and potentially - supply stops. Demand for critical materials can be high. The supply and prices of critical materials are subject to a complex and dynamic range of forces including both political and geopolitical (Peck, et al, 2015).

Critical materials cannot easily be substituted (substance for substance) with a less critical alternative, to achieve the physical or chemical properties that are wanted, because of the cost and time required. This narrow definition of substitution (substance for substance) is normally used. The substitution of critical materials, quantity reduction and recycling of critical materials from end of life product, is technically, scientifically and economically challenging (Peck, et al, 2015).

In addition to the narrow substance for substance definition of substitution there are other complimentary substitution options. These are: changes to processes (process for process), new technology (engineering) approaches (new technology for substance) and the introduction of a service to replace new products (service for product). Service for product includes reuse, remanufacturing and recycling activities (CRM_InnoNet, 2014) (Peck, et al, 2015).

As with all metals, primary and secondary extraction and processing of critical materials have environmental impacts, but the use of critical materials can also provide opportunities to significantly reduce environmental impacts during product use and critical material use should not be automatically avoided (Peck, et al, 2015).

From these points the following generic definition for product designers has been developed. The structure of the definition follows the literature main points outlined above. In addition the definition has also been written in a style more attuned to product designers:

Title: Critical materials for product designers;
Critical materials are elements from the periodic table of elements (metals / rare earths) that may be at risk of price volatility and supply restrictions. They are applied through the selection of parts and materials during the product design process and that are often

present in small quantities in technology products, providing unique performance characteristics, that the product depends on and the user highly values. Physical material substitution usually changes a product's properties and / or performance. Substitution of a critical material can entail high financial / environmental costs and can take a long time (Peck, et al, 2015).

3.8 Chapter 3 conclusion

This chapter has highlighted that there is a generic description of critical materials which has been developed in the 21st century which has the common theme of the two axis graph showing a scale of the importance of a material against the risk of disruption of supply. Concerns over price volatility and supply are relatively recent and given the complexity of the subject it is not surprising that knowledge and understanding is poorly developed in the field of product design (Peck, et al, 2015).

It is clear that the majority of the definitions were not written for product designers – but increasingly they are being 'tasked' to help to 'fix' the challenge, as seen in UK and EU documents. Critical materials literature that engages with the topic of product design comes from both Ashby and Allwood. There is a range of accepted approaches towards materials in product design which excludes critical materials thinking (Peck, et al, 2015).

Research question 2 asks; How can critical materials be defined within the context of product design? This chapter has put forward a definition which, includes all of the key points raised in the literature. It is hoped that others will challenge this definition and work to develop it further as the challenges and opportunities, that critical materials presents to the field of product design, unfolds (Peck, et al, 2015).

The next chapter addresses how companies are responding to critical materials risks and will conclude with the role product design is playing in that response.

Note: This chapter has been developed from: Peck. D, Kandachar. P, Tempelman, E, *Critical materials from a product design perspective*, Journal of Materials and Design, Volume 65, January 2015, Pages 147–159. This journal paper was 70% written by Peck and this chapter is a further development from the paper.

4 Critical material awareness and responses in companies

4.1 Introduction – background

The chapter 3 review of the critical materials literature, covering the period 1999 to 2014, outlines the important role of product design in both contributing to and helping to solve critical material problems. It is unclear from the literature if responses to critical materials problems in product producing companies includes product design strategies. In order to understand how product producing companies are responding to critical materials problems, research was conducted.

The product producing companies are cautious about publically stating any position on critical materials. As David S Abraham states *'..metals…mired in obscurity and secrecy (where) companies.. often conceal their use, behind a veil of patents and trade secrets'* (Abraham, 2015, p xi). For many companies it is the critical materials that provide, as Steve Jobs stated, 'the magic' in their products (Abraham, 2015, p 2). It is also this 'magic' which provides the competitive advantage for a company, allowing them to outperform their competitors. It is normal practice for companies to carefully protect their intellectual property, as such knowledge could give a competitor an advantage. Equally, given the problems associated with critical materials it is not in the companies' best interests to state there may be critical materials problems associated with their products, as it may raise concerns with shareholders or investors. This includes legal requirements to have an understanding of materials used in products.

This chapter addresses sub-research question 3:

How are companies responding to critical materials?

The question presented a combination of challenges for the research; the possible lack of understanding of critical materials in the companies, combined with concerns over confidentiality. The research was developed to overcome both of these challenges.

There is limited published literature concerning how companies are responding to critical materials problems. As the literature review in chapter three shows most critical materials research has been conducted by either governmental or scientific organisations, with a focus on the fields of geo-sciences, mining, industrial ecology, etc. The term 'product' in this chapter applies to both the material 'product' and the end product. The 'end product' includes parts, sub-assemblies and the fully assembled product.

The research was conducted by a consortium of partners, closely geographically situated within the Netherlands and consisting of M2i (Derk Bol, Hans Christ) and TNO (Ton Bastein, Niels van Loon, Gerrit Oosterhuis). The third research partner was Delft University of Technology, Faculty of Industrial Design Engineering. The team leaders were Derk Bol, Ton Bastein and David Peck. This research project formed the basis of the masters graduation project of Ivana Moerland-Mašić (under the supervision of David Peck and Conny Bakker), and this chapter builds on her work extensively (Moerland-Mašić, 2012), (Bol & Bastein, 2012).

This chapter will present the research method. The method of data gathering will be explained, as well as the reasoning behind the choice for this method. In the following section, the nature and origin of the participants will be explained. No names or personal data of the participants will be shown, in order to guarantee the agreed confidentiality of the participants. The penultimate section in this chapter will elaborate on the execution of the data gathering and results analysis. In the chapter conclusions the links to other aspects of this thesis are highlighted.

4.2 Method

This section shows the method chosen for this research and is developed from Stephen Potter, *Doing Postgraduate Research* (Potter, 2006). This section also elaborates on how a questionnaire was used to prepare for interview, the action plan, time schedule and the team behind the data gathering process.

4.2.1 Choice of data collection method

The three organisations M2i, TNO and TUD were commissioned by FME to conduct the research, who were in turn funded by Dutch government funding. Following the establishment of a budget for the research a series of research planning meetings took place to detail the research work and at an early stage the choice of data collection was carefully made. This approach was important because the research challenge presented a number of difficulties as shown in table 6 below:

Table 6 The research challenges and solution deployed

Challenge	Solution approach
1. The bias challenge. The product producing company understanding of the critical materials field is at an early stage. As shown in chapter	The research team decided to develop a questionnaire which would not be required to be filled in by the respondent. The questionnaire was sent out before the face

three, the subject is complex and open to interpretation. This would mean there would have to be an explanation given and boundaries set with the research participants. This in turn is highly likely to create bias. In other words the researcher explains what the topic is all about, asks questions and gets back what he / she explained in the first place.	to face interviews. The interviews were structured around the questionnaire. This allowed the respondent to see the type of questions which would be asked and prepare accordingly. There was a second aspect to this approach. By seeing what critical materials are from the questions it might help focus the responses on the materials which are deemed, by the EU, to be critical.
2. The problem of confidentiality and intellectual property. The details of the knowledge held by the company about the materials composition of the parts in their products is of high value and may not be openly discussed. The same is true of their suppliers.	The use of a 'trusted intermediary' was deployed in the form of the initial contact being by FME-CWM. Signed confidentiality forms were then provided.
3. Possible shortage of experts with critical materials knowledge to be interview participants. The number of materials experts in product producing companies has reduced as the skills and knowledge are pushed upstream in the supply chain. This corresponds to a contraction in subjects like materials science in Dutch (and European) universities.	This relates to the bias challenge (1) above. The method used to overcome lack of knowledge was the pre-interview questionnaire to allow for preparation and the request by FME-CWM for the companies to provide the most suited respondents.
4. Sensitive price information for materials. Even though	Exact prices were not needed – only if they are going up, down or stable. Asking this

confidentiality agreements would be signed the companies would not disclose exact prices paid for materials. Such information would be too time consuming for the companies to obtain and process.	solved the problem.

It was determined that the data is to be gathered by means of interview, guided by a pre-questionnaire, see Appendix 1. A number of factors supported this choice of data collection. This includes not only the considerations shown in table 4 above but also; project time constraints, the skills and experience of the research team, research budget, number of participants and the time the participants could give (Kumar, 2005).

There are various approaches in administer a questionnaire, as shown in figure 27, below. Due to the issues raised above it was decided by the research team that questionnaire administration needs to be conducted face-to-face in the form of a structured interview. In case of a face-to-face administration of an questionnaire, the interviewer can clarify any parts of the questionnaire.

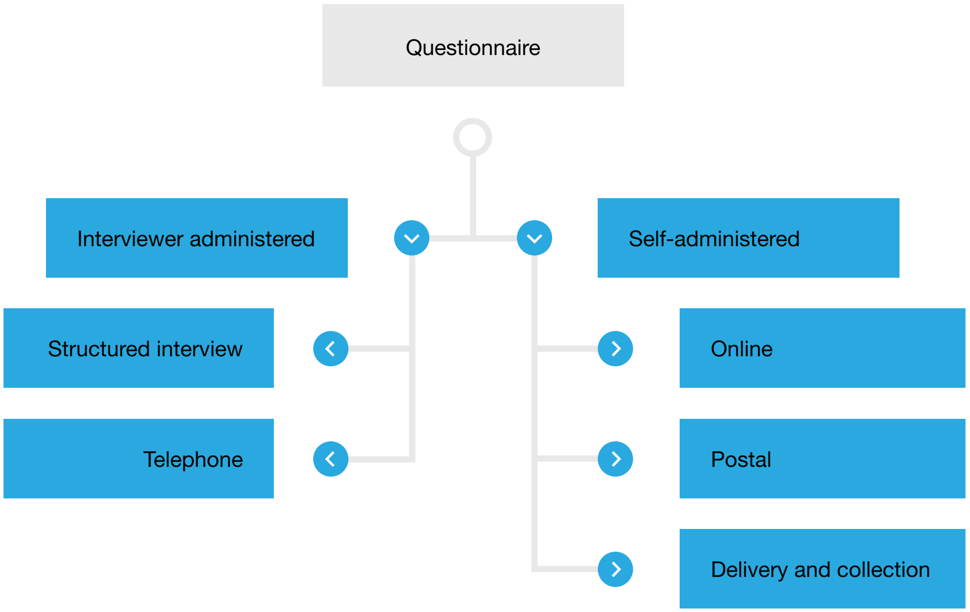


Figure 27: Types of research using questionnaires (Saunders, 2003)

An important advantage of a structured interview is that it ensures comparability of the data (Groves et al., 2009), (Kumar, 2005). Due to the fact that the interview questions are predetermined by the questionnaire and all questions are asked in the same order, data can be more easily compared. Another advantage is the personal contact the interviewer has with the participant which can often lead to deeper insights being shared.

Many of the participants would not have a full understanding of what critical materials are. The team discussed producing a pre-interview information pack to inform the participants but it was realised that this could heavily bias the responses and generate the bias as raised in table 4. A questionnaire was therefore chosen as a way of raising pre-interview awareness and allowing the participant to prepare, but not of producing a strong bias. Participants were told they did not need to return a filled in questionnaire but to use it to provide a guide to the interview. Participants could fill it in / make notes on them and these were collected at interview for cross checking with the interview responses. No other background information was provided.

4.2.2 Research planning

The research was conducted in 4 phases and the planning was as follows:

- Preparation phase - weeks 35 - 39
- Pilot - Interviews - week 40
- Company Interviews - week 41 - 45
- Reporting - week 45 - 49

(Bol, 2011)

4.2.3 The questionnaire design

The questionnaire contained five categories. These categories were developed to answer the questions the funder had on the topic. Knowledge around historical responses was confined to activity going back 5 years (2008 onwards).

The five categories are as follows:

1. Familiarity with the term "critical materials" in the company

   This is an introductory section in the questionnaire. It helps to introduce the participant to the subject, but more importantly it provides data on the awareness of the participant concerning the subject.

2. Role of critical materials in the company

   In this section, questions are asked concerning use of critical materials in the company. This provides an overview of the critical materials most used in the company, but also an insight if the defined materials are indeed really seen as critical by the companies and whether the term “critical” is interpreted by the companies in the same way as the literature.

3. Risk-management and critical materials

   This asks if critical materials are considered in the risk management activities of the company. This can be a strong indicator of the awareness and understanding of the company concerning the subject.

4. Business and critical materials

   The readiness of the company to react to the risks posed by critical materials can be seen in the strategic planning over defined timescales. Therefore, this section deals with business opportunities & threats and the role of the critical materials.

5. Support concerning critical materials

As a result of the complexity of critical materials no company is capable of dealing with the subject totally independently. In order for others to effectively support the companies, it is necessary to understand the kind of support that is sought.

The questions posed in the questionnaire and administered in the interviews, can be categorised into three different types:

1. Open ended questions with text boxes which the interviewer can fill in.
2. Multiple choice questions.
3. Ranking questions, using Likert scales.

Considering the number of participants and the challenge of the subsequent analysis of the data that was collected, it was initially felt by the research team that only the multiple choice and Likert scale questions would be used. It was expected, however, that for many participants the topic would be unfamiliar and that the participant responses would be lost if open ended questions were not used. It was therefore decided to use open-ended questions.

4.2.4 Conducting the interviews.

As all the interviewers and respondents were Dutch speakers, the interviews were all conducted in Dutch. In order to maximise the budget allocated for the research and speed the data gathering phase, it was decided that the interviews be conducted in parallel to one another, by multiple teams of interviewers.

There were however some drawbacks to this approach which had to be accounted for. For example the research design sought to minimize the risk of interviewer bias by having teams of interviewers. There is however the risk that one team interprets a question in a different way to another team (Groves et al., 2009), (Kumar, 2005). This can be mitigated by staying close to the structure and questions in the questionnaire and using a set of written instructions. The instructions, which are shown in appendix 2, served as a guideline to help the interviewers correctly and consistently conduct the interviews, with a minimum of bias and to ensure the generation of sound and comparable data.

Interviews were conducted on the company premises. Each interview took approximately one and a half hours.

The total data collected from each interview was in the form of an audio recording (later transcribed), a completed questionnaire (done in notes on the questionnaire pages by the interviewer) and the general notes of the interviewers (usually on the questionnaire pages as well). These was processed and analysed according to the method explained later in this chapter.

4.2.5 Participants from both researchers and companies

The research was conducted by a consortium of partners, closely geographically situated within the Netherlands and consisting of M2i (Derk Bol, Hans Christ) and TNO (Ton Bastein, Niels van Loon, Gerrit Oosterhuis). M2i was supported by the Faculty of Industrial Design Engineering at Delft University of Technology (Ivana Moerland-Mašić, under guidance of David Peck and Conny Bakker). This research formed the basis of the masters graduation project of Ivana Moerland-Mašić. The team leaders were Derk Bol, Ton Bastein and David Peck. As all the interviews were conducted in Dutch David Peck did not take part, but all preparation and post-analysis fully involved David Peck.

The research was commissioned by Vereniging FME-CWM (FME: an industry representative body in the Netherlands) and financially supported by AgentschapNL, which is a Dutch governmental agency from the Ministry of economic affairs, agriculture and innovation. The research objective was to gain a better understanding of company awareness of, and responses to, critical materials. With a view to acquire a representative sample, a spread of companies over a variety of sectors and at different places in the materials supply chain, were selected.

All the participating companies are member companies of FME. Prior to this project, FME held an annual meeting where all member companies (300+) are invited to receive an update on recent developments in a variety of fields of company interest. During this meeting, member companies were asked whether the subject of material criticality had their interest and whether they would like to participate in an in-depth study concerning the subject. The companies that expressed an interest in participation were contacted after the event by FME. There were in total 56 companies contacted in order to arrange the interviews. This initial contact was made to the most senior company person possible. In most cases this was the managing director for the business in the Netherlands. For many companies the expression of interest did not translate into firming up on interviews and 32 companies agreed to participate. The 32 companies were deemed by FME to be suitable for the interviews according to the scope of the M2i-TNO-TUD project. As is often the case in research, not all 32 companies followed through on their initial agreement to actually participate in the research and 6 dropped out, which meant that that additional companies had to be contacted in order to have the desired 32 participants. The intention was to ensure that a wide spread of sectors were represented in the research, as determined by M2i-TNO-TUD, but the need to find alternative companies meant that this intention was not to be fully realised. This event did have a fortunate consequence from a research perspective. The original list of companies generated were dominated by the most likely candidates to have something to say on critical materials, the so-called ‘usual suspects’. The need to supplement the candidate list with companies found on a more random basis helped to reduce the bias in the results. The final total of companies interviewed was 29. An overview of the participants can be seen in table 7 below.

Table 7. Participants in the research on critical materials.

Company type	Description	Product examples
Material producers	Processed raw materials	Copper (bar, wire)
Component producers	Producing components (mostly B2B market), using metals, basic metals and intermediate goods	Electronics, LED's
Sub-assemblers	Producing subassemblies: more complex assemblies	Computing, lighting
Producers	Producing relatively simple products, with relatively simple supply chain	Domestic appliances, electric tools
Integrators	Producing complex products and equipment (OEM) with a complex supply chain	Medical equipment, production systems

An administrative team from FME contacted the senior person in the company to facilitate finding the right person for an appointment for the interview. It was important for FME to make these arrangements with the companies, as they were deemed by the company as trustworthy and would provide the company with value for the time invested. A major advantage of this approach was the very high response rate. In this first contact a basic outline of the research was provided. The administrators were not in the core research team and had limited knowledge and therefore could not bias the participant with too much information.

Once an appointment was made, an e-mail was sent to each company nominated participant (some companies provided two people in the interview), containing the confirmation of the appointment, a copy of questionnaire and a set of instructions for the preparation for the interview. The instruction leaflet reminded the participant that the research would focus around a chosen product / product group from their company. This product(s) would be selected by them, in consultation with the researchers, during a telephone conversation prior to the main interview.

In order to help make the main interview more effective, participants were asked to read through the questionnaire beforehand and to gather the necessary information as required. This would include discussing the questions with colleagues. The questionnaire was not required to be filled in but many participants chose to do so in preparation for the interview.

Another aspect of preparation for the interviews was getting to know the participant. In many companies participants were chosen either because they belonged to a certain function (job title for example), or because they expressed an interest in the topic.

The functions of the participants who received the questionnaire and were interviewed varied in detail but fall into 2 distinct functional groups, with an even distribution across the companies:

- Technology / Engineering / Materials / Research & Development manager.
- Logistics / Supply chain / Purchasing manager.

This selection of participant(s) was done by the companies themselves following the initial agreement to take part during the FME meeting. This approach is connected with a concern highlighted earlier in this chapter about the lack of knowledgeable participants.

Details about the companies, the participants and their role cannot be revealed due to strict non-disclosure agreements which were required by the companies. There was concern from the companies that details of material supply knowledge could be interpreted by investors, suppliers, customers and regulators as ‘weaknesses’. This led to the requirement for legally binding non-disclosure agreements to be signed by all parties involved.

In this research each of the participants came from different companies from different sectors. In order to gain a deeper understanding of the participant, it was necessary for the interviewer to explore some background information concerning the participant. This in turn helped the research team gain an indication of the depth of knowledge on the topic in the company.

The research did not seek to ensure product designers were participants (the company chose the participant themselves) but all the companies design and manufacture products and all the participants were part of the wider design and production team as outlined in chapter 3. None of the participants who took part were named as product designers.

4.2.6 Data analysis method.

In this section the analysis methods are described. As outlined above, the interviews were executed in a semi-structured way, and three types of questions were asked:

1. Open ended questions with text boxes which the interviewer can fill in.
2. Multiple choice questions.

3. Ranking questions, using Likert scales.

Answers to open end questions can be extremely rich in in-depth insights. Such non-variable data is, however, very complex and almost impossible to compare in a raw form. In order to convert answers into useful data, text-coding was applied. The coding was done individually for each question. When applying text-coding, all the answers were reviewed and compared, in order to find reoccurring terms and sections of text, indicating the themes. After establishing these themes, the text was examined once again and the text divided into parts either containing a theme, or not. In this way, the full interconnected context of each individual set of answers is lost, but comparable text parts are gained, which can be used for data comparison. Due to the fact that more than one theme can occur in the answer, the acquired data has similar properties, comparable to that of multiple choice (response) questions.

The second type of question, multiple choice questions, were subdivided into two possible forms. One form is where the participants are allowed to choose only a single possible answer. The other form is where participants have the possibility of multiple answers to a single question.

The third type of question used in the questionnaire is the ranking question. Participants are asked to rank a certain variable, whether on a word scale, from for example; very bad to very good, or by assigning it a rank number, for example 1 for very important and 7 for least important. These questions are based on a Likert-scale.

The most straightforward form of analysis, univariate analysis, was used. Based on the results of the univariate analysis, patterns and groups can be seen.

4.2.7 Pilot interviews

There are several reasons for conducting a pilot study (Groves et al., 2009), not least of which is testing out the chosen research method. If there are significant problems, there is still a chance to make changes in order to perform valuable research.

There were five pilot interviews executed for this research. The first two pilots are conducted with two different individual students from TU Delft, at a very early stage of the questionnaire design. One student was from Aerospace Engineering and the other Industrial Design Engineering. Both had some knowledge in the topic. The aim of the pilots was to identify possible ambiguous and difficult questions and adapt or remove these from the questions (Peat et al., 2002). The input acquired from the participants led to simplifying certain questions in such a way that participants with lower levels of knowledge of critical materials can also answer the questions. The first two pilots also demonstrated that the method of structured interviews was the right choice for this research. It was demonstrated that it was possible to collect comparable data from the different interviews, due to the structured approach.

An additional two pilot interviews were conducted in a later stages of the questionnaire development, when the setup of the questionnaire was finished. The purpose of these pilots was to check whether the revised version of the questionnaire would work with company participants. These second pilot participants were both engineers, but neither of them were then working in an engineering field: one of them was a procurement manager at a software developing company and the other worked for a technology consulting agency. The feedback on the revised questionnaire was reassuringly positive. The questions were clear and even though none of the participants had the expertise to provide in-depth answers to the questions, they had no difficulty in understanding them. An important advice that came out, is that some of the sections in the questionnaire needed more face to face explanation than others.

The third and last pilot was executed with an operation manager employed in a large international company. The aim of this last pilot was to investigate whether the answers could be converted into data required for answering the research questions. This pilot confirmed the validity of the questions and the translation of the answers into the required data.

4.3 Data presentation and results

In this section, the data resulting from the administered interviews, is presented. The chapter begins by laying out the univariate analysis of the answers. This section is divided into sub-paragraphs according to the categories in which the questionnaire based is structured. In this way, an overview of the data is given. The answers to each question are visually represented by a graph or pie-chart, depending on the type of question.

The percentages in the graphs indicate which part of the participants have given that particular answer to the stated question. For questions that are of a multiple response type, the total percentage can add up to over 100%.

4.3.1 Familiarity with the term “critical materials” in the company

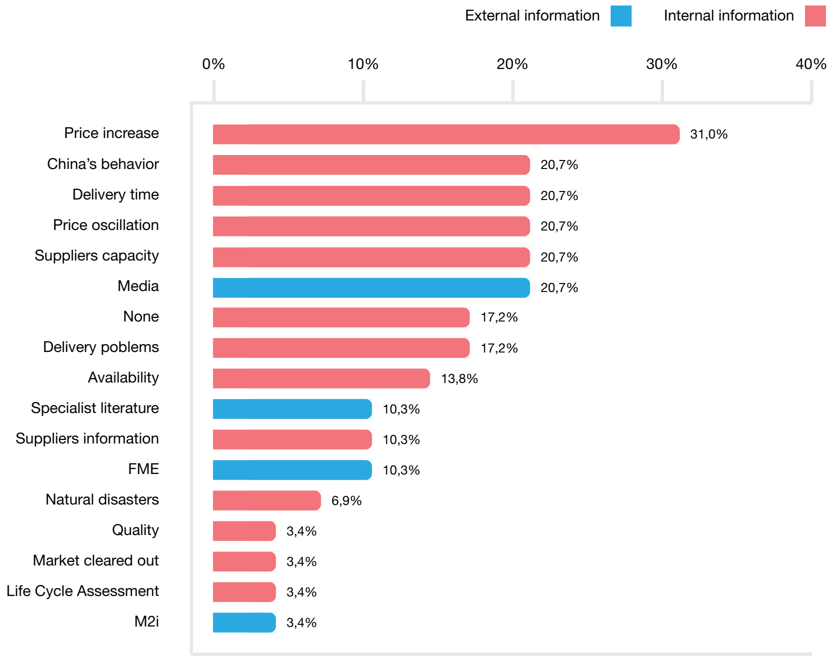


Figure 28: Q1.1 How has your company become aware of the problems concerning critical materials (material scarcity)? n=29

From the graph above (Q1.1), it can be seen that most of the companies indicate price increase as the awareness trigger for materials criticality. Note how both of the main terms ‘critical’ and ‘scarce’ are used in the question. It is also important to observe how supplier / delivery issues dominate when added together. Prices and delay in deliveries are key issues. Universities do not appear to raise awareness in the companies.

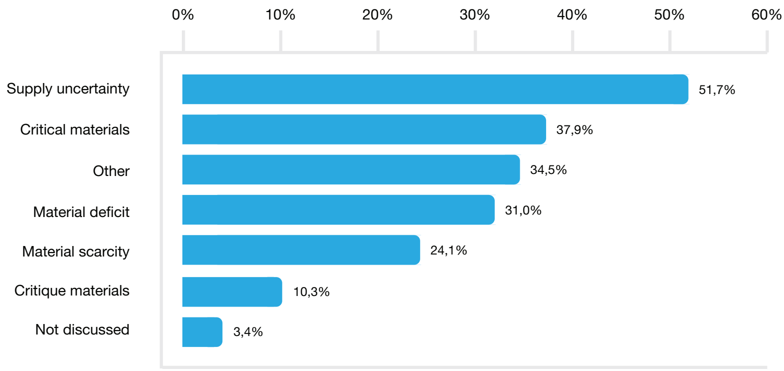


Figure 29: Q1.2 How does your company describe material shortages or critical materials? In other words, which terms are used to refer to this problem? (multiple answers possible) n=29

Figure 29 (Q1.2), shows a large proportion of the companies raised supply chain concerns. An example of this is the response “supply uncertainty”. In addition respondents that have indicated “other” spoke of stock outs or delivery delay. Material deficit is also interpreted by the participants as a problem of supply.

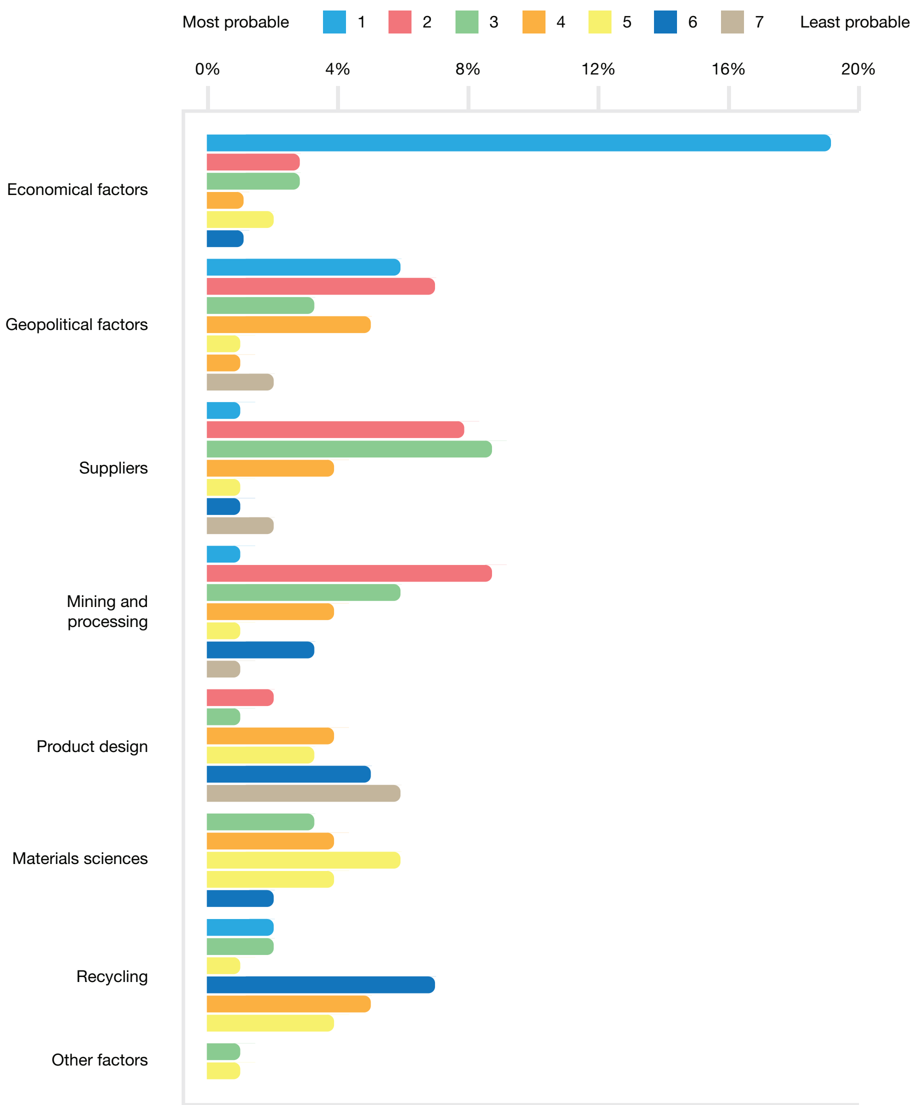


Figure 30: Q1.3: Indicate which factors you think have probably contributed to the emergence of critical materials. Rank the factors from 1 to 7, where 1 is the most probable cause and 7 is the least probable cause. n=29

This question introduces product design as an option. Four factors (product design, material sciences, recycling and other) have been ranked lower, with product design scoring highly as 'least probable'. Eight participants have filled in only the first two ranks, leaving out product design, material sciences, recycle and other completely. Economic factors are seen as the main cause.

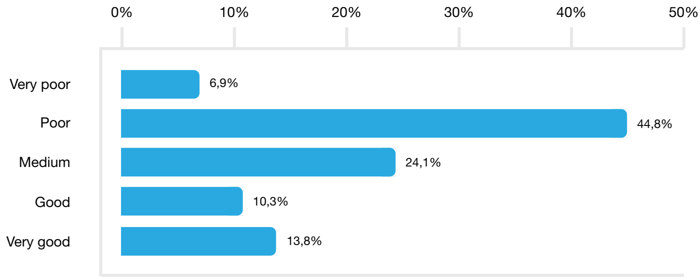


Figure 31: Q1.4: Place a cross on the scale shown below, as to how closely the developments in the field of material criticality are followed within your company. n=28

Question number four is of a single response type. The non-respondents are excluded from the question, which brings the total amount of the participants for this question to 28. The answers indicate that majority of participants estimate that the developments on the field of materials criticality are poorly followed. Only just under 25% estimate that the company's following of the field is good to very good.

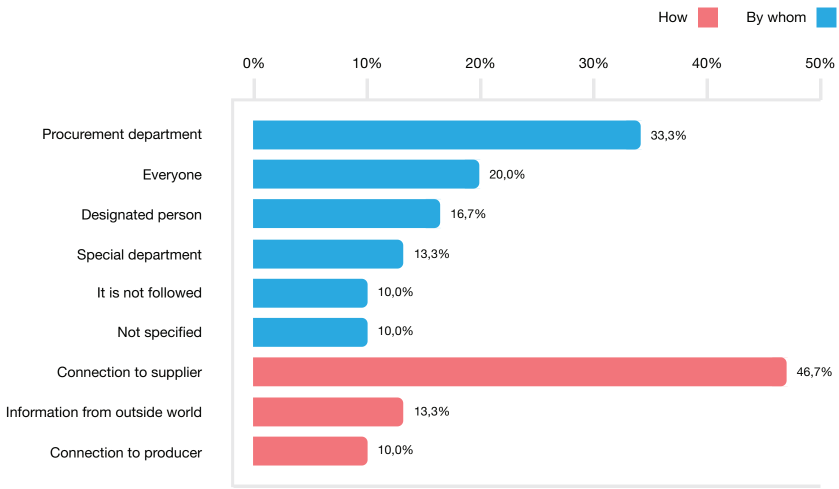


Figure 32: Q1.5 How (and by whom) are the developments followed within your company? n=29

This multiple-response question is a more in depth response to Q1.4.

From Q1.5 it was observed that for three companies the developments are not followed at all. In contrast, four companies have a special department, with some dedication to the subject. The majority of the companies use their procurement department to be kept informed on the subject. In the “how” part of the question the developments are found out from the supply chain. The three companies that are following developments from the outside world (media etc.) indicated to also do so from the suppliers.

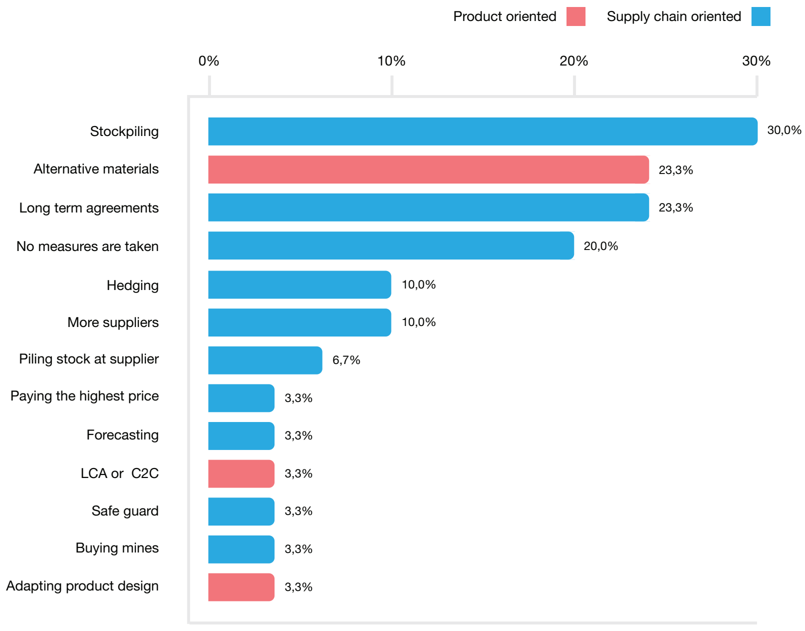


Figure 33: Q1.6: Can you name the measures your company has taken as a reaction to the problem of critical materials? n=29

Question 1.6 is an open-end question. Few participants have provided answers which indicate product design measures as a reaction to critical materials problems. Stockpiling is seen by most as the preferred option. Only one company was using life cycle analysis (LCA), combined with a cradle 2 cradle tm (C2C) approach, which included considering adapting the product design. Equally one company responded that buying a mine to secure supply as a response and it was their only response. The adopting the product design company and the LCA / C2C company were different companies.

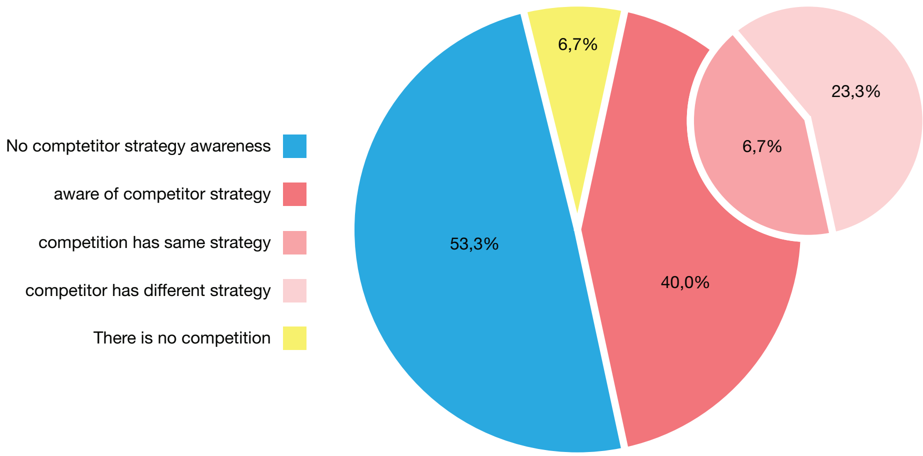


Figure 34: Q1.7: Are you familiar with the strategy of your competitors concerning critical materials? n=29

The participants could answer ”yes” or “no” to the question and elaborate on the answer, if they wanted to. Through the elaboration of the answer, a multiple-response set is created. Majority of the companies are not aware of the competitor strategy concerning materials criticality. Three of the participants which have declared not to be aware of the competitors strategy, have also declared they have no (direct) competitors. For those who said they were aware of a competitor strategy most said it was different to their own.

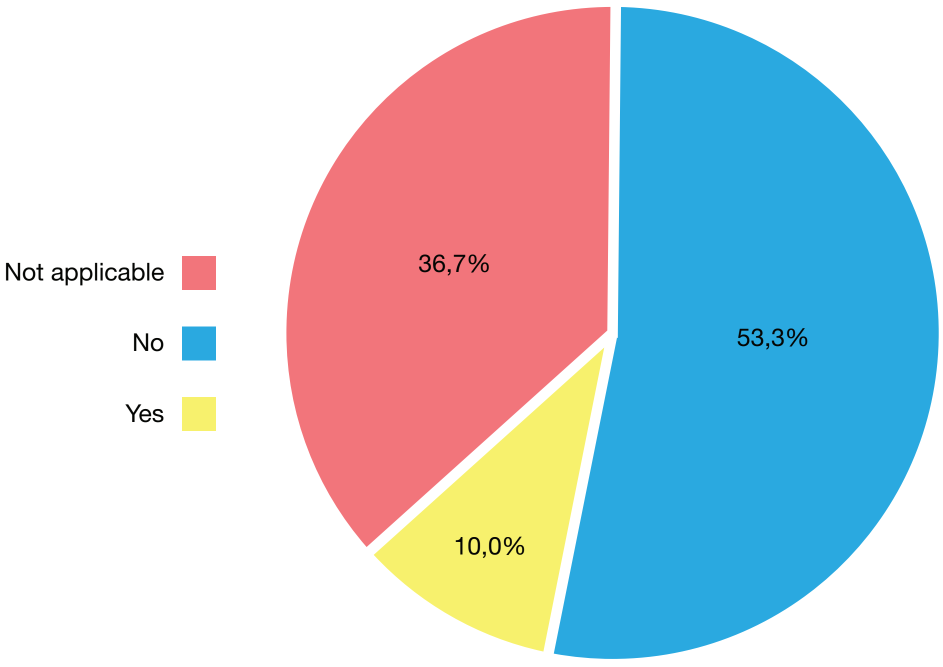


Figure 35: Q1.8: If so, does that affect the operations of your business? n=29

This question follows on from the previous question, and was of open-ended type.
Only 3 companies said the strategies of their competitors would affect their own operations.

4.3.2 Role of critical materials in the company

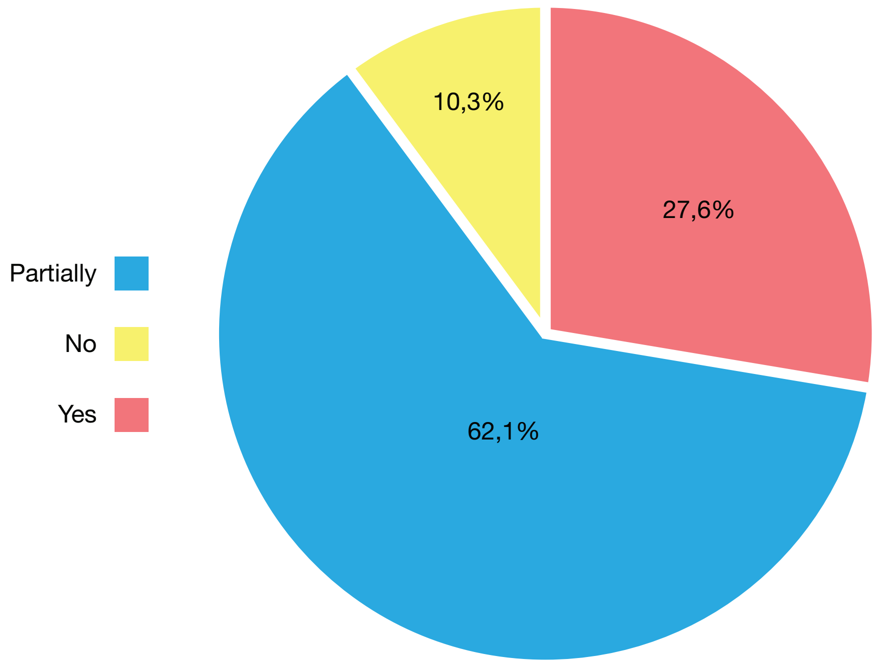


Figure 36: Q2.1: Can you name all components and parts, across the entire product range of your division or business, that contain critical materials? n=28

In this single response question, it is notable that only just over 10% of the participants have declared not to be able to name all the products containing critical materials in their company. Over 60% said they were partially able to answer.

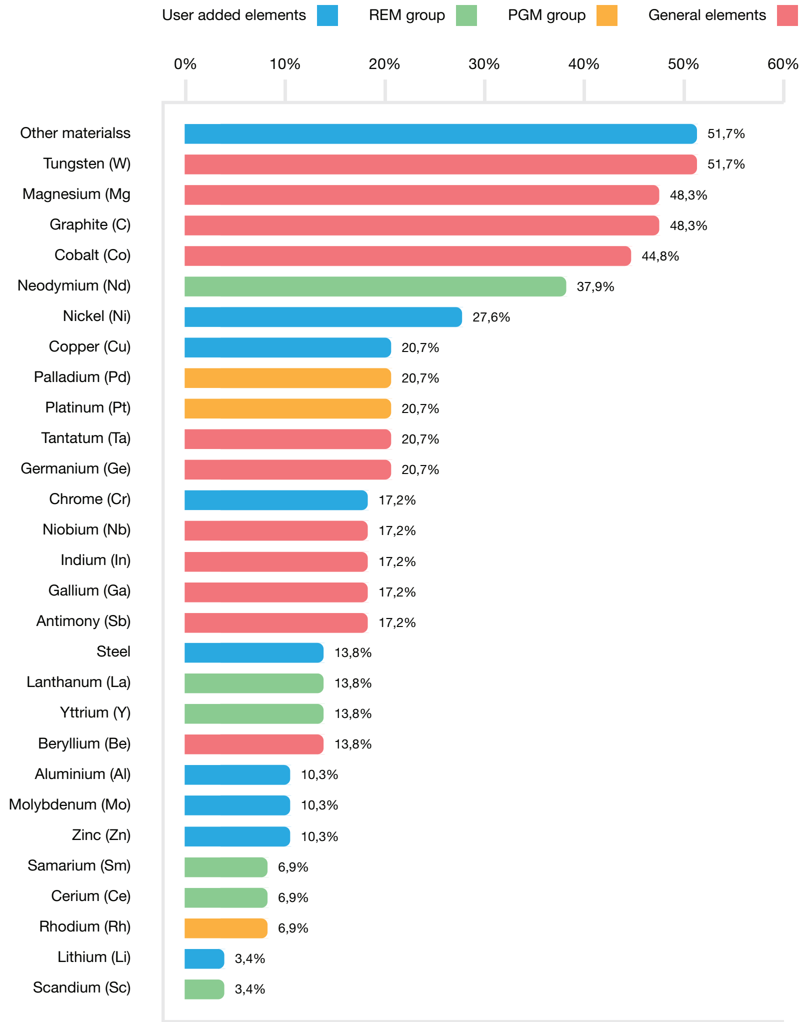


Figure 37: Q2.2: Which element(s) from tables below are used in the chosen product/product group? (More than one box may be ticked) n=27

As can be seen the elements most often mentioned to be used in the company products are tungsten (W), magnesium (Mg), graphite (C), and cobalt (Co), closely followed by neodymium (Nd). Many of the participants named materials are not listed as critical. The group “other materials” contains specific materials, like spring steel, rubber, alcohols and different bonding materials. In general, this group seems quite large, however each company has mostly added own specific material, important to their own specific business. No respondent ticked Promethium (Pm).

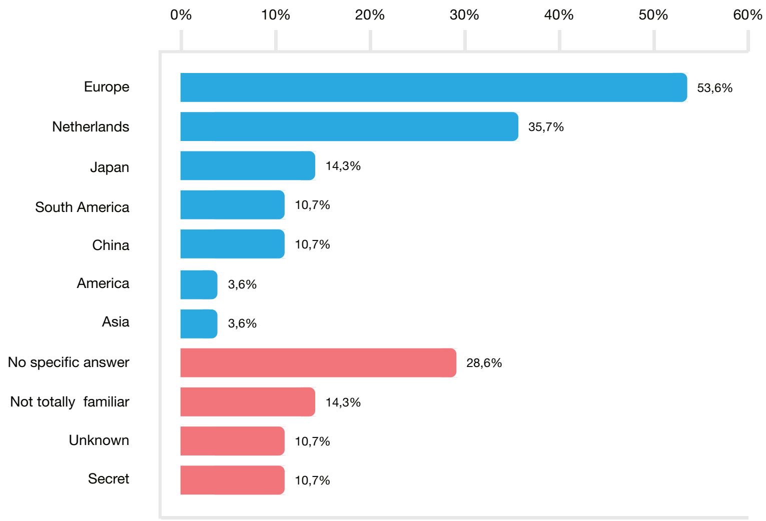


Figure 38: Q2.3: In the last question you have ticked several critical elements used in the product. Could you, for each element, state in which material it is used and which company (or any company) supplies to you?
Note: upper blue bars = supply origin, lower red bars = in which material it is used. n=29

Question 2.3 shows the results obtained for the part of question concerning the materials and suppliers. It can be observed that a significant number of the participants were not fully aware of the original origin of the critical materials they use. They either give no specific answer, said they were not familiar with the location, or named only the location of their immediate material supplier.
The respondents also did not appear to know which material the critical elements ended up in or it was a secret which even the confidentiality agreement could not cover.

Q2.4; In the table below, state three important critical materials in your company and indicate on a scale of 1 to 5 if the price of the materials has increased or decreased over the last 5 years. n=28

Q 2.5; On the table below, indicate, on a scale of 1 to 5, if the quantities, required by your company, has increased or decreased over the last 5 years. n=23

Scale: 1 = significant increase, 2 = increase, 3 = unchanged, 4 = decreased, 5 = significantly decreased

Table 8: Combination of Q2.4 and Q2.5:

Material	**Price**	**quantity**
Nd	1	2
C	2-3	3-4
Co	1-2	3
Pt	1-2	2
In	1	2
W	2	2
Sm	1	1
Ge	1	1
Sb	Not known	2

The ‘last 5 years’ would have meant the years 2007 to 2011. Out of twenty-six materials named as “critical” and named in response to this question by the companies, only nine are actually listed as critical materials. These nine are listed in the table. The table shows that the participants have indicated increases in both quantity and price for these materials.

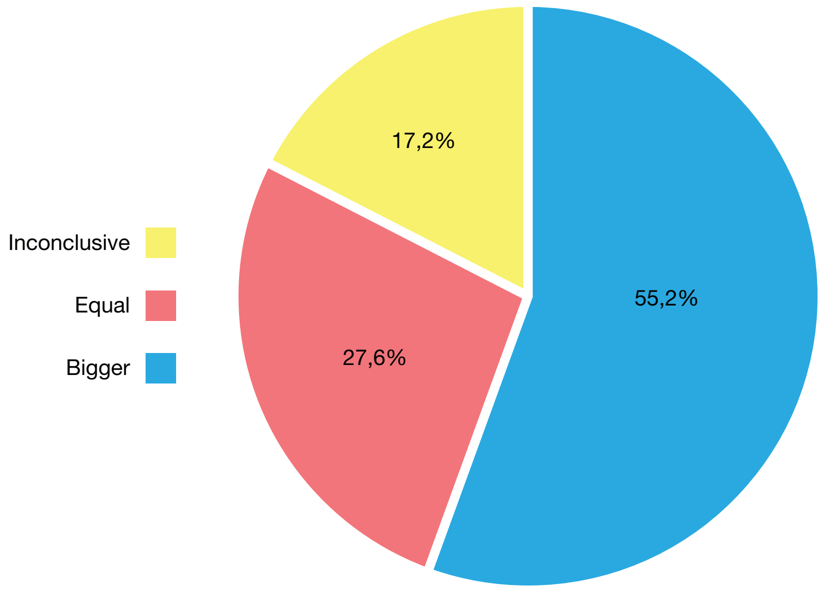


Figure 39: Q2.6 The question above asked about the role of critical materials in your current products. Do you expect, as a result of further product developments or new products, that the role of critical materials will become bigger or smaller? n=28

It appears that the majority of the participants believe that the role of critical materials will increase with the continuation of existing products and the development of new products. None responded ‘smaller’ even though the question gave this as an option.

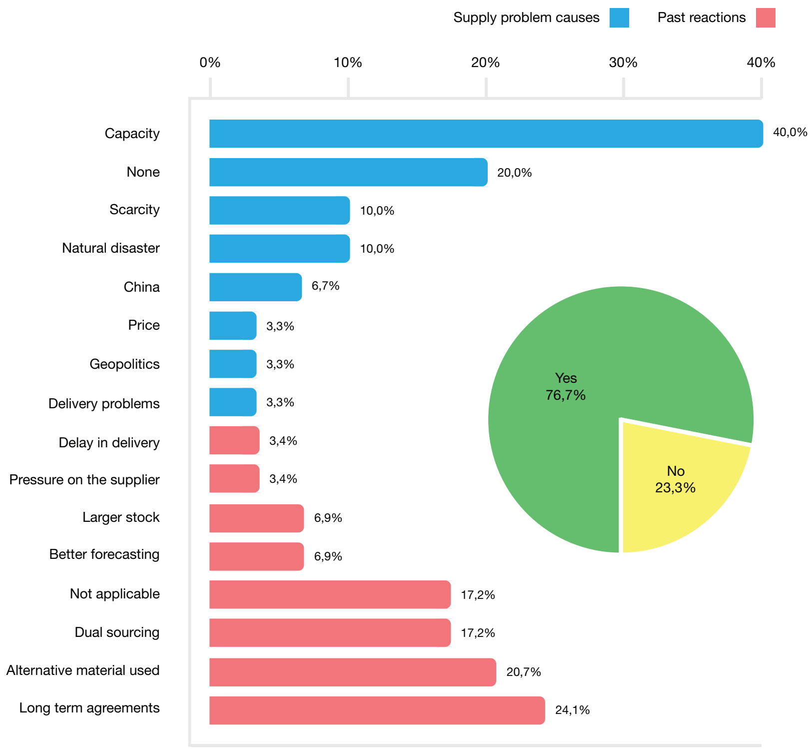


Figure 40: Q2.7 Did your company experience problems with the supply of critical materials over the last 5 years? (inset pie chart)
If yes, what, in your opinion, caused those difficulties? (top, blue bar chart)
If yes, what was the reaction of your company at that time? (lower, red bar chart)
n=29

This question was a ‘stage gate’ type. Firstly the pie chart shows the yes/no answer. The pie chart illustrates that about three quarter of the participants have experienced problems with supply of critical materials. The capacity of the supplier was deemed to be the largest cause. The materials were asked to be named and in only six cases the affected materials were on the EU critical materials list and none named the most critical materials. The reaction of most companies is to ensure stability of the supply chain by forming long term agreements with the suppliers. In the case where the response was to search for an alternative material, the materials were not on the EU critical materials list, and the materials sought were commercially available substitutes in easier to change applications. Changes to the product design was not named as a reaction but a material change may have resulted in a bill of materials change.

4.3.3 Risk-management and critical materials

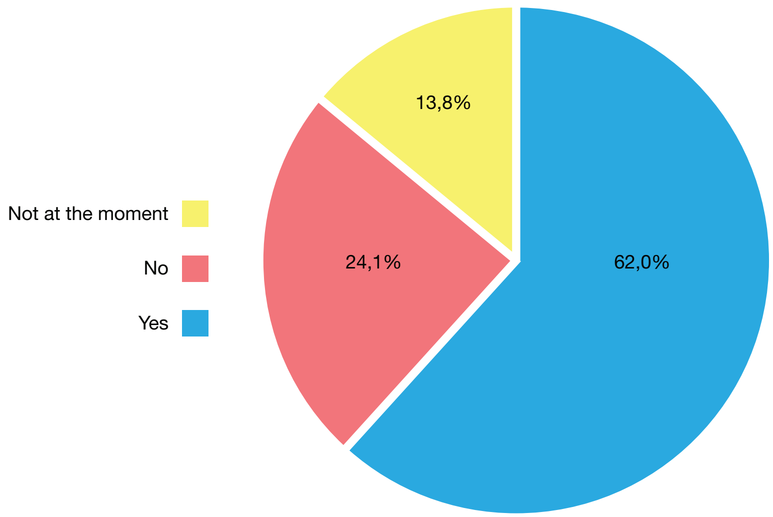


Figure 41: Q3.1 Do critical materials play a role in the risk management of the company? n=28

A majority of the participants said that critical materials play a role in the risk management of the company. A large minority, over a third, said it did not (not and not at the moment). n=28

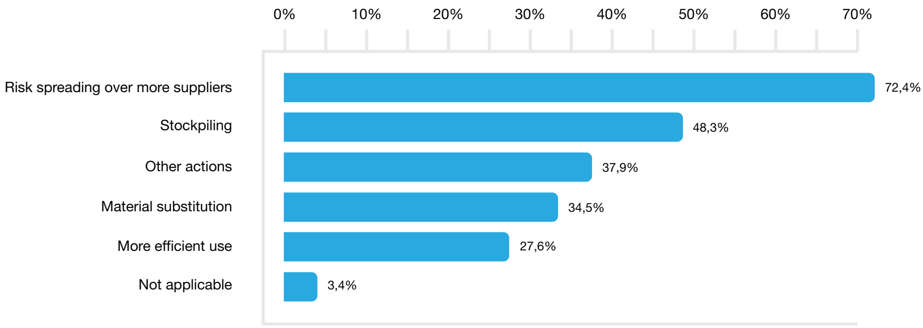


Figure 42: Q3.2 What (material-specific) actions have been/are taken in order to deal with critical materials? (Multiple answers possible) n=28

It can be seen that increasing the number of direct suppliers to spread the risk is seen as the preferred future strategy with stockpiling as second. More material substitution and efficient use could include product re-design, but the respondents indicated a preference for direct, one for one, material substitution and more efficient use through waste reduction measures.

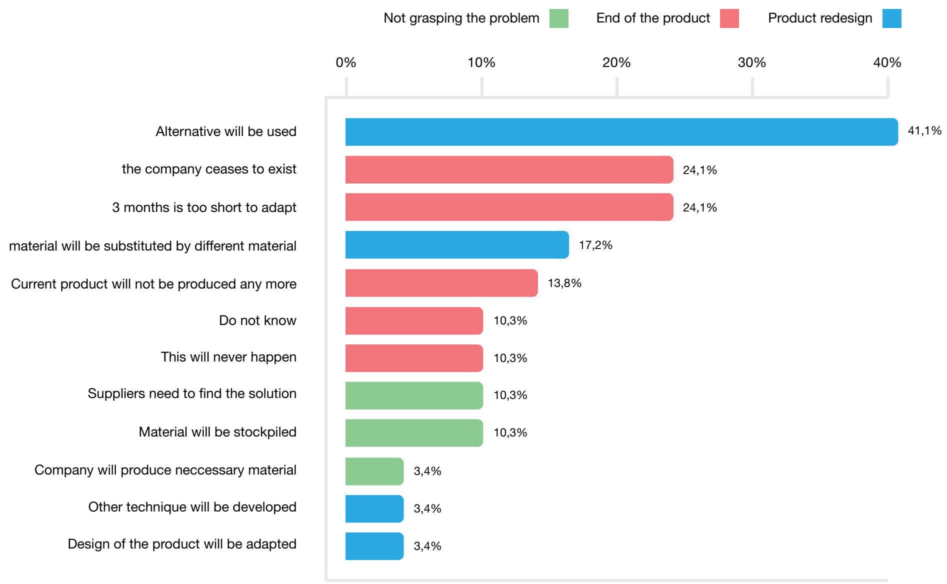


Figure 43 Q3.3 Imagine that one or more of the critical materials indicated by you in question 2.2, were to become unavailable in 3 months' time, what steps could your company take now to avoid possible problems? N=19

This question aimed to present the respondents with an extreme hypothetical future scenario concerning critical materials. Ten companies chose not to answer this hypothetical scenario producing the lowest response to any question. The majority who did respond went for an alternative material being used. The answers 'The company ceases to exist', 'Too short to adapt', 'product not produced anymore' and 'this will never happen', if brought together, show a majority feel that this scenario could not be addressed at all. One company proposed taking action by adapting the product design.

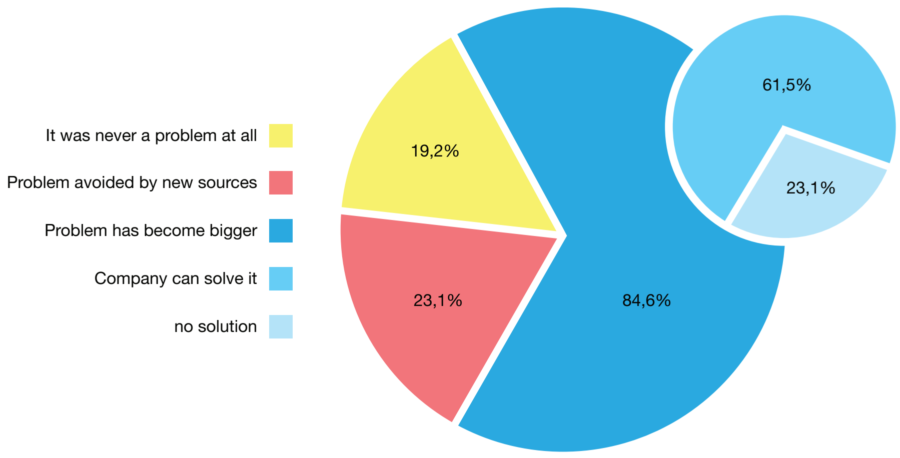


Figure 44: Q3.4 In the field of critical materials, what changes does your company expect within 3-5 years? n=26

Over 40% of the companies state that critical materials have never been a problem for them and / or any problem will be avoided by new sources of critical materials. A majority of the respondents expect that the problem of critical materials will have become bigger over the 3 to 5 year time frame (2012 to 2014-16). From those indicating that the problem has got bigger, the right hand pie chart shows that a majority feel confident that their companies have a critical materials risk solution. Only four companies thought the problem would get bigger and they did not have a solution.

4.3.4 Business and critical materials

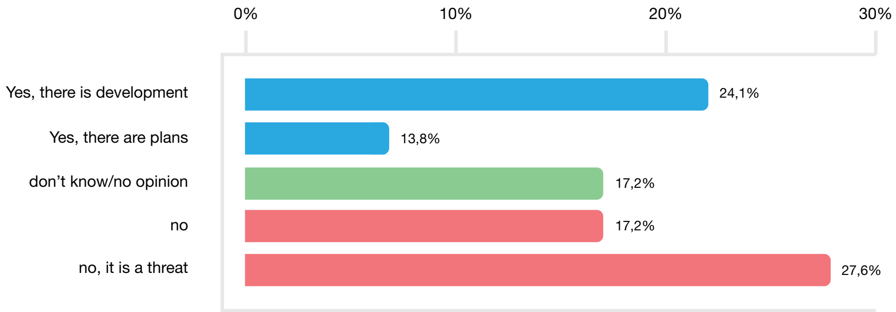


Figure 45: Q4.1 Does the company see any opportunities resulting from material criticality? n=28

The response to this question almost splits 40/60. Over a third of the respondents have indicated that they see business opportunities in critical materials, whether in the short or longer term. More see critical materials issues as a threat with a number unsure.

4.3.5 Support concerning critical materials

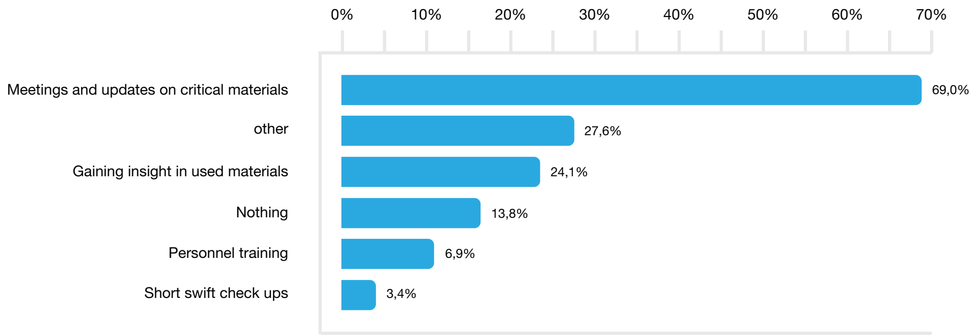


Figure 46: Q5.1 Which of the following options would your company like to use, to help reduce the risk from critical materials? n=28

This shows the support options the companies would like to have. Most, 19 companies, opted for meetings and updates on critical materials where the company could be passive and gain more knowledge and information thorough being informed. Under the ‘other’ two companies suggested cooperation with universities and other research organisations. Just under a quarter of the companies wanted more insight into which critical materials they are using in their business. A minority of companies indicated that support from outside is exaggerated and unnecessary. On the option of ‘Hiring experts on a long term basis to gain advice on strategy’, none of the companies indicated that as a course of action they would take.

4.4 Discussion of the results

4.4.1 Familiarity with the term "critical materials"

There are a number of key messages coming out of this first part – familiarity with critical materials. Critical Material risks is driven by an external series of events placed onto the company, most of which the respondents feel is well beyond the control of their company. The risk is seen through a range of events such as price increase, delivery time (delays), supplier capacity (lack of), delivery problems and price oscillation (fluctuations).

There appears to be a correlation between the terms used in the literature in chapter 3 and the terms used by the respondents. This could be explained by the terminology used in the questionnaire and interviews. The externality of the risks from critical materials were highlighted by the view that geopolitics, suppliers and mining concerns were responsible for the problems.

The majority of the companies are following developments in CRM 'poorly' in their opinion. When it is followed it is usually done by the procurement department and does not involve product designers. This purchaser-supplier focus is seen in the preferred responses - Stockpiling (in the participant company), long term agreements, more suppliers, stockpiling at the supplier, paying the highest price and safeguarding the supply chain are the chosen responses. Watching or benchmarking from competitors was not widely practised.

The role of product design is seen by only two of companies as relevant. LCA (Life Cycle Analysis) or C2C™ (Cradle 2 Cradle™) approaches was referred to as a reaction to the problem of critical materials but they do not actually change product designs. This same company said it would adapt the product design.The perceived drivers and responses to critical materials indicate that the costs and risks involved do not warrant product changes. The majority are taking appropriate responses until things return to 'normal'.

To summarize the companies see the changing risks of critical materials as something beyond their control but most do take some action. Product design is not a preferred choice of action to address critical materials problems.

4.4.2 Role of the critical materials

It appears the number of companies who are aware of the critical materials in their product is high but most did not really know what were critical materials and which were materials critical to their business. Out of twenty-six materials named as "critical" and selected by the companies, only the nine listed in the Q2.5 are actually within the EU critical materials list.The companies did not name all the critical materials in their products, even those who thought they knew them all.

During the interviews many of the participants said they had not ever heard of some of the materials on the questionnaire list. When asked where the critical materials came from most made reference to the direct supplier of the material but this was often just the top tier supplier to them. The respondents often included parts, sub-assemblies, alloy materials as well as elements. It is clear that the REE's (take Nd) for example did not originate from Europe or The Netherlands. What is notable is that Russia is not mentioned nor is any country in Africa.

Companies are very aware of the negative impact to their business of not having on time, to quality, to cost supply of materials, parts and sub-assemblies from their suppliers. There has been a movement over the past decades to take cost out of the supply chain and increase on-time, high quality supply. Approaches deriving from total quality management (TQM) thinking such as lean manufacturing, six sigma, Toyota total production system (to name a few), have all had a focus on the customer supplier relationship. The advent of highly automated supply management systems predicated on ICT innovations have supported this movement. All of this allows supply chains to be not only seemingly highly reliable but also global, complex and in many ways very opaque.

The increase of critical material content in the next generation of products is highlighted as the majority of the participants think that the role of critical materials will increase with the development of their new products. This indicates that they feel that it is not very likely that something will change much in the design of their products such as substitution or avoidance. The respondents indicated that one of the main reasons for this view is that increased electronics devices are expected to be used in a broad spectrum of their products. Some participants also said they were aware that renewable energy technologies rely on critical materials. None of the participants said that the role of critical materials will decrease due to new product developments.

Most said they had had some critical materials problems. Responses preferred included stockpiling, long term agreements and more suppliers.

4.4.3 Risk management and critical materials

When asked if critical materials play a role in the risk management of their company a majority of the respondents answered that it did. Given that the question really asks 'does the security of materials supply play a role in the risk management of your company?', it is surprising that nearly a quarter of the respondents answered 'no'. It is also clear that at this stage of the interview the majority of the respondents had indicated that critical materials were at risk of supply disruption.

It is interesting to note that when asked how well critical materials were followed the answers were that it is poorly followed in the company, and yet this poorly followed topic is being used by many as part of their risk management activity.

Given that the most likely person to be engaged in the topic of critical materials is a procurement person talking to a direct supplier, then the risk management responses may be somewhat limited. This is further compounded by the lack of knowledge about the source of critical materials and in which materials they are used and for what purpose.

When asked to *'Imagine that one or more of the critical materials indicated by you in question 2.2, were to become unavailable in 3 months' time, what steps could your company take now to avoid possible problems?'* this was the least responded to question. The majority opted for an alternative material being used, which in itself is usually, to some degree or other, a product redesign option. The selection of alternative or substitute materials suggests that there is a lack of awareness around alternatives and substitutes for the EU 14 CRM's. The answers 'The company ceases to exist', 'Too short to adapt', 'product not produced anymore' and 'this will never happen', if brought together show a majority feel that this scenario could not be addressed at all and therefore is not worth considering. Only one company said the design of the product would be adapted. This is interesting as the design of the product is one area over which the company has control and knowledge and yet it is, by most, not considered. Their design of the product is also the 'pull' that creates critical materials challenges, but this is also not acknowledged. Earlier in the interviews the option to adapt the product design was given as an option and most rejected that option. The one that did also said it would use LCA or C2C™.

Most of the companies felt the problem of critical materials would get bigger but that they themselves could handle it but most not through product design changes.

The risk management of the critical materials seems to be focused on maintaining a stable supply chain in most cases. This is in line with the observations made in the first category.

4.4.4 Business and critical materials

On balance, more companies see critical materials more as a threat than an opportunity. It is not clear if for those who see opportunities are basing their approaches around new business models and corresponding new product designs, but given that only two companies said they would consider changing product designs this seems unlikely. The responses to earlier questions seemed to indicate a focus around working with suppliers and stockpiling.

4.4.5 Support concerning critical materials

Most opted for meetings and updates on critical materials where the company could be passive and gain more knowledge and information without interaction. This could well reflect the reluctance around engaging with others outside the business on the topic. This is also supported by the rejection of the option of ‘Hiring experts on a long term basis to gain advice on strategy’. This is also possibly due to a cost issue.
Under the ‘other’ two companies suggested cooperation with universities and other research organisations. A minority of companies indicated that support from outside is exaggerated and unnecessary. The development of skills and knowledge in the company was not given as a priority.

4.4.6 Critical materials – other activity

The research was conducted in the Autumn of 2011. In the following years a number of changes have taken place and these are listed below:

Prices dropped and then flatten for critical materials and no supply problems have happened. There is over production in some critical materials leading to a feeling the problem has gone away. It could appear the strategies put forward by the companies have worked. If any changed their product design, it would now be seen as a costly, risky approach and was not needed. There was action on the design of materials over 2010-2016 and the percentage of critical material content was reduced significantly in some cases (CRM-Innonet, 2014). This had the effect of helping to push down prices.

REE; outside of China, new mining and processing facilities first increased (2010-14) then dramatically decreased (2014-16). Example: Molycorp chapter 11 bankruptcy 2015. Mining / processing / supply now faces the same challenges and new challenges ahead. More widely the commodity ‘supercycle’ collapses meaning oversupply and therefore cheaper metals.

In terms of support, more funding in EU (H2020 and KIC EIT RM) and USA (CMI) on research, education and support.

4.5 Chapter 4 conclusions

From the research conducted on the 29 companies in the Netherlands some key conclusions can be drawn. *RQ3: How are companies responding to critical materials?*

The level of familiarity of the term and the role of critical materials problems is high amongst the respondents. The majority of the companies are following developments in critical materials ‘poorly’ in their opinion. When it is followed it is usually done by the procurement department and does not involve product designers. This purchaser-supplier focus is seen in the preferred responses - Stockpiling (in the participant company), long term agreements, more suppliers, stockpiling at the supplier, paying the highest price and safeguarding the supply chain are the chosen responses.The role of product design is not seen by the companies as a relevant reaction to the problem of critical materials and they do not actually change product designs.

5 The potential role of product design in addressing critical materials problems

5.1 Introduction

This chapter brings together the findings from chapters 2, 3 & 4 to address the question: *What could be the role of product design in addressing critical materials problems?* This question is the forward looking (the ‘could be’) part of the central research question; ‘*What has been and could be the role of product design in addressing critical materials problems?’.* This chapter concludes with the development of a critical materials & product design framework, upon which further work on research and education, may be developed.

The company research detailed in chapter 4, shows that the company respondents did not indicate that product changes were being made as a strategy to address critical materials problems. Only one company said LCA or C2C™ could form part of their product design approach to address their critical materials problems. The literature review in chapter 3, on the definitions of critical materials, establishes that the majority of the critical materials definitions were not written with the aim to engage product designers. Increasingly, however, product design based approaches are being proposed by governments to help address the critical materials challenge, as seen in the proposed EU circular economy package in 2015. In spite of such proposals, however, it remains unclear how exactly product design can mitigate critical materials problems.

In order to address this challenge, chapter 5 makes a comparison between the past product design approaches for solving material scarcity (shown in chapter 2) and recent (post 2015) proposed product design approaches to address critical materials problems. The differences and similarities between these historical and recently proposed approaches, are assessed, in order to better understand which proposed design strategies were useful in the past, and may be useful, in a revised form, going forwards.

Some of the current design strategies, such as eco-design, make use of guidelines or frameworks that are not always applicable in solving critical material problems. A comparison with past product design approaches towards material scarcity can help clarify which design strategies for solving critical material problems are more likely to prove useful over time.

The outcome of the review outlined above is the development of a product design & critical materials framework, which can be used to support the development of education and research programmes, aimed at helping to address the problem of critical materials through product design.

5.2 Product design approaches to address critical materials.

In chapter 3, literature from 1999 to 2014 was reviewed to establish critical material definitions. The conclusion in chapter 4 highlighted that none of the companies, out of the 29 interviewed, said they were actually changing their product designs to address critical materials problems.

The literature search in chapter 3 was extended to cover the period June 2014 and March 2016 . The focus of this search was on the product design aspects, looking for publications which explained for example, product design cases for specifically addressing critical material problems. This had been done for the period 1999 to 2014 with no results. This new search applied the same approach as was taken as for the 1999 to 2014 search, as explained in chapter 3. Important keyword search terms were “product design and critical materials” and “product design and scarce materials”. The search was also looking for critical materials as defined in this thesis, in particular the metals.

The aim of this new search was firstly to establish how relevant the results from the companies in chapter 4 were, particularly where they said there were no product design changes or implemented product design strategies to address critical materials problems. A second aim was to establish if further publications had developed the field since the company interviews and literature search (chapter 3) was conducted.

There were no publications found which exactly matched the keywords / aims of the search.

A publication of close fit to the search requirements, is the 2016 work entitled; Materials and Sustainable Development, by Mike Ashby. This was the only publication found which proposes a framework, including a significant product design aspect, that indicates aspects to address the critical materials problem. In his 2016 book Ashby presents *‘The Vision: A Circular materials Economy’,* where he highlights the problem of high loss rates of materials through the take-use-waste, linear approach to product consumption. Ashby proposes a circular materials economy framework to show the contributions needed to create his vision of a circular materials economy to address materials challenges. In the book Ashby explains how he has developed his framework in part from natural eco-system thinking. The framework is shown below in figure 47 (Ashby 2016).

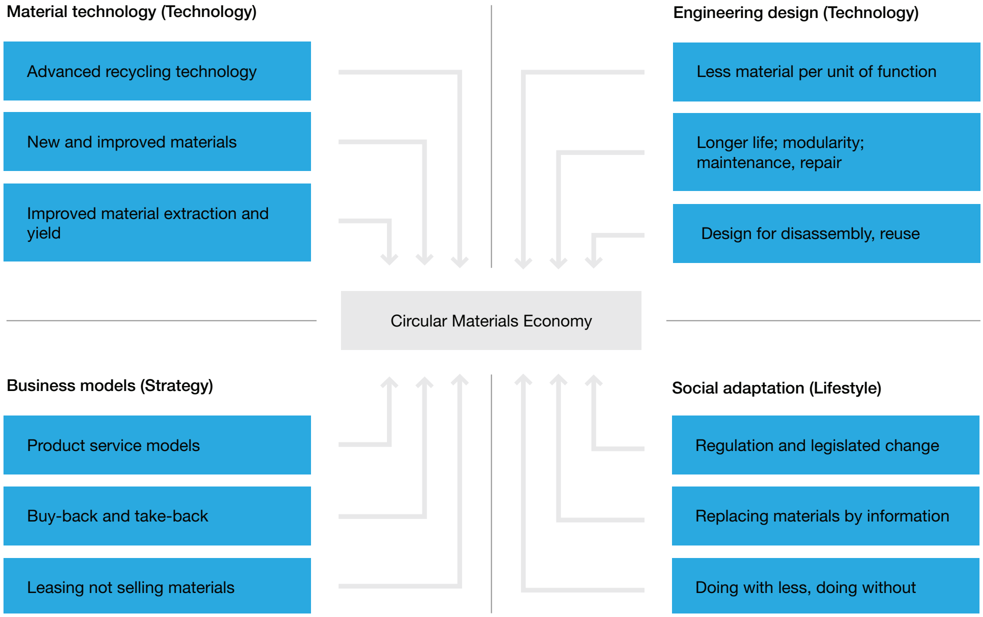


Figure 47 Ashby ‘circular materials economy model (Ashby, 2016)

The review of Ashby’s 2016 proposals led to a consideration of the reasons why changes to product design has currently a limited role in developing critical materials solutions in practice. The issue of what product design aims to achieve in an increasingly complex context, in particular in relation to materials, where, as chapter 3 highlights, there has been a rapid increase in the range of materials being selected.

The Ashby 2016 circular materials economy vision model was selected because the circular materials economy seeks to utilise product design approaches to address critical materials problems. Prior to this 2016 publication, Ashby has produced a number of collaborative publications concerning sustainable materials use, materials and product design (Ashby 2009 & 2013).

Ashby (2016) proposes a radical shift from linear to circular thinking in order for product design to address critical materials problems. End-of-life products can be considered as a resource for another cycle, while losses and stocks of unused materials be minimised everywhere along the materials value chain. In addition, the interactions between materials are considered to define the best circular solution from a systemic standpoint. There are however tensions in this framework, for example the low to zero critical material recycling rates (see figure 22 in chapter 3) and the difficulty of substance for substance substitution (Graedel, et al, 2013), both of which could lead to increased primary critical materials (mined materials) being needed, which will be discussed later in this chapter.

5.2.1 Comparison of models

This thesis takes the Ashby 2016 circular materials economy framework (figure 47) as a proposal on how to address critical materials problems and compares it to the historical product design for materials scarcity model (figure 12, Ch2). The figure 48 below shows this comparison.

Product design addressing materials scarcity:
five cases, 1943

Utility and Austerity product

Product Design
- Less material
- Lightweight
- Robust and long lasting
- Designed for repair
- Specified materials, local where possible
- Standardised designs and parts common
- Complimentary but limited product range
- 'Modernist' design style, 'good' design
- No decoration or ornament
- Designed by single design committee Government, Industry, Academics & Society involved

Production
Governmental control of the following:
- Production location specified
- Material allocated
- Production licences required
- Labour allocated
- Energy supply controlled
- Production volumes and timings given

Customers
- Only product legally available, CC41 stamp used
- Permits required, based on need
- Coupons required
- Products in catalogues not showrooms
- Purchase or lease or sharing
- Open to all, value for money
- Low cost
- Make do and mend encouraged

Product design addressing critical materials:
Ashby 2016

Circular materials economy

Technology
Material Technology:
- Improved material extraction & yield.
- New and improved materials.
- Advanced recycling technologies.

Engineering design:
- Less material per unit of function.
- Longer life, modularity, maintenance and repair.
- Design for disassembly, reuse.

Strategy
Business models:
- Product Service System models.
- Buy back & take back.
- Leasing not selling materials.

Lifestyle
Social adaptation:
- Regulation and legislated change.
- Replacing materials by information.
- Doing with less, doing without.

Figure 48 Comparison of the two approaches of product design addressing material scarcity, 1943 and product design addressing critical materials 2016.

The following section discusses the differences in the two approaches from the perspective of critical materials problems today.

5.2.2 The differences - WWII scarcity product design and 21st century critical materials / circular product design

The parallels with the product design approaches shown in figure 48 are significant, but so are the differences. This section outlines the differences when viewed from the 21st century critical materials perspective.

The first difference is the context for product designers in relation to governmental product design controls, implemented because of being at war. In any developed economy today, any attempt at product design legislation, in order to control critical materials, is met with strong resistance from companies. The prevailing view is the free market can provide what is needed and government should only be required when the free market is failing to supply and/or prices are out of control. In turn the societies in free market economies do not have a clear, apparent urgent reason to accept any controls on their freedom of product choice, in any material they want. These societies also have a low level of trust on their governments ‘telling them what they have to buy’.

The second significant difference is in the materials used. The range of materials in the 21st century covers nearly all of the elements in use. This is true for both the number of elements used from the periodic table of elements and the number of materials available on the market. For example, the use of rare earth elements in advanced materials today is high, with increasing demand in products. This is demonstrated by the number of elements used in the materials in hi-tech products, which has grown over the past 20 years: the magnetic materials for electrical generators, motors, etc. can contain Al, B, Co, Cr, Cu, Dy, Fe, Nd, Ni, Pt, Si, Sm, V and W. (Ashby, 2016). In addition, the technologies upon which societies and economies rely, has expanded, with high levels of societal and economic dependence on, for example, information and communication technologies.

The third difference is in complexity of the supply chain. 21st century supply chains are complex and for critical materials, often opaque, with many intermediaries involved. The number of stakeholders varies from case to case but at the product design end there is usually no clarity on where the materials have come from, never mind the companies involved (Abraham, 2015).

A fourth difference concerns the current size of economies and the size of the change. Today the world population is over 7bn and set to continue growing. The global economy is one based on free market trading. Equally importantly global wealth is rising with an increasing number of people moving into higher socio-economic positions. The global demand for materials is correspondingly increasing and governments find it difficult to make changes to this larger, increasingly complex, global, free market, materials supply chain. The design of products relies on these materials as such emerging markets are seen as essential to companies futures.

A fifth significant difference concerns issues around the protection of the environment. Today there are regulations and controls on a range of environmental activities across the materials value chain, in particular when materials are mined and processed in developed countries. Connected with materials processing is the burning of fossil fuels and the link to climate change. The use of materials recycling is, in many countries, widespread and growing. There are controls, accepted by product designers, on hazardous and toxic materials such as radioactive materials, asbestos, cadmium, etc.

A sixth difference is in the willingness and ability of governments and markets to invest in changes to the material / product design changes. In the 21st century the finance required to develop a 'circular materials economy' and circular designed products, across all sectors, will be very large. In the current economy, financial crisis excepted, banks and other finance sources are usually not under governmental control. There is not a willingness of governments to risk distorting markets, suspend markets and control companies.

The final, and perhaps most important difference, is the time frame of the materials problems. There is not a short term, temporary, set of circumstances concerning critical materials in the 21st century. The problems of material supply, in particular of critical materials, are predicted, to increase for decades to come. This means there is not a temporary materials shortage situation and that 'traditional practice' can resume once 'things get back to normal'.

These seven main areas of differences highlight a number of important aspects; The contexts are very different. Main point here is there is no urgency brought about by world war. That situation allowed the triggering of total governmental authority over materials and products. The normal operation of the British economy was to a large extent 'suspended'. The technologies, and the flexibility to change, was very different. Britain operated very much as an independent nation and trade with the British Empire and Dominions could be strongly influenced and even controlled by Britain.

These differences also allow the highlighting of the similarities or parallels, in particular in product design, and these are further examined in the next section.

5.2.3 The parallels - WWII scarcity product design and 21st century critical materials / circular-sustainable product design

Firstly the field of product design is exploring, through sustainable / circular design of products, to realise a number of actions such as design for: longer life, modularity, maintenance, repair, disassembly, reuse, remanufacturing & recycling (Bakker et al, 2014), (Abraham, 2014), (Ashby, 2016). This is a striking parallel with the activities undertaken to mitigate material scarcity during WWII.

In addition, in the past as well as today, designs are changing as a result of materials substitution. As materials are replaced with less critical substitutes, the change in the materials properties can lead to changes in the product design. In turn the redesign of a product function can lead to the reduction or elimination of critical materials. An example of this is the change from direct drive to geared wind turbines, which reduces the rare earth content in the generator magnets.

The product design changes are being facilitated by new circular business models which in turn again change the design of the product. Examples of new circular business models include products designed at a higher grade to last longer, higher grade long life products with short life consumables, products which have a long life where revenues come through service such as access, performance or repair / maintenance (Bakker et al, 2014). Such business models effectively slow down the rate of consumption of materials and facilitate increased recycling at end of life. This approach could be seen in the proposed National Motor Vehicle design from WWII.

Governments are proposing developing policy, with regards to critical materials supply, including changes to product design. Governments are funding critical materials research and education with a focus on linking a circular economy to critical materials problems, including material substitution (EU CE package 2015), (EU KIC EIT Raw Materials, 2015).

Governments conduct planning for shortages and make preparations, for example the stockpiling of critical materials for the defence sector. An important activity governments are undertaking is the understanding of the size of the problem of critical materials by funding research to establish where critical materials are in both primary and secondary stocks. Governments oversee the regulation of materials supply markets and attempt to restrict monopolies forming in markets. Tariffs and controls on the flow of materials can be applied when required. In the preparation phase before WWII the British stockpiled materials for 6 months of reserves.

The differences and parallels shown above highlight a number of key points. In WWII the urgency was high, government had complete authority, the economy was ‘suspended’, technologies were simpler and the global trade lines were shorter. This having been said it is remarkable how similar the product design approaches were to those in the circular / sustainable proposals of today. The WWII British approaches worked and the current proposed approaches might therefore be valid. Of note however is that without the urgency the British faced in WWII, the prospect of government and companies taking control of the situation and working closely together today is significantly reduced. In that case it will be very difficult for product design to really make a difference to critical materials problems and the role of product design in mitigating the critical materials problem will at best, be modest. What remains clear however is that when an urgent situation does arise, governments turn to product design to help provide solutions. The question remains as to how well the current generation of product designer could rise to that challenge.

5.2.4 Tensions in existing sustainable / circular product design approaches to address critical materials.

Materials criticality literature frames eco-design as a solution strategy (EU CE package 2015) and there have, over the past few years, been governmental and research think tank publications on the topic of critical materials, which have raised the opportunities provided through product design and in particular eco-design (UK Government, 2012), (EU Circular economy package, 2016) .

When established eco-design guidelines and strategies are applied to solve critical materials problems, tensions can arise. This section explores this in more detail, in order to assess the usability of the design strategies shown in the Ashby model.

A well-known example of generic guidelines is provided by Brezet and van Hemel with the eco-design checklist. Using this framework as a model, tensions in the context of critical materials, are highlighted, see table 9.

Table 9 Eco-design strategies, Ashby 2016 and tensions with critical materials Adapted from H. Brezet and C. van Hemel, *EcoDesign: A promising approach to sustainable production and consumption*, UNEP, France, (1997)

DfS – eco design strategies	Ashby 2016 circular materials economy design	Tension with critical materials problems
EcoDesign strategy @ new concept development • Dematerialization • Shared use of the product	• Less material per unit function • Doing with less, doing without • Leasing not selling materials • Product service models • Buy-back and take-back • New and improved materials	Critical materials '*provide unique performance characteristics, that the product depends on and the user highly values'* – so to remove the critical materials (via dematerialisation / less material) may lead to loss of functionality and value of the product making it 'less-shareable' and more difficult to integrate functions. The ongoing quest for electronic miniaturization has led to dematerialization, with more and more critical

• Integration of functions • Functional optimization of products (components)		materials embedded to provide the necessary functions.
EcoDesign Strategy 1: Selection of low-impact materials • Clean materials • Renewable materials • Low energy content materials • Recylced materials • Recyclable materials	• Improved material extraction and yield • New and improved materials • Advanced recycling tech	Critical materials are inherently not 'clean' in either extraction or processing. Further improvements in yield may require greater use of toxic chemicals. The critical metals are not renewable. The extraction and processing is energy intensive. Most metal critical materials are not recycled and are very difficult to be recycled.
EcoDesign Strategy 2: Reduction of material usage • Reduction in weight • Reduction in (transport) volume	• Less material per unit function	Critical materials are often used to achieve weight reduction, for instance in the case of light-weight super alloys. So, in order to achieve further advances in light-weighting, the use of critical materials could increase.
EcoDesign Strategy 3: Optimization of production techniques • Alternative production	• Doing with less, doing without	Critical materials allow metals to be formed in novel ways, using fewer production steps and less metal waste which would

techniques • Fewer production steps • low/ clean energy consumption • less production waste • Few/ clean production consumables		mean grater volumes would be used. Critical materials are not 'clean' in either extraction or processing and can be used in production consumables leading to higher use.
EcoDesign Strategy 4: Reduction of material usage • Reduction in weight • Reduction in (transport) volume	• New and improved materials • Doing with less, doing without	Critical materials lead to weight reductions in metal alloys which can be significant. Critical materials allow metal alloys to be smaller in volume. Both would lead to greater use.
EcoDesign Strategy 5: Optimization of the distribution system • Less/ clean/ reusable packaging • Energy-efficient transport mode • Energy-efficient logistics		Critical materials are essential in low carbon, energy efficient mobility systems. Critical materials are essential in low carbon energy production. Both would lead to greater use.
EcoDesign Strategy 5: Reduction of impact in the used stage • Low energy consumption • Clean energy source • Few consumables needed • Clean consumables	• Doing with less, doing without	Critical materials are essential in low energy consumption equipment and products. Critical materials are essential in low carbon energy production. Critical materials are not 'clean' in either extraction or processing. All would lead to greater use.

• No wastage of energy or consumables		
EcoDesign Strategy 6: Optimization of initial lifetime • Reliability and durability • Easy maintenance and repair • Modular product structure • Classic Design • Strong product-user relation	• Doing with less, doing without • Longer life; modularity; maintenance, repair • Design for disassembly, reuse • Leasing not selling materials • Product service models • Buy-back and take-back • New and improved materials	Critical materials can make metals robust and durable. Their application can ensure repeated assembly and disassembly and facilitate interchangeability of parts. All would lead to greater use.
EcoDesign Strategy 7: Optimization of the end-of-life system • Reuse of product (components) • Remanufacturing/ refurbishing • Recycling of materials • Safe incineration	• Doing with less, doing without • Longer life; modularity; maintenance, repair • Design for disassembly, reuse • Leasing not selling materials • Product service models • Buy-back and take-back • Advanced recycling tech • New and improved materials	The durability of critical material components facilitates reuse, remanufacturing and refurbishment. Most metal critical materials are not recycled and are very difficult to be recycled. Most critical materials are incinerated (in the Netherlands). All would lead to greater use.

Note: Ashby 2016 addresses business and social aspects, which are not addressed by the Brezet and van Hemel eco-design checklist. Conversely the Brezet and van Hemel eco-design checklist does address energy use.

The main tension which arises is the general direction to use less critical materials, but the requirements of the eco-design checklist can result in using more.

Often tensions like this may be resolved via life cycle analysis by weighting factors to allow a judgement to be made but in the case of critical materials this also leads to a further complication. The eco-design checklist asks:

- How much, and what types of additives are used?
- How much, and what types of metals are used?

If under 'additives' the small trace critical material metal elements in electronic components are included (and they are metal anyway, so are covered by the second bullet point), then this information is often not known. Nor is the environmental impact of production and distribution.

All of this will leave the product designer with a set of challenging tensions, which current eco-design approaches and LCA data find difficult to resolve.

Both Ashby 2016 and the eco-design checklist have the potential to resolve the tensions and to that end both approaches are considered in the development of an improved framework. This will act as a starting point on addressing critical materials and product design .

5.3 A new framework for critical materials and circular product design education

The Ashby 2016 circular materials economy vision, the gaps in current company practice and knowledge and tensions in eco-design & Ashby 2016 and critical materials, indicate that for product design and critical materials a new framework is required.

In addition the Ashby 2016 framework showing the contributions needed to create his vision of a circular materials economy has all materials included. A new framework with a focus on critical materials (metals) is needed.

Half of the Ashby 2016 framework (figure 55) is taken up with Engineering design and materials technology. The role of government and policy is placed into social adaptation. The review of the historical approach to material scarcity indicated a prominent role for government and policy. Given the low levels of product design activity towards critical materials in companies, it appears an increased role for government actions and policy is needed today. The role of society is acknowledged by Ashby 2016 but there also needs to be a cultural shift too.

The proposed framework was developed using lessons learnt from the historical cases, developments in critical materials approaches, current gaps in company practice and tensions between the eco-design checklist & Ashby 2016 and critical materials.

The first step was the decision to base the new framework on the existing Ashby 2016 model and the new framework is a adaptation of the Ashby 2016 model. Then the framework was divided into four main headings instead of the three used by Ashby 2016 (figure 55). This allows policy and regulation to have its own distinct quadrant. This is important as the historical cases demonstrated the vital role government played in securing scarce material supply.

5.3.1 Materials, engineering and design

The design for longer life is a key aspect for product design, engineering and material design. Longer life requirements is a significant shift in product design which has been used to developing product for higher life cycle rates (Bakker et al 2014 and Ashby, 2016). The product design approaches includes design for; modularity; maintenance, repair, disassembly, reuse, remanufacturing. Material recycling is designed for through modularity and disassembly (Ellen MacArthur Foundation 2013).

Critical materials problems will require the development of substitute and improved materials, as shown in chapter 3. In tandem with that approach improved material stocks, improved extraction and yield (both primary and secondary sources), is required.

5.3.2 Business

One of the main barriers to longer product life is that companies producing products reduce their revenue streams as products do not need replacing so quickly in the linear business models of take-make-waste (Ellen MacArthur 2013). To address this challenge product service business models, where materials are leased not sold, can be an answer. Therefore the revenue comes from use not ownership.
Such a systemic approach is complex and would need to be done through open and fair conditions. It will also lead to product life cycles being more carefully managed, which in turn will need openness and fairness to be in place.

Such approaches would only slow the rate of critical material use, but if combined with the materials, engineering and design strategies above could lead to companies being willing and able to fund the development of new materials and new product designs.

5.3.3 Policy and regulation

As shown in the historical cases the role of government and policy is essential in allowing the materials, engineering & design and business strategies to succeed. Data on critical materials is a first key requirement. The collection and availability of data needs, on the generic level, to be supported by government funded research. In tandem with this countries need to have a robust, regularly updated planning in place for potential critical material supply failure, with product priorities assigned. This plan needs to include product design requirements for such a supply crisis eventuality.

In terms of incentivising company change, governments can make changes to public sector procurement to require companies to make only circular proposals. In addition governments can develop a shifting of tax away from income and corporate taxes to taxes on materials. This would have the effect of making materials far more valuable whilst lowering the cost of labour (The ex-tax, 2014).

Governments will also need to regulate to ensure a level playing field for companies and to ensure society has confidence in the changes. The EU is proposing the use of eco-design and producer pays policies, for the open, fair and managed supply of circular products and services which will address critical materials problems (EU Circular economy package, 2016)

5.3.4 Societal

The engagement of wider society will be essential to ensure the product design solutions to critical materials problems will be accepted and grow. A sense that the proposals are fair and not simply companies and governments taking advantage of the situation, is important. In the shift from owning to product access and sharing, fair value for money will need to be felt by all.

The actual, true costs of materials, including environmental costs, will need to be understood by all. At the same time the true value of materials through their ability to ensure that new product designs can not only deliver great products but can also address challenges like critical materials, pollution, water supply, food, mobility, etc. The understanding of the value of materials, including the critical metals, can help all accept the changes proposed and should be done in a way which leads not to sense of ‘less’ but of greater ‘societal wellbeing’.

5.3.5 The new framework

Taking the four aspects above into consideration the Ashby 2016 model has been adapted and developed and a new framework model shown below in figure 49 below. The entire critical materials and product design should as far as possible be run on renewable energy to limit unforeseen rebound effects, such as logistics companies moving more product around more often, but using diesel vehicles. This example highlights a tension again. More alternative forms of mobility such as electric vehicles will require more critical materials. But this tension can be offset by the use of the product design, new materials and new business model approaches. There is also a trade-off between the impacts of more critical material use and the increase of climate change gas emissions.

Using renewable energy

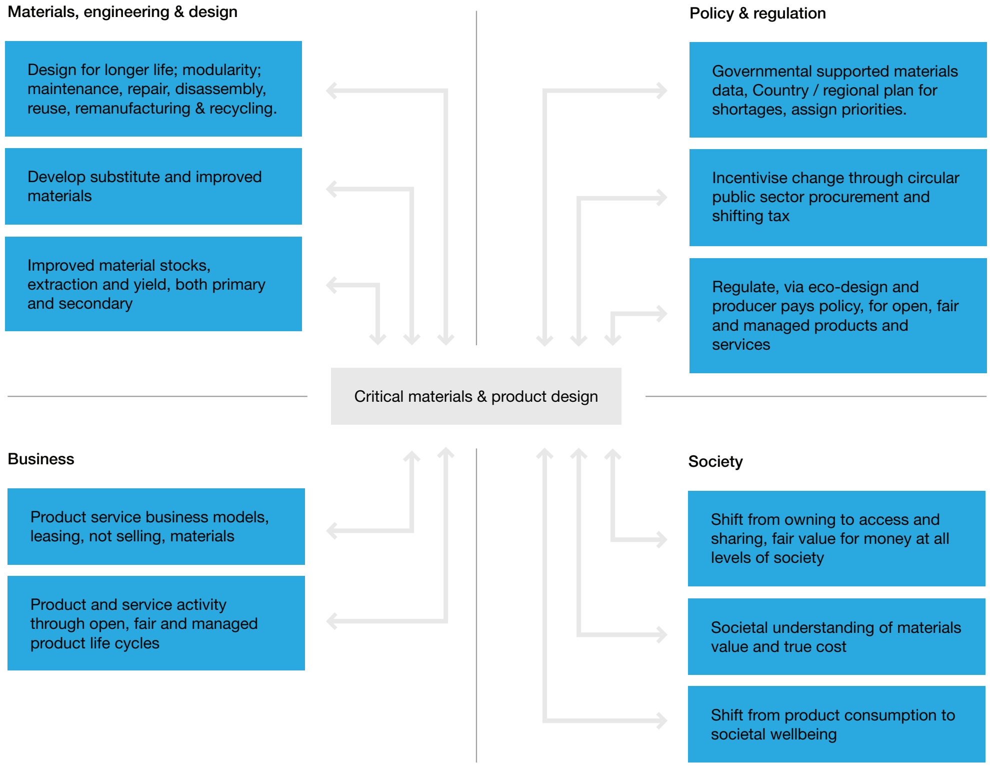


Figure 49 A framework for a critical materials, circular product design education approach. Adapted from Ashby, 2016.

This new definition and framework is designed to be the basis for the development of the education and research programmes designed to develop knowledge and skills in circular product design for critical materials. On the question of resolution of the tensions highlighted in table 9, it cannot be established in this thesis if the deployment of the proposed framework would help resolve the tensions.

In the new framework model proposed, product designers would be made much more aware of the materials they select, new business models, regulations, policy, public sector requirements, costs, etc. Currently the focus in much product design education is on the user interaction with materials, engineering & design and the societal and cultural issues surrounding design.
An important first step of what should be done is highlighted by Kohler, Bakker & Peck, 2013, where they advocate setting up an open access knowledge system that hosts information such as:

• Detailing application areas of critical materials and their range of functions.
• Recyclability indices and actual recycling rates of critical materials.
• Listing the material substitution potential.
• Design guidelines in relation to critical materials.

Kohler, Bakker & Peck, 2013

Across all 4 quadrants of the framework for a critical materials - product design education approach, the following education activities and approaches should be undertaken:

• Fostering entrepreneurial, creative and innovative thinking;
• Delivering new ways of learning and teaching;
• Providing open learning environments;
• Facilitating the mobility across a learning system.

This educational approach mobilises the participants through working in projects and learning collaboratively. The learning environments should include a combination of interactive e-learning and mobile learning apps for access anywhere and anytime. Other approaches to teaching product design need to be introduced such as the use of serious gaming. This educational approach was developed in the proposal document for the successful bid for a Knowledge and Innovation Community (KIC) for Raw Materials from the European Institute for Innovation and Technology (EIT). This large European programme is called EIT Raw Materials. Peck was on the proposal writing team in 2014. He has been involved in many such projects on the programme through 2015 and 2016.

An example of critical materials and product design in a circular economy context can be seen in the development of a serious game called ‘In the Loop™’ This game, which can be seen in figure 50 below, contains many of the aspects shown in the new framework (Whalen & Peck, 2015).

Figure 50. The ‘In the Loop™’ serious game.

This serious game was designed and developed by Katherine Whalen, originally as part of her Masters graduation with TU Delft. This work was published in Whalen and Peck, 2015, where the authors explain that, a set of learning outcomes were developed. The players should by the end of playing the game:

- Have an awareness of their company’s products and/or processes which involve critical materials.
- Identify critical materials issues which could have a company impact.
- Demonstrate a knowledge of actions which could cause material criticality.
- Identify strategies that prevent or mitigate materials criticality.

Whalen and Peck, 2015

These learning outcomes were partly derived from an earlier version of the literature review shown in chapter 3 of this thesis.

It is important that in more traditional learning settings, students should work together on real industrial cases. They would have different learning goals and roles in each project. Industry provides the cases, and this participation role delivers excellent continuing education opportunities for employees as well. The approach will be based on the approaches of problem-based learning, self-organisation and learning-by-doing. The alumni networks from the partner universities should be utilised to support the learning.

To promote the collaboration a variety of events and workshops should be organised bringing all the ecosystem stakeholders together to work collaboratively. Events could include participation in trade fairs, site visits and critical materials / circular design web talks (KIC EIT Raw Materials proposal, 2015).

Addressing materials criticality should become a key part of the competencies in all industrial design and engineering design courses. It can seem that the subject of critical materials can be addressed through teaching a number of well-known sustainable design principles by covering topics like minimization of resource usage, design for reuse/ recycling, and/or use of renewable resources. These are the eco-design approaches. As discussed above, these principles are in need of revision to be applicable for developers of high-tech products that use critical materials, which in turn are vital in current sustainability transition plans (Köhler et al, 2013).

5.4 Chapter 5 conclusions

This chapter has shown a synthesis of the findings from chapters 2, 3 and 4. The historical cases from utility and austerity design were used to develop a comparison of the two approaches of product design for material scarcity, 1943 and product design for critical materials 2016, with the focus on 2016.

The differences between the two periods have been discussed followed by the parallels, in particular the parallels in product design. Eight main areas of difference were identified but significant parallels were observed. In terms of product design, design for: longer life, modularity, maintenance, repair, disassembly, reuse, remanufacturing & recycling were seen as important parallels. In addition governmental policy, business, not for profit organisations and wider society demonstrated important parallels.

The domain of eco-design was identified as important and was analysed. It was observed there are some tensions in the approach when critical materials are considered.

Finally in response to the chapter title ‘The potential role of product design in addressing critical materials problems’ a framework for education and research was developed using, as a product designer engagement, the definition of critical materials for product designers as developed in chapter 3. A framework was developed from the model from chapter 2 and the Ashby 2016 model. This new circular product design for critical materials framework, together with the new definition provides the basis for the development of new education and research programmes to address the problem of critical materials through circular product design.

6 Conclusions & recommendations

6.1 Conclusions

This thesis addressed the question of what role product design has played and can play, in tackling critical material problems. The starting point was an examination of what could be learnt from a historical set of product design cases which successfully addressed material scarcity. Following this the research turned to more recent developments around definitions of critical materials and observed that the definitions were not written for product designers. To address this gap a definition of critical materials for product designers was produced. In order to establish the responses to critical materials problems from companies, an empirical study with 29 companies was carried out. This demonstrated an awareness of critical materials problems but that no product design change activity was being undertaken to address critical materials problems.

The work outlined above addressed the central research question:
What has been and what should be the role of product design in addressing critical materials problems?

This central research question entailed the following sub research questions;

Sub-research question 1: *What can be learnt from historical product design responses to materials scarcity?* This was addressed in chapter 2.

Sub-research question 2: *How can critical materials be defined within the context of product design?* This was addressed in chapter 3.

Sub-research question 3: *How are companies responding to critical materials?* This was addressed in chapter 4.

The penultimate chapter 5 brings chapters 2, 3 and 4 together in a synthesis and develops a framework for further research and education on critical materials and product design.

The main finding is that product design can address critical material problems, and this position is considered in the answers to the research questions.

6.1.1 Sub-research question 1: What can be learnt from product design responses to material scarcity?

This sub-research question was answered in chapter 2. Five WWII British cases covering Austerity and Utility designs were analysed (using synchronic and diachronic analysis techniques). The response to material scarcity in the five WWII British cases can be sub-divided into product design strategies around three categories; product design, production and customers. Examples includes the grade of materials being selected to give a longer life (control of materials), standard parts, standard machine joints, use of jigs and fixtures, simple joining, fewer parts (production) and design for repair via design for disassembly and reassembly (customers).

Early in the war stockpiling provided a 'breathing space' but it was realised it could not address material scarcity issues in the medium to long term. The substitution of materials led to an expansion of types of materials which could be used. The bringing together of government, companies and a powerful committees of designers was essential.

The five Austerity and Utility design cases demonstrate what product (industrial) design can do when faced with material scarcity. It used design approaches to design products fit for the materials scarcity context.

The most important lesson from the cases is that the British government could have simply restricted the range and volumes of existing designs, but they did not. The government chose to instruct the companies to produce new products and to develop new sets of designs, which the government oversaw. They did this because it provided the most product for the least material, energy and labour, at the lowest financial cost. The redesign of products is costly in time, people and materials and would not have been taken lightly in the war. New product designs were deemed essential to address materials scarcity.

6.1.2 Sub-research question 2: How can critical materials be defined within the context of product design?

This sub-research question was answered in chapter 3. This chapter has shown an example of an existing critical material definition:
"To qualify as critical, a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance. In such a case, the likelihood that impediments to access occur is relatively high and impacts for the whole EU economy would be relatively significant." (EU, 2010)

This generic definition of critical materials has the common theme of the two axis graph showing a scale of the importance of a material against the risk of disruption of supply. It is clear that such definitions were not written for product designers and therefore a new definition of critical materials for product designers is produced in chapter 3:

Critical materials are elements from the periodic table of elements (metals / rare earths) that may be at risk of price volatility and supply restrictions. They are applied through the selection of parts and materials during the product design process and are often present *in small quantities in technology products, providing unique performance characteristics, that the product depends on and the user highly values. Physical substitution of a critical material changes a product's properties and / or performance, can entail high financial / environmental costs and can have a long lead time.*

It is proposed that this new definition of critical materials written for product designers addresses the second sub-research question. Importantly the new definition may lead to greater engagement, from the product design community, with respect to critical materials.

6.1.3 Sub-research question 3: How are companies responding to critical materials?

The 29 companies interviewed showed high levels of awareness of critical materials. This could be explained by the then (2011-12) higher level of concerns over rare earths. Their interpretation of what is a critical material differed from the lists of materials in the published definitions from chapter 3. The topic was often addressed by company procurement people in consultation with their suppliers.

The companies are mixed on their level of knowledge concerning the role of critical materials in their products. They see critical materials as vital to their businesses but the mixed understanding of what critical materials are, led to many knowledge 'blind spots' in companies. The preferred actions in response to critical materials were stockpiling materials (including at their suppliers), developing long term supply agreements with suppliers and hedging the prices. Where it were possible, and if it required no design change, the material would be changed (substituted), but only where the new material already existed and was approved for use.

Most of the companies use risk management as a response tool for critical materials but the companies named materials critical to them which were often not the listed critical materials. In terms of actions from risk management assessments, working with their direct suppliers is the preferred choice. There is very little role seen for changes to product design to help manage critical material risks.

In terms of business strategy and critical materials there are opportunities seen by some of the companies but most see it as an external threat. Only one company mentioned that they might consider changes to the product design and proposed using LCA or C2C™ as part of that approach. None of the companies were using product design to address critical materials problems or had an immediate plans to do so.

The answer to the research question is that companies feel they can address any critical materials problems in their products and they have deployed what they see as successful strategies in the past. They would prefer to see limited governmental involvement in addressing critical materials and changing the design of products is not seen an option at this time.

6.1.4 Main research question: What has been and what should be the role of product design in addressing critical materials problems

The role of product design in British WWII material scarcity was significant and made a major contribution to solving the materials scarcity problem they faced. Product design as a field, benefitted from the role it played in responding to material scarcity.

There are parallels with the WWII responses and the critical materials solution proposals of today. The main points are that knowledge, planning and preparedness are vital in managing critical materials shocks.

The field of product design has largely ‘forgotten’ historical material scarcity experiences and in addition sees critical materials as a topic outside of its field. Furthermore the security of supply of all materials is seen by most as not in its scope. Product design does however provide the ‘pull’ of materials and can therefore facilitate solutions.

In terms of solutions, the application of eco-design strategies, underpinned by robust data for materials use in product, is an good starting point. One challenge here is that in the field of eco-design, materials use in product has not been widely connected to critical materials research. Such an alignment of eco-design strategies, materials use in product and critical materials research, requires a significant enhancement of product design skills and knowledge.

In the current situation concerning critical materials such an enhancement will be challenging due to a number of difficulties. The dominant model is ‘design-make-sell-use-throw’ and product design in faculties, consultancies and the company design office, are deeply versed in such an approach. Where changes are being considered, the preference is towards design for recycling, but given the technical and economic limitations on the recycling of critical materials, this will be very difficult.

As seen in the 1940’s cases, the change from materials supply as normal to a very disrupted state can be dramatic and happen in a short time frame. To the credit of product designers they grasped the challenge and provided solutions. They chose to change designs radically to help manage materials supply.

With the new definition and framework (see figure 51 below), educators and researchers can develop programmes to educate product designers to develop new product designs to address the critical materials problem.

Using renewable energy

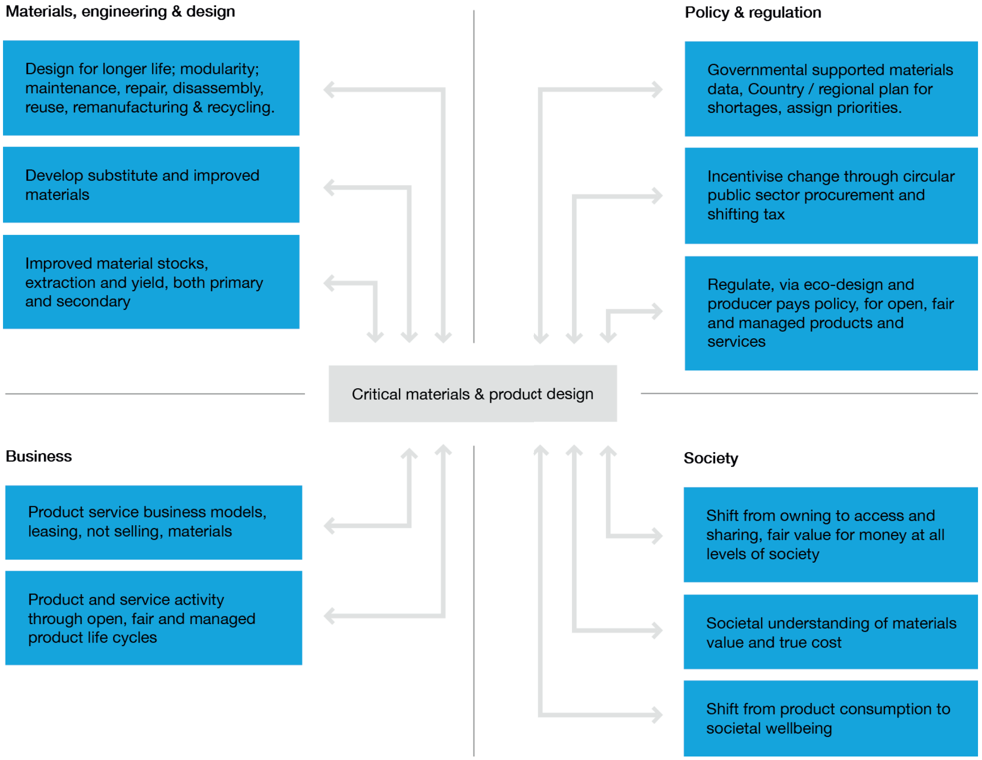


Figure 51 A framework for a critical materials, circular product design education approach. Adapted from Ashby, 2016.

6.2 Recommendations for further work

The critical materials and product design framework shown in chapter 5 could be the used as a starting point for the development of new research and education on critical materials and product design, but this field needs development.

The framework model can be developed for companies to develop their awareness, knowledge and skills, as not only a risk mitigation strategy but also as an opportunity development.

Governments could take a range of actions, and adopt a leadership role in addressing critical materials problems and product design.

Wider society should be engaged by re-packaging the messages it into meaningful and engaging ways that has a resonance in communities.

Design history has not explored the wealth of knowledge that past material scarcity actions can provide. In particular during the 20th century, and not only in times of war. This review can provide valuable cases to develop solutions today.

The emerging field of circular economy and in particular circular product design offers a framework for engagement with critical materials problems and further work to understand this, could be undertaken.

7 Appendix

7.1 Appendix 1 The questionnaire (English translation)

Critical materials in The Netherlands
- A response from industry -

Questionnaire

Dear Sir/Madam,

Firstly, thank you for agreeing to participate in this important research.

This questionnaire forms a key part of the 'Critical materials in the Netherlands' project, which has been ordered by the technological sector industry representative body, FME-CWM. The project is led by TNO, M2i, and Delft University of Technology (TU Delft). With this research we will gain a better insight into the reaction of Dutch companies to the phenomenon of material criticality.

Critical materials are materials which are important or even essential, for your products, are likely to experience price fluctuations and supply insecurity. This phenomenon has also been called material scarcity.
The following pages contain the questionnaire, which will serve as basis for the follow-up interviews.

The questionnaire is divided into five main themes:

1. Knowledge of the term "critical materials" in the company
2. The role of critical materials in the company
3. Risk management and critical materials
4. Business and critical materials
5. Support concerning critical materials

A core theme in the research is the focus around a chosen product / product group from your company. This product is selected by you, in consultation with the researchers, during a telephone conversation prior to the follow-up interview.

In order to help make the follow-up interview more effective, we would ask you to go through the questionnaire beforehand and to gather the necessary information as required. 'Explanation' boxes are provided below some questions in order to allow for expansion or additional comments.

If the materials which are critical for your company, are not named in the questionnaire, please raise this during the interview.

Finally, once again, we would like to thank you for your cooperation.

The FME/M2i/TNO/TU-Delft team.

1. **Familiarity with the term "critical materials" in the company**

1.1 How did your company become aware of the challenges concerning critical materials (material scarcity)?

Which terms are used in your company to describe the phenomenon? (More than one answer can be given)

- ☐ Material scarcity
- ☐ Material security
- ☐ Critical materials
- ☐ Priority materials
- ☐ Supply insecurity
- ☐ Other term, namely: ______________________
- ☐ No term is used
- ☐ I am unsure

1.2 Indicate factors which, in your opinion, have directly or indirectly caused material criticality. Rank the factors from 1 to 7, where 1 is the most probable cause and 7 is the least probable cause.

Rank	Factor	Example
______	Economic factors	More demand than supply, resulting in higher prices
______	Geopolitical factors	Limitation of export quota by producing countries
______	Suppliers	Suppliers monopoly on certain materials
______	Mining & processing	Not enough new capacity
______	Product design	Products are not designed for reuse and recycling
______	Material sciences	Not enough research on alternative materials
______	Recycling	Not enough recycling of critical materials
______	Other, namely:	______________________

Explanation:

1.3 Tick on the scale, shown below, how closely the developments in the field of material criticality are followed within your company.

Not at all — Very closely

1.4 How and by whom, are these developments followed within your company?

1.5 Can you name the measures your company has taken as a reaction to issues raised by critical materials?

1.6 Are you aware of the strategy of your competitors concerning critical materials?

1.7 If yes to 1.6, does that knowledge influence decision making in your company?

2. Role of critical materials in the company *This part of the questionnaire – except the first question - concerns the role of critical materials for the chosen product/product group.*

2.1 Can you name the critical materials contained in all products throughout entire product range of your company?

- ☐ Yes
- ☐ No
- ☐ Partially

2.2 Which element(s) from tables below are used in the chosen product/product group? (More than one box may be ticked)

Element:	**PGM group:**	**REM group:**	**Other:**
☐ Antimony (Sb)	☐ Platinum (Pt)	☐ Yttrium (Y)	☐ ____________
☐ Beryllium (Be)	☐ Iridium (Ir)	☐ Neodymium (Nd)	☐ ____________
☐ Cobalt (Co)	☐ Osmium (Os)	☐ Cerium (Ce)	☐ ____________
☐ Fluorspar	☐ Palladium (Pd)	☐ Lanthanum (La)	☐ ____________
☐ Gallium (Ga)	☐ Ruthenium (Ru)	☐ Scandium (Sc)	☐ ____________
☐ Germanium (Ge)	☐ Rhodium (Rh)	☐ Dysprosium (Dy)	☐ ____________
☐ Graphite(C)		☐ Samarium (Sm)	
☐ Indium (In)		☐ Terbium (Tb)	
☐ Magnesium (Mg)		☐ Praseodmium (Pr)	
☐ Niobium (Nb)		☐ Promethium (Pm)	
☐ Tantalum (Ta)		☐ Europium (Eu)	
☐ Tungsten (W)		☐ Gadolinium (Gd)	
		☐ Holmium (Ho)	
		☐ Erbium (Er)	
		☐ Thulium (Tm)	
		☐ Ytterbium (Yb)	
		☐ Lutetium (Lu)	

Explanation

2.3 In the last question, you have indicated the critical elements used in the product. Could you, per element, state in which material it is used and who are the suppliers?

Element	**Material**	**Function of the element(s)**	**Suppliers**

2.4 In the table below, state three materials critical to your company and indicate on a scale of 1 to 5 if the price of the materials has increased or decreased over the last 5 years.
1 = significant increase, 2 = increase, 3 = stable, 4 = decrease, 5 = significant decrease

Material	**Price**

Explanation:

2.5 Using the same materials in the previous question, in the table below, indicate on a scale of 1 to 5 if the quantities, used by your company, has increased or decreased over the last 5 years.
1 = significant increase, 2 = increase, 3 = stable, 4 = decrease, 5 = significant decrease

Material	Quantities

Explanation:

2.6 Do you expect, as a result of new product developments, the importance of critical materials to decrease or increase?

Can you name any examples?

2.7 Has your company experienced difficulties with the supply of critical materials over the last 5 years?

☐ No
☐ Yes

If yes, what, in your opinion, caused those difficulties?

If yes, which critical materials were concerned?

If yes, what was the reaction of your company?

3 Risk-management and critical materials

3.1 Do critical materials play a role in the risk management activities of the company?

- [ ] Yes, this is an active part of the risk management activity
- [ ] No, not at this time, but there are plans to include it in the near future
- [ ] No, critical materials are not involved in risk management activity

Explanation:

3.2 Which measures are/will be taken to address material criticality? (Multiple answers possible)

- [ ] Substitution of critical materials by other, less critical materials
- [ ] More efficient use of critical materials in products and production
- [ ] Mitigating risk by selecting multiple suppliers from different countries
- [ ] Stock-piling of critical materials
- [ ] Other, namely: ______________________________
- [ ] not known

Explanation:

3.3 If one or more of the critical materials indicated by you in question 2.2 (page 4), were to become unavailable, which steps could your company take now to avoid problems?

3.4 Concerning critical materials, what changes does your company expect within 3-5 years?

☐ Critical materials will become a much bigger challenge and limit the production of certain components and or products.

☐ Critical materials will become a much bigger challenge, but due to the timely reaction of the company we can deal with it.

☐ Critical materials will not be a challenge in the 3 to 5 year time frame, due to the discovery and exploitation of new materials.

☐ Critical materials have never been a problem and will not be in the near future.

Explanation:

4. Business and critical materials

4.1 Does the company see any opportunities resulting from material criticality?

☐ Yes, there are already developments ongoing in the company.
☐ Yes, there are plans, but no concrete developments yet
☐ No, this phenomenon presents no opportunities for the company
☐ I do not know

Explanation:

5. Support concerning critical materials

5.1 In the list below several possibilities are stated which could provide support to the company in mitigating the risk arising from critical materials. Which ones would your companies consider using? (Multiple answers possible)

☐ Regular meetings and updates from experts on the latest developments

- [ ] Check-ups by experts to determine the company risk exposure
- [ ] Hiring experts on a long term basis to gain advice on strategy
- [ ] Insight into the role of critical materials in all products and components of the company
- [ ] Employee training and development to increase knowledge and skills
- [ ] Other, namely: ______________________________
- [ ] None of the above

Explanation:

The end
The completed questionnaire can be returned to: **d.bol@m2i.nl** but remember we will be meeting you to discuss your responses soon.
Thank you for your time.
The FME/M2i/TNO/TU-Delft team

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Member of European Union Operational Group of the European Innovation Partnership on Raw Materials – Strategic Implementation Plan. This is the strategic policy document for the European Union. Work Package 4: Promotion of excellence in resource efficiency in business. 2012 to date

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Member of Working Group III - European end-user industries and rare earth supply trends and challenges, the current and future rare earth needs of European industry.
The working group consists of experts and representatives from manufacturers and other end-user companies. 2013 -2015

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David Peck was born on the 5th of March 1964 in the village of Saxlingham Thorpe. Saxlingham Thorpe is south of the city of Norwich in the English county of Norfolk.

David began his career in the aerospace sector as a time served technical apprentice, completing with an Engineering Diploma. Following this David's first degree was in BEng Honours Degree in European (German), which was studied in Coventry University (UK) and Fachhochschule Osnabrück (Germany) from 1992 to 1996. The European study was supported by the EU Erasmus student exchange programme. Following a further period in the aerospace sector David completed a Master of Business Administration (MBA) at the University of Warwick from 1998 to 2001. During this period David moved into academia and after completing his MBA he also attained a Post Graduate Certificate in Teaching and Learning at Coventry University in 2001.

David worked in both Business School and Design School (Open University, UK) as a Senior Lecturer and in this period registered for a PhD with the Open University in 2007. In January 2009 David moved to TU Delft and began in faculty Industrial Design Engineering. His OU PhD transferred to TU Delft in 2010 and was considerably revised.

In 2016 David was appointed as a senior research fellow in the faculty of Architecture and the Built Environment with a focus on critical materials and circular cities. David's research proposes a circular approach to product design and development in cities.

David is the TU Delft lead for the pioneer university status with the Ellen MacArthur Foundation for a circular economy. David is adjunct Professor at MIP Politecnico di Milano Graduate School of Business on Critical Materials and Circular Economy. He is the TU Delft lead for a Horizon 2020 project, ProSUM - Prospecting Secondary raw materials (CRM) in the Urban Mine and mining waste and H2020 project ERN – European Remanufacturing Network. David was on the writing team on the successful bid EU KIC EIT Raw Materials (sustainable exploration, extraction, processing, recycling and substitution). He is now the TU Delft manager for this 2 bn Euro project that has a focus on critical materials and circular. David is also a manager in the Leiden Delft Erasmus Centre for Sustainability – a 3 university collaboration on circular and resources with cities as the nexus. Recently David is a member of the lead team in an edX Massive Open On-line Course (MOOC) entitled 'The circular economy an introduction'.

Selected Publications, Journal and Conference papers:

Critical materials and higher education - a review of the Netherlands
E. Fromberg, D. Peck, P. Kandachar
Management Research Review Journal - accepted, under review

Exploring standards for quantified analysis of a Circular Economy
E. Reitfeld, A. Tukker, E. Keijzer, D. Peck, T. Bastein
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Longer Lifetime for Products: Benefits for Consumers and Companies
Elmer Rietveld, David Peck & Carlos Montalvo
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Book rapporteur: Forward Looking Workshop on Materials for Emerging Energy Technologies. D Peck, Chapter 10 author: chapter title Materials and Design
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