Optimizing the use of critical materials in the built environment

using Building Information Modelling

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Optimizing the use of critical materials in the built environment using Building Information Modelling (BIM)

by
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Preface

This research is the final assignment of the Master track Building Technology at the faculty of Architecture, Urbanism and Building Technology at Delft University of Technology.

Innovation and sustainability have always triggered me. The interest in information technology and my curiosity and willingness to learn new things led to the combination of topics for this research. In October 2017 I started this research with BIM as a starting point, supported by my mentor Boris Bähre. Without a clear objective for this research in mind, I started looking for possibilities of BIM concerning sustainable designs and material efficiency. In December I met for the first time with my other mentor; David Peck. David introduced me to the topic critical materials, warning me I should not focus on this topic because of its complexity. Boris convinced me this could be very interesting focus point and an opportunity. Indeed it was very interesting, leading to a new possibility of using BIM and the introduction of a new topic in the built environment.

Acknowledgements

The last nine months have been an exciting learning process. Throughout the graduation period, I was supported by many people who helped me and have been important to me.

First of all I would like to thank my supervisors for guiding me through this research. It was a bit of a slow start. However Boris Bähre, who was my first mentor at that time, kept enthusiastic and helped me brainstorming on possibilities within my field of interest. David Peck helped me specify my goals and shared his expertise on critical materials; a new and challenging topic which became more and more interesting to me during this research. This became the main topic of this research, which resulted in a mentor switch. From that moment on David Peck was my first mentor. Both supervisors spent a lot of time with me discussing the principles of both topics, each meeting made me more enthusiastic about this research. The network of David helped me connecting to experts on this field. I have been extremely lucky with two supervisors who cared so much about my work and gave me a lot of support.

Finally I would like to thank my friends and family. My roommates for having dinner ready for me after long working days. Jet for giving me inspiration and helping me with the graduation process and presentations. My parents for giving me support and for brainstorming with me. My mother in particular for helping me with the interviews as an experienced interviewer. My father for reading my report over and over again and giving me advise on many different aspects. Last but not least Youri, who kept listening to all my findings and profoundly read my report to give feedback.
I would like to thank all of them for continued encouragement and advice throughout this whole period.

Charley Meyer
Delft, June 2018

ABSTRACT

Keywords: critical materials, built environment, BIM, IFC

The energy transition plays an important role in the building industry. Energy efficient buildings with smart and renewable energy technologies are developments to realize a more sustainable built environment. Photovoltaics, energy efficient lightning and smart grids are examples of these active building components which are broadly implemented to optimize energy efficiency. However, crucial resources for these technologies are critical materials. The European Union outlines critical materials (CRMs) as materials which are highly important for our current economy while the risk of disruption of supply is high. This is not only depending on the limited availability in the earth's crust, but also on the concentration of their mining areas which causes political interventions. To become less dependent on the import of these materials, more attention must be paid on the current stocks of the EU and an optimized use of critical materials. Hence, a circular use of these materials is required to retrieve the critical materials at the end of the life-time of a product. The extreme small quantities of critical materials within many different applications make them hard to trace. Hence, data on the exact location materials and their next opportunity is required. Data about the stocks and flows of critical materials is considered as highly important to the European Commission and new possibilities need to be developed to link information to datasets of dynamic economic models. These datasets should be standardized to easily compare and combine them.

A positive development in the built environment is the increasing use of Building Information Modelling (BIM). A BIM model makes it easy to collect data of the whole lifecycle of a building and share it amongst all involved stakeholders in the process. This data can be easily exported to other formats for further use.

The aim of this research is to test if BIM is compatible to facilitate knowledge of and solutions for critical materials in the built environment. Firstly, relevant information has been determined on critical materials and circular use of building products containing critical materials, to optimize their lifetime. Subsequently, BIM is tested as an approach to process this information into standardized datasets to make it easily accessible and comparable.

As a case study, a sensor has been analyzed to show a relevant example of the current use and composition of objects containing CRMs. Literature and empirical results shows the difficulty of circular use of critical materials. The extreme small components and amounts of critical material make it difficult and labour intensive to dismantle objects containing CRMs. Thereby the recycling rate of critical materials is low. More efficient use of the materials can be achieved through technical changes in designing for a longer lifetime, new business models and more responsibility for manufacturers and users. Documentation of all required information to lengthen the lifetime of CRMs in BIM appears to be an appropriate solution through the use of IFC files. Herein standardized datasets can be created and exported into many formats for further use. On the basis of specified information in IFC's, objects in a BIM model can be find searching for instance for 'critical materials', 'Gallium' or 'Ga' and schemes can be exported outlining this information. Concluding a framework is created which provides information on critical materials, material selection processes, optimized used of the materials and finally converts this data into the so called 'Property Sets' suitable for IFC. A further challenge is the transparency of the supply chain to receive all the required information. To document all elements, full collaboration and transparency from the beginning of the supply chain is required.

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LIST WITH ABBREVIATIONS

AEC	architecture, engineering and construction
BIM	Building Information Modelling
BREEAM	building research establishment environmental assessment methods; assessing, rating and certifying the sustainability of buildings
CAD	computer-aided design; the use of computer software to aid in creation, modification, analysis or optimization of a design
CES	Cambridge Engineering Selector: tool from Granta Design on material selection
CRMs	critical raw materials
EEE	electrical and electronic engineering
EOL	end-of-life
EOL-RIR	end-of-life recycling input rate
EC	European Commission
EU	European Union
FME	organization for Dutch technical industry
HREEs	heavy rare earth elements
HVAC	heating, ventilation and air conditioning
IFC	Industry Foundation Class: data standards that defines an extendable set of consistent data representing building information for exchange and interoperability between AEC software applications (BuildingSMART)
iOS	operating system developed by Apple Inc.
IOT	internet of things
ISO	International Organization for Standardization
IT	information technology
LCA	life cycle analysis
LCD	liquid crystal displays
LED	light emitting diode
LEED	leadership in energy and environmental design, rating system devised by USGBC to evaluate the environmental performance of a building
LOD	level of detail; accuracy of virtual shape representation in BIM
LREEs	light rare earth elements
MEP	mechanical, electrical and plumbing engineering
PCB	printed circuit boards
PIR	passive infrared detectors or pyroelectric sensors
PGMs	Platinum Group Metals (6 elements)
ProSUM	Prospecting Secondary raw materials in the Urban Mine and Mining wastes
PVs	photovoltaics (solar cells)
REACH	registration, evalution, authorization and restricition of chemicals, EU regulation on chemical substances
REEs	Rare Earth Elements (distinguishes HREE and LREE, 16 elements in total)
TNO	Dutch Organisation for Research in Applied Sciences
USGBC	United States Green Building Council
WEEE	waste of electrical and electronic engineering/equipment

Glossary of terms

ArchiCAD	Modelling application generally used for BIM, available for iOS and Windows.
Components	Uniquely identifiable parts or subunits of products which can consist of sub-components (ProSUM).
Elements	Elemental composition of products or components without considering their chemical speciation (ProSUM).
Granta Design	company leading material information technology
Materials	Refers to 'engineered materials' that are composed, manufactured and processed to achieve intended properties (ProSUM).
Placeholder	A simplified or generic representation of a 3D object.
Revit	Modelling application generally used for BIM, available for Windows.
Stocks	The products which are in use or stored before thrown away (ProSUM).
Sub-component	Constituent part of a component.
Substances	Elements with unique and identical constitution and thus homogenous (ProSUM).
Urban mine	All materials stocked in products and buildings around us.

1. INTRODUCTION

BACKGROUND

Over the last century, resource extraction has grown rapidly and is expected to increase even more due to growth in global population and economic development. Especially the environmental impact of the building industry is enormous, as it accounts for the use of 40% of the natural resources and the production of 45-65% of the waste disposed to landfills (Franzoni, 2011).

Another urgent problem we are facing currently is climate change. With increasing evidence of accelerated climate change, urgent actions need to be taken to reduce the carbon footprint. The building industry is a large contributor to CO2 emissions, with buildings responsible for 40% of the total energy consumption (Circulaire Bouweconomie, 2018). To reduce the carbon footprint, the building industry is responding with smart technologies; renewable energy and smart and efficient energy systems.
However, the risk of disruption in the supply of the resources needed for these high-tech industries and renewable energy technologies is high. Researchers and governments like the European Commission labeled them as critical materials. Critical materials can be described as materials which are highly important for our current economy, while their risk of disruption is high. The EU aspires to reduce the dependency on the import of critical materials.
When buildings become more energy efficient and their systems more advanced and complex, the demand for critical resources increases (Ruuska & Hakkinen, 2014). Critical materials are often present in extreme small quantities and provide unique performance characteristics (Peck, 2016). This makes them not easy to substitute and therefore indispensable to achieve sustainable development goals.

While critical materials are obviously highly important, there seem to be significant gaps in awareness and understanding of these materials. Critical materials are elements or combination of elements, which are part of materials. A building technologist or architect does not take this level of detail into account. However, better understanding of these materials could lead to more efficient use. Not only in an adaption of the design of the products containing these materials, but also in the use of these products.

A closure of material loops, better known as circular economy, is necessary to make more efficient use of these resources. Optimizing the design of products for longer lifetimes, facilitating predicted reuse and high intensive recycling can be part of possible solutions (Kohler, Bakker and Peck, 2010). Securing quality and material recovery of the building components needs to be integrated in a very early stage of the design process of a project (Geldermans & Jacobson, 2015). The decision of materials is made during the design phase and the design of the building product affects the potential of reusing or recycling of its components. This phase decides the length of the life of the product, which if shorter, speeds up the rate of the (critical) material consumption (Peck, 2016). Moreover, many critical materials still have very low recycling rates which increases the demand of virgin materials (EASAC, 2016), this makes it urgent to make components containing these materials reusable, instead of recyclable.
The life cycle of the design should be analyzed to optimize the use of materials and to give a better understanding of what is expected during its whole lifetime. The lifecycle of buildings extends from the extraction of raw materials, through the construction and use phases to demolition and eventually waste disposal, reuse or recycling of building components (Herczeg, Mckinnon & Milios, 2014). Life Cycle Analysis of buildings make new type of information necessary compared to a traditional building process. The abundance of needed information requires efficient information technologies.

To make the materials and their components reusable, resource information and data sharing is crucial. Information is required about the location and application of materials and for which future applications they could be used within the Urban Mine. The Urban Mine can be described as all materials stocked in products and buildings around us. According to Umicore (2012), the Urban Mine can be much richer than primary mining ores.
Data about the stocks and flows of critical materials is therefore considered as highly important to the European Commission and new possibilities need to be developed to link information to datasets of dynamic economic models. Datasets need to be standardized to easily compare and combine them. Currently product or building information is described in dissimilar datasets and data about the exact content of materials is generally missing. Information about the stocks and flows of materials via harmonized database systems can be an approach from material, product and waste perspective. To realize this, the content over the full value chain must become transparent (Tukker & de Koning, 2018).

Building Information Modelling (BIM) as a method to organize building processes, can take into account all data needed for the whole life cycle of a building by collecting information from all involved stakeholders. The model can be used during the whole lifetime of the building to make better informed decisions. Documenting all the relevant material data in the model, the model could function as an Urban Mine Platform; a platform wherein data is available on different flows of materials in buildings and products around us.

The Urban Mine of Rotterdam (Arcadis)

Problem statement

Based on the preliminary described background, the problem definition can be described in threefold:

1. The materials needed to realize the energy transition of the built environment towards energy efficient buildings and renewable energy technologies are critical; the risk of a disruption is high, while they are highly important for our current economy.

2. Criticality of the materials seems to be an unknown field in the built environment, while we strongly rely on them.

3. Information about stocks and flows of critical materials is needed; data is missing or only available in dissimilar datasets.

Objective

The aim of this thesis is to facilitate knowledge of, and solutions for, critical materials in the built environment using Building Information Modelling.
The first objective is to find relevant information for building components containing critical materials to optimize their lifetime. The second objective is to test Building Information Modelling as an approach and tool to process the relevant information within standardized datasets.

Research questions

Based on the described objectives, the main research question of this research is formed:

> *Is BIM as an approach compatible to facilitate knowledge and solutions for critical materials in the built environment?*

The main question consists of two parts: the first part focusses on knowledge and solutions for critical materials in the built environment. The second part focusses on BIM and its capabilities. The sub- and background questions reflect the different parts of the research:

1) *What is the level of knowledge about critical materials in the building industry?*

2) *What strategies are available to mitigate critical material problems?*
    - *What are critical materials in the European Union?*

3) *What data of critical materials should be disclosed per phase of the life cycle?*

4) *What role can BIM play to facilitate knowledge and solutions for critical materials?*
    - *What is the role of material parameters in Building Information Modelling processes?*
    - *What steps can be taken to develop critical material data processing?*

Scope

The scope of this research is limited to critical materials in the built environment. Thereby, there is a focus on active building components. Secondly, the scope is limited to the European Union; based on their research, regulations and goals concerning critical materials and circularity.

Keywords: critical materials, built environment, smart buildings, BIM, IFC

Relevance of study

With all developments in the built environment at the moment, this study is highly relevant. With increasing fact of climate change and a thrive to reduce the carbon footprint, the built environment reacts with high-tech systems and renewable energy technologies to reach sustainable development goals. Critical materials are indispensable for the clean energy transition and the aim for energy efficient buildings.

The European Commission is looking for new possibilities to trace materials and receive more accurate information about the stocks and flows of the materials.

Building Information Modelling is increasingly used in architecture, engineering and construction industry to provide a more efficient information flow among all stakeholders.

Methodology

This chapter describes the methods used in order to answer the research questions.

Literature research

The first phase of this research analyses the basic principles of the three topics parallel; critical materials, the circular economy and Building Information Modelling.
An in-depth literature study has been conducted. This research mainly focusses on finding relevant data to optimize the lifetime of critical materials, which can be documented in a BIM model. Literature about critical materials and materials in general is consulted to find relevant information to extend their lifetime. Literature about the optimized material use is mainly focused on circularity. The last part of the literature review is about Building Information Modelling and standardized data. Herein, general literature about BIM as an approach and earlier research on material passports is consulted.

Empirical research

Part of the research is discovering information technology programs to make better informed decisions on the material choice and to process the found data into Building Information Modelling. For material decision making CES Edupack is explored.
To gain experience in the use of Building Information Modelling, practical experiences within different BIM environments has been gathered to find data processing possibilities. The software Revit Autodesk (Windows) and ArchiCAD Graphisoft (Windows and iOS) are mainly used during this research. This thesis explores various methods of processing datasets within BIM.

Case study

The empirical part of this research is supported by a case study to understand the composition of a relevant building product and to process this data into BIM. A building component is chosen as a case study. During the analysis of this building component, relevant information about the composition has been identified and processed into a standardized dataset. This data is tested in different BIM environments; ArchiCAD, Revit, text formats and BIM viewers.

Interviews

The first interview has been developed for the industry and is linked to the case study. Before composing the interview questions, questionnaires and their outcomes have been analyzed on a similar topic. The reviewed interviews have the same objective; namely to identify the response and knowledge of the industry on critical materials. That way the outcomes could be compared with each other to find conceivable differences. Preliminary, a pilot interview has been conducted with a start-up company to test the relevancy of the questions and to get an insight on the knowledge within this industry.
The second interview is conducted after re-consideration since the industry did not seem willing to collaborate on this research. Experts concerning critical materials and circularity with different backgrounds are interviewed to get their perspective on critical materials in the built environment and their documentation. This part has been done in the end phase of this research and serves mainly as a validation.

FRAMEWORK

Based on the results a framework is elaborated step by step. In this framework relevant information about material choices, the application of materials for an optimized lifetime and the corresponding data is outlined.

Finally, conclusions and recommendations for further research are provided. The methodology is outlined in Figure 1.

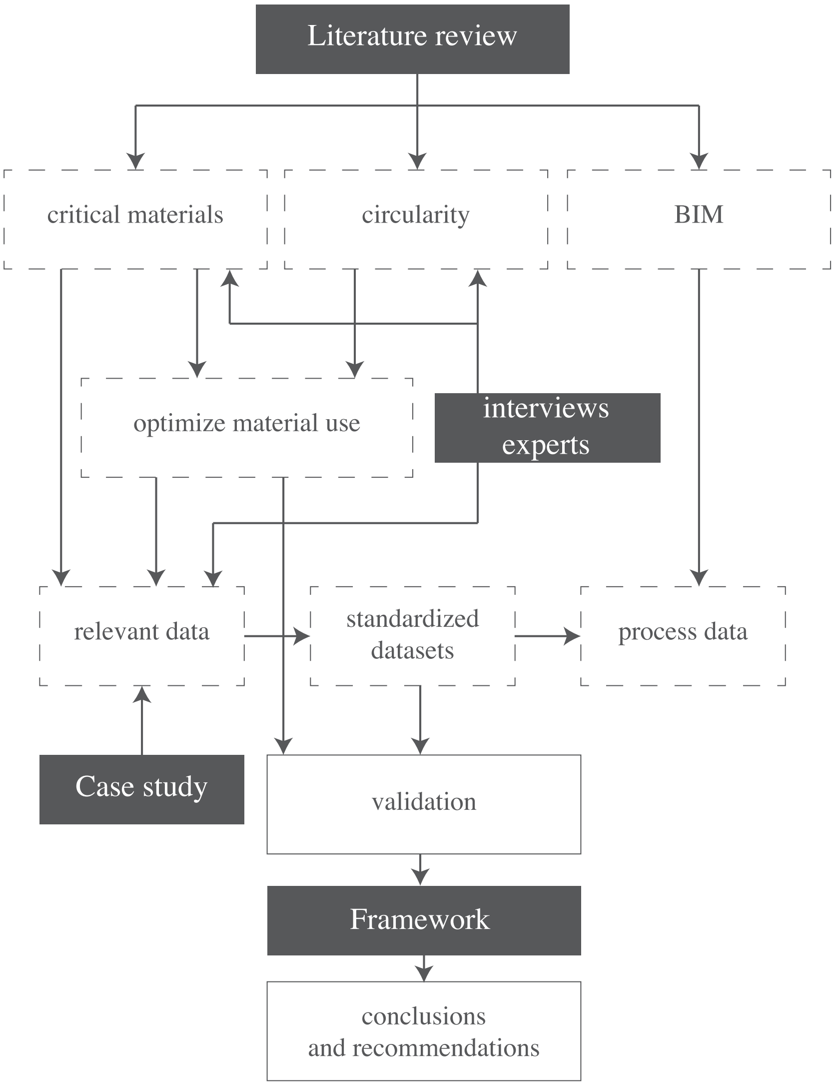

Figure 1 - Methodology

TIMEPLANNING

The Gantt Chart in Figure 2 describes the subdivision of tasks throughout the graduation period. The first phase ends with the P2 report. In the phase before the P3 more tasks were elaborated parallel; finding relevant data, the case study and the interviews. In the phase before P4 the focus relies on the empirical research; processing the data in BIM and conducting the interviews. The P5 period is characterized by the dataset optimization, refining the framework and the report.

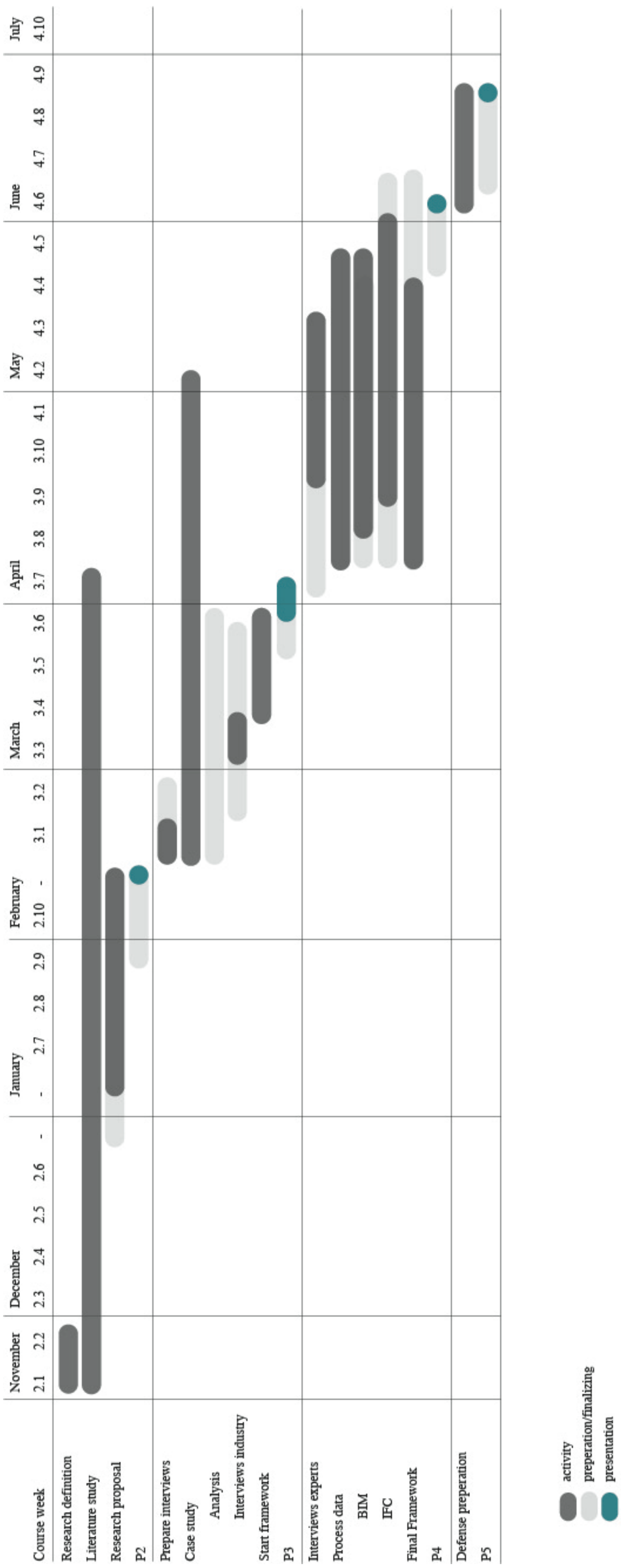

Figure 2 - Time planning

Structure of the report

Chapter 2 describes background information, wherein the considerable problems and developments are discussed.

Chapter 3, 4 and 5 form the basis of the research and describe the results per topic.
Chapter 3 presents results on critical materials in the built environment. Herein, critical materials in general are described and their need in current innovations in the built environment. In this chapter the selection of materials is discussed. Chapter 4 describes optimized material use, with a focus on circularity of materials and building components. In chapter 5 material information technology is outlined. Connected to the previous chapters, the need for material information and possibilities within Building Information Modelling are extensively described.
In the end of each chapter the results will be discussed in the chapter conclusion and step by step a framework is created.

Chapter 6 describes the case study, an analysis of a sensor, wherein the relevant data of this case study will be identified and tested within Building Information Modelling. Chapter 7 describes the interviews conducted for this research. Outcomes of the interviews are already mentioned within the basis of this report (chapter 3, 4 and 5).

In chapter 8, this thesis is concluded and discussed. Also recommendations for further research are described. The reflection on this research and topics can be found in chapter 9. Ultimately all appendices can be found in the last part of this report.

Electronic components (Umicore)

List of critical materials

List of critical materials according to the European Commission (2017):

Sb		Antimony
Ba		Baryte
Be		Beryllium
Bi		Bismuth
Bo		Borate
Co		Cobalt
-		Coking coal
-		Fluorspar
Ga		Gallium
Ge		Germanium
Hf		Hafnium
He		Helium
HREEs + LREEs		Heavy and Light Rare Earth Elements (HREEs and LREEs)
	Ce	Cerium
	Dy	Dysprosium
	Er	Erbium
	Eu	Europium
	Gd	Gadolinium
	Ho	Holmium
	La	Lanthanum
	Lu	Lutetium
	Nd	Neodymium
	Pr	Praseodymium
	Sm	Samarium
	Sc	Scandium
	Tb	Terbium
	Tm	Thulium
	Yb	Ytterbium
	Y	Yttrium
		* The only exception of HREE and LREE is Promethium (Pm)
In		Indium
Mg		Magnesium
C		Natural graphite
-		Natural rubber
Nb		Niobium
PGMs		Platinum Group Metals
	Pt	Platinum
	Os	Osmium
	Ir	Iridium
	Ru	Ruthenium
	Rh	Rhodium
	Pd	Palladium
-		Phosphate rock
P		Phosphorus
Sc		Scandium
Si		Silicon metal
Ta		Tantalum
W		Tungsten
V		Vanadium

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2. BACKGROUND INFORMATION

2.1 Grand challenges

The world is facing enormous challenges. Our climate is changing, global warming is a fact and overpopulation only makes this worse. Carbon emissions from human activities are driving climate change and continue to rise. We are experiencing significant impact of climate change, which include natural disasters, a rising sea level and more extreme weather events. Continuing the current case of events will cause further warming and long-lasting changes, unless the billions of tons of annual emissions worldwide decrease substantially (European Commission, 2015).
This is globally more acknowledged and parties all over the world are working together to find solutions and to set goals. Sustainable Development Goals (SDG's) have been set by the United Nations, which cover 17 global goals among others on climate action, sustainable cities and clean energy. Sustainable development can be defined as complying the needs of the present without influencing the ability of future generations to meet their own needs. These goals resulted in the United Nations Climate Change Conference 21st session (COP21), which took place in 2015 in Paris. This global agreement aims for a reduction of climate change and is signed by 17 countries (European Commission, 2015).

2.2 Planetary boundaries

Continuous economic growth increases the demand for resources, while the availability decreases. 'The limits to growth' was first mentioned in 1972 by Dennis Meadows; according to him the earth's interlocking resources could probably not support present rates of economic and population growth far beyond the year 2100. This led to a study of researchers at the Massachusetts Institute of Technology (MIT) of the implications of continuing worldwide growth. Herein they examined the five basic factors that determine the ultimately limit to growth on this planet; population increase, agricultural production, non-renewable resource harvesting, industrial output and pollution generation. Forward casting of these factors within a computer model, brought them to different scenarios wherein eventually the population would collapse and the environment damaged (Figure 3) (Meadows, 1972).

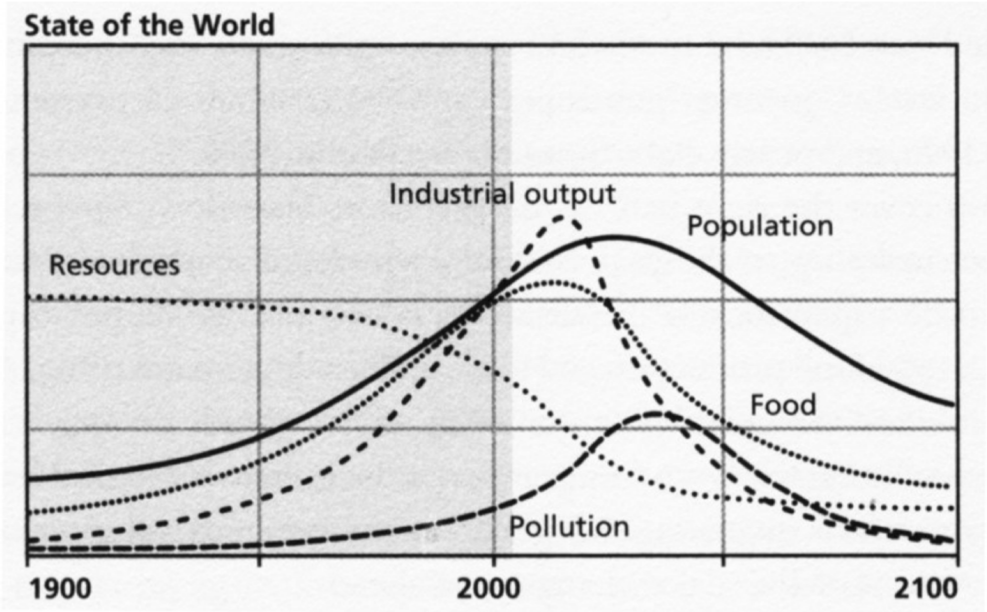


Figure 3 - Limits to growth study 1972 (Meadows, 1972)

The term planetary boundaries is often mentioned regarding to resource use. This concept was introduced by Rockström et al. (2009) to show the limits of our planet. It describes nine planetary boundaries related to climate change, to avoid major human-induced environmental change on a global scale (Rockström et al. 2009; CBS, 2015).

Especially the environmental impact of the building industry is enormous, as it accounts for the use of 40% of the natural resources and the production of 45-65% of the waste disposed to landfills (Franzoni, 2011). The continued population growth and increase in prosperity are the most important factors. Urbanization results in increasing use of raw materials for building construction, but also water supply and sewage systems, roads and other facilities (Bastein et al., 2013).

A broadly accepted goal for a sustainable future is an extreme reduction in the use of raw materials and material efficiency is a way to reduce this demand (Berge, 2009). In a roadmap of the European Union to a resource-efficient Europe, the buildings sector is highlighted as one of the key sectors for improvements. Improved construction and better use of buildings in the EU would have a positive impact of 42% on the energy consumption, approximately 35% on our greenhouse gas emissions and more than 50% on all extracted materials (Ruuska & Hakkinen, 2014).

2.3 Energy efficient buildings and cities

The built environment is a large contributor to CO2 emissions and is responsible for 40% of the total energy consumption (Circulaire Bouweconomie, 2018). To reduce the carbon footprint, the building industry responds with high-tech technologies; renewable energy and energy efficient systems. The use of technologies creates smart buildings which are operationally more efficient for its users. Certifications for environmental performance of a building such as LEED (Leadership in Energy and Environmental Design) are often a key objective for the project developer and the design team. According to USGBC, the developer of LEED, smart buildings are the future of green building design and construction, containing renewable energy systems and high-tech solutions, e.g. sensors, LEDs and solar panels.

This energy transition in the built environment is the ambition of the government, leading to requirements on energy usage of buildings in the near future. In the Netherlands the government aims to reduce CO2 emissions from the built environment by 80% in 2050 compared to 1990. Amongst others, by realizing that the built environment will be gas free and energy neutral in 2050 (Rijksoverheid, 2018). This transition means the built environment has to generate electricity from solar panels, install heat pumps, electricity grids and other sustainable energy sources need to be explored. Also urbanization is a fact. The growth of population leads to more households, which requires more new residences. Expected is that the majority will settle in the big cities (CBS, 2016). These new residences and urban expansion have to be build following the requirements towards sustainable development.

2.4 Building Information Modelling

In the last decade the traditional processes in the architecture, engineering and construction industry made place for more efficient approaches due to a better understanding of integrated processes and the help of technology. In the traditional process, many parties work separately on different aspects of a building. Moreover, there is a static hierarchy of decision making where every phase has to deliver specifics. These cause a slow process, making communication and design changes challenging. The use of computer tools such as CAD has been progressive, but these are still just digital replications of layer based paper drawings. Next, Building Information Modelling was introduced; an integrated process that involves collaboratively developing and using a computer generated virtual representation of a building. This made place for a dynamic decision-making process and an organizational change with improved communication and data sharing (Durmisevic, 2010). Within BIM, a virtual representation of a building is shared among many stakeholders, wherein information over the whole lifetime is shared. This provides a better integrated process with collaboration between all stakeholders. A BIM model is meant to contain a lot of data, which can be broadly used within the building process and is advantageous for different activities. Building Information Modelling is increasingly used in the architecture, engineering and construction industry to provide a more efficient information flow amongst all stakeholders.

2.5 Critical materials

Natural resources are usually defined as ‘renewable’ or ‘non-renewable’. Renewable resources can be renewed or harvested, for example timber. Although renewable resources also have their limits. Non-renewable resources can only be harvested once, often referred to as ‘stocks’. A large part of those resources is seriously limited; metals and fossil oils are generally known as limited, but in certain areas even materials such as sand and gravel are becoming scarce (Berge, 2009). Lately high concerns are being expressed by governmental parties about a certain group of the non-renewable materials. High-tech applications and renewable energy technologies require specific materials, the risk of a disruption in the supply of those resources is very high. Researchers and governments like the European Commission labelled those resources as critical materials. Critical materials are materials which are highly important for our current economy.

RESEARCH ON CRITICAL MATERIALS IN THE BUILT ENVIRONMENT

Bismuth (Theodore Gray)

3. RESEARCH ON CRITICAL MATERIALS IN THE BUILT ENVIRONMENT

3.1 Introduction

The exact selection and weighting of factors which make a raw material critical differs. For instance, if materials are of national significance for economies and their supply is at risk, other sources of criticality may originate from price volatility and supply restrictions (Peck, 2016) or specific ecological, social, or political considerations (Ruuska & Hakkinen, 2014).

In this research the definition of critical materials of the European Commission is considered. The main parameters used to determine the criticality of materials for the EU are:

- Economic importance; Insight into the importance of a material for the EU economy in terms of end-use application and the value added of corresponding EU manufacturing sectors.
- Supply risk; Reflects the risk of a disruption in the EU supply of the material. It is based on the concentration of primary supply from raw materials producing countries, considering their governance performance and trade aspects (European Commission, 2017).

The thresholds of these parameters are shown in Figure 4. The criticality is among others caused by the limited amount of countries accounting for the share of critical materials of EU supply, shown in Figure 5 and Figure 6. Among 90 percent of the critical materials in Europe must be imported, primarily from China (Rijksoverheid, 2016).

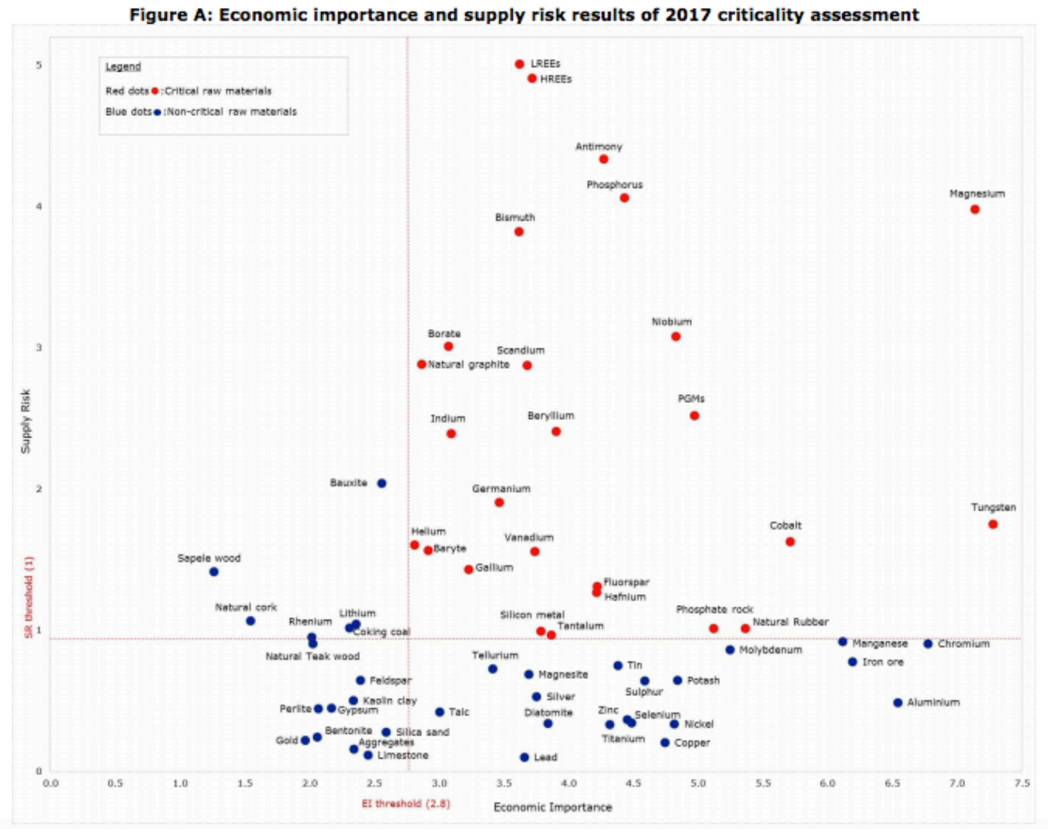


Figure 4 - EU diagram CRMs - supply risk vs. economic importance (European Commission, 2017)

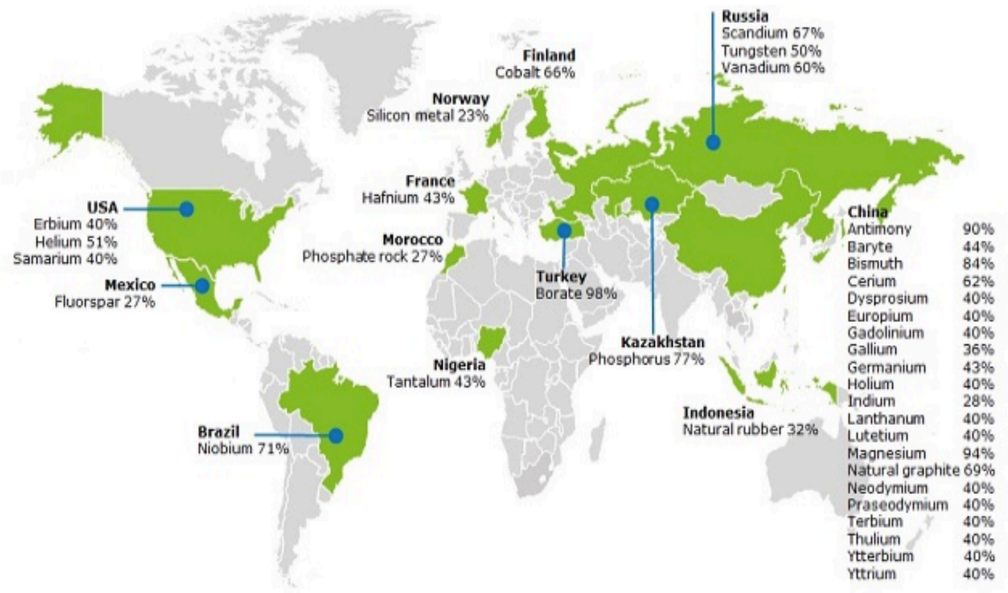


Figure 5 - Countries accounting for largest share of EU supply of critical materials (European Commission, 2017)

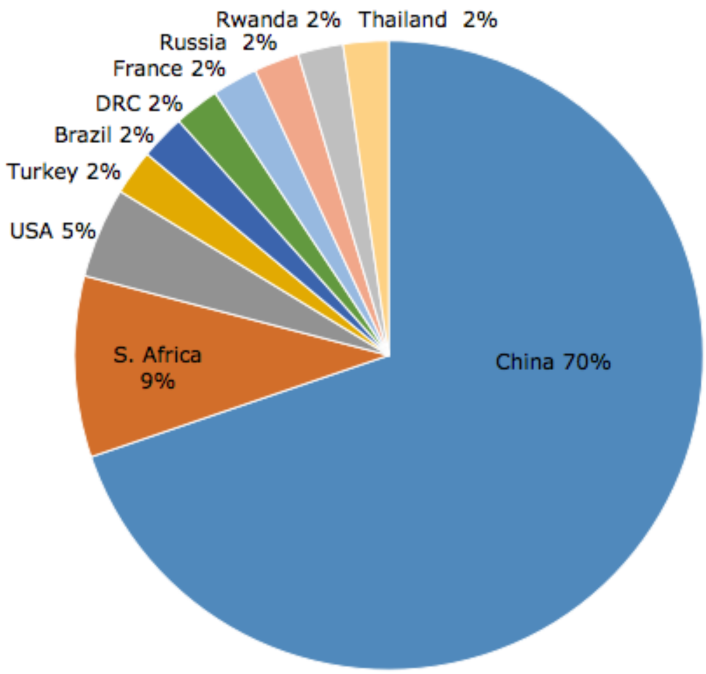


Figure 6 - Global suppliers of CRMs EU 2010-2014 (European Commission, 2017)

The EU aspires to reduce the import dependency of critical materials. In this respect, critical materials resource information and data sharing is crucial. In 2011, 2011 and 2017 the European Commission released a report on critical materials with a list of critical materials according to their parameters. Comparing the critical material lists of 2011, 2014 and 2017, the amount of CRMs increases (European Commission, 2017). The number of critical materials in Table 1, includes three groups of materials merged per group (Light Rare Earth Elements (LREEs), Heavy Rare Earth Elements (HREEs) and Platinum Group Metals (PGMs)). Most critical materials are elements of the periodic table, seven critical materials from the current EU list are chemical compounds, which means those are combinations of elements (Figure 7).

Since buildings have a long lifetime, the criticality of materials within the building could change during its existence or even before its construction. In reality the choice of the material should not be made only on the basis of the EU list, since criticality varies per moment (Goddin, 2018). A useful tool to review the criticality of a material is CES Edupack. In this program, resources can be found based on their properties and other linked information. This will be further discussed in chapter 3.4.

Table 1: CRMs lists of EU – (European Commission, 2011; 2014; 2017)

Element	2011	2014	2017	EOL-RIR*
Number of elements	15	19	27	-
Antimony	x	x	x	28%
Baryte			x	1%
Beryllium	x	x	x	0%
Bismuth			x	0%
Borate		x	x	0%
Chromium		x		13%
Cobalt	x	x	x	0%
Coking coal		x	x	0%
Fluorspar	x	x	x	1%
Gallium	x	x	x	0%
Germanium	x	x	x	2%
Graphite	x			0%
Hafnium			x	1%
Helium			x	1%
HREE**	x		x	8%
Indium	x	x	x	0%
LREE**	x	x	x	3%
Magnesite		x		0%
Magnesium	x	x	x	9%
Natural graphite		x	x	3%
Natural rubber			x	1%
Niobium	x	x	x	0.3%
Platinum Group Metals	x	x	x	14%
Phosphate rock		x	x	17%
Phosphorus			x	0%
Scandium			x	0%
Silicon metal		x	x	0%
Tantalum	x		x	1%
Tungsten	x	x	x	42%
Vanadium			x	44%

* EOL-RIR: 'End-of-life Recycling input rate' measures the ratio of recycling from old scrap

** HREE/LREE: Heavy and Light Rare Earth Elements, list of 16 elements in total

The end-of-life recycling input rate (EOL-RIR) measures which part of total material input into the production system comes from recycling of old scrap. It does not take into account scrap that comes from manufacturing processes; new scrap (European Commission, 2017). The EOL-RIR of critical materials is generally low (Table 1), which makes the recycling contribution of CRMs insufficient to meet the growing demand. For a few CRMs the EOL-RIR is relatively high, this can be explained by the high collection rate of these materials, namely vanadium, tungsten, cobalt, antimony and some Platinum Group Metals (PGMs). Circularity of CRMs strongly benefits from take back-schemes (Mathieux et al., 2017).

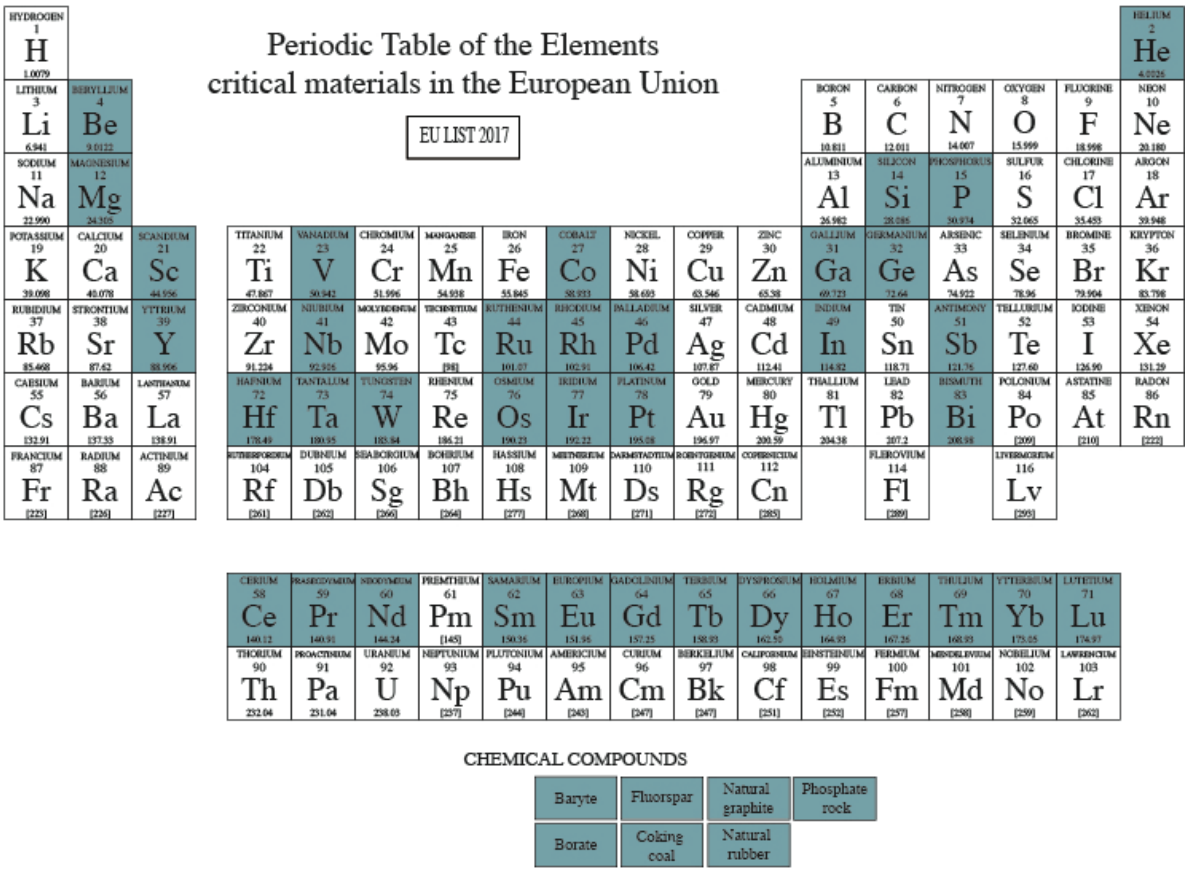


Figure 7 - Periodic table with CRM elements of EU list 2017 indicated in green

Energy efficient lightning (Umicore)

3.2 Applications of critical materials

Critical materials are primarily found in high-tech industries; electronic gadgets and sustainable technologies rely heavily on the use of CRMs. High tech industries and renewable energy are essential for energy efficient buildings to reduce the carbon footprint. When buildings become more energy efficient and their systems more advanced and complex, the demand for critical resources may increase (Ruuska & Hakkinen, 2014). Applications of critical materials are for example energy efficient lightning (LEDs), wind turbines, electric vehicles, permanent magnets, batteries, sensor technology and photovoltaics (PVs) (European Commission, 2018). Analysing the components of EEE applications, there are some basic components which are used frequently. Mostly used are resistors, capacitors, diodes, light-emitting diodes (LEDs), transistors and integrated circuits (Lowe, 2012).
Critical materials are only used in very small amounts; grams to even milligrams per component (Cuchiella, 2015). Their unique performance characteristics make them essential and often not easy to substitute. Hence the substitution of the CRMs is not desired; it changes the properties and performance of a product, it often requires high financial and environmental costs and thereby it can lead to a long delivery time (Peck, 2016).

Besides Electrical and Electronic Equipment (EEE) for smart technologies and renewable energy within buildings, critical materials can be important in constructions. Critical materials are often used to reduce weight and volume in construction (Goddin, 2018), for instance in light-weight super alloys. According to Goddin (2018), for construction purposes there is always a compromise between the performance you get from the materials and the amount of critical materials within the structure. The application of critical materials in construction ensures durability of components, which facilitates reuse, remanufacturing and refurbishment (Peck, 2016).

The built environment and especially its sustainability and efficiency is increasingly depending on electrical and electronic equipment and thereby on critical materials. Common applications per critical material of the 2017 list of the European Commission are shown in Table 2.

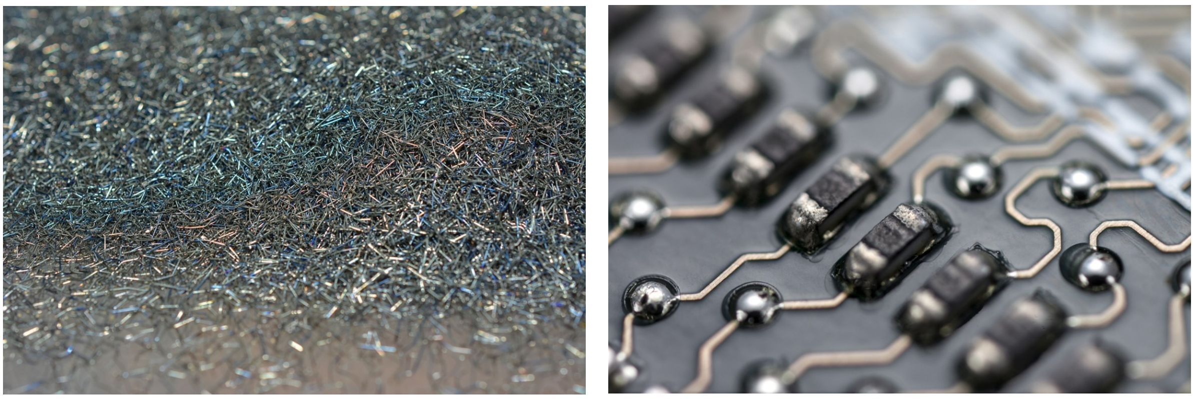


Figure 8 - Tantalum supply and application within motherboard (AZO Materials)

Table 2: Common applications per critical material from EU list 2017

	CRM	applications
Sb	Antimony	Flame retardants as lamination for other materials (43%); alloys with other metals (mostly with lead) (14%); lead-acid batteries (32%); cable sheathing [1; 2]
Ba	Baryte	Filler in paint, rubber, paper and plastics, filler in concrete to increase density for special applications such as radiation shielding, glass, coating for corrosion [1]
Be	Beryllium	Alloy with copper, aluminum, magnesium and nickel, magnetic applications, electronic and tele-communications equipment, energy applications. Copper Beryllium is used in electronic and electrical connectors, batteries and chips [1]
Bi	Bismuth	Low melting alloys [1], pigments (paint), metals and alloys with other metals, automatic sprinkler systems for fires, lead replacement, precision machining properties [1]
Bo	Borate	(Fiber)Glass, ceramics, basic metals (iron and steel) [1]
Co	Cobalt	Superalloys, hard materials, batteries and accumulators, metal structures, treatment and coating of metals, paints and coatings, magnetic and optical media [1]
-	Coking Coal	Furnace and metallurgical coke as a input in coking ovens, resulting product is carbon and steel [1]
CaF2	Fluorspar	Steel and iron making, domestic appliances, electric lightning, cooling and ventilation equipment [1]
Ga	Gallium	Manufacturing of Integrated Circuits and optoelectronic devices, semiconductors, low-melting alloys (tin), thermometers, biomedical applications [3], Electric Lightning Equipment (LEDs), CIGS solar cells, wireless communication systems [1]
Ge	Germanium	Optics (wide angle camera lenses, microscopy, optical fibers in communication equipment, infrared), electronics (chips, photovoltaic cells, fluorescent lamps, LEDs) catalysts PET, metal alloys [2]
Hf	Hafnium	Base metal alloys (nickel-based super alloys), machinery parts [1]
He	Helium	Semiconductors, optical fibres, welding, [1]
REE	Heavy and Light Rare Earth Elements	(Heavy and Light Rare Earth Elements; s set of in total 17 elements in the periodic table): Catalysts, metallurgy, permanent magnets, power transistors, chips, batteries, fluorescent lighting [1; 3], LEDs, glass, ceramics, polishing [1]
In	Indium	Mainly in thin-film coatings (55-85%; PV cells, Flat panel displays, solders), electronics (transistors, rectifiers, thermistors, photoconductors), low melting allows, LEDs, batteries [1; 3]
Mg	Magnesium	Transportation, light metal packaging, metal structures, other metal products [1]
C	Natural Graphite	Refractories for steelmaking and foundries, basic iron and steel alloys, flat glass, batteries [1]
-	Natural Rubber	Rubber tyres and tubes, electric domestic appliances, pumps and compressors, kitchen furniture [1]
Nb	Niobium	Steel production (construction and pipelines), superalloys, superconducting magnets [1]
PGM	Platinum Group Metals	(Group of six elements) Electronics, glass with high processing temperatures; among others glass fibres and LCD manufacture [1]
P	Phosphate Rock Phosphorus	Electronics, metal products, treatment and coating of metals [1]
Si	Silicon metal	Welded aluminium components, special lamps, electrical equipment, metal structures and parts of structures; photovoltaics[1]
Ta	Tantalum	Corrosion resistance. Superalloys, electronic components [1]
W	Tungsten	Hard metals (50%), steel alloys, armaments, (nickel, iron, cobalt), halogen lamps [2], other lightning and electronic uses [1]
V	Vanadium	HSLA (high strength low alloy, e.g. pipes), special steel (carbon), superalloys [1]

1. European Commission (2017)
2. USGC, National Minerals Information Center (2016)
3. Sabur (2016)

3.3 Level of knowledge of critical materials in the built environment

In the built environment most systems to make buildings more sustainable by energy efficiency and renewable energy, rely on critical materials. Important examples are photovoltaics (PV's), heat exchangers, the electricity grid, heating- and cooling appliances and energy efficient lightning (Zeph et al., 2014). This makes critical materials highly important in the current energy transition of the built environment.

A building product, which is in this research an active building component, consists of a large number of sub-components. Each sub-component consist of one or more materials, which are built up from elements (Figure 9). Those elements are in fact the critical materials. Each element has their own lifecycle before they come together into one product; origin, transport, refining process and more.

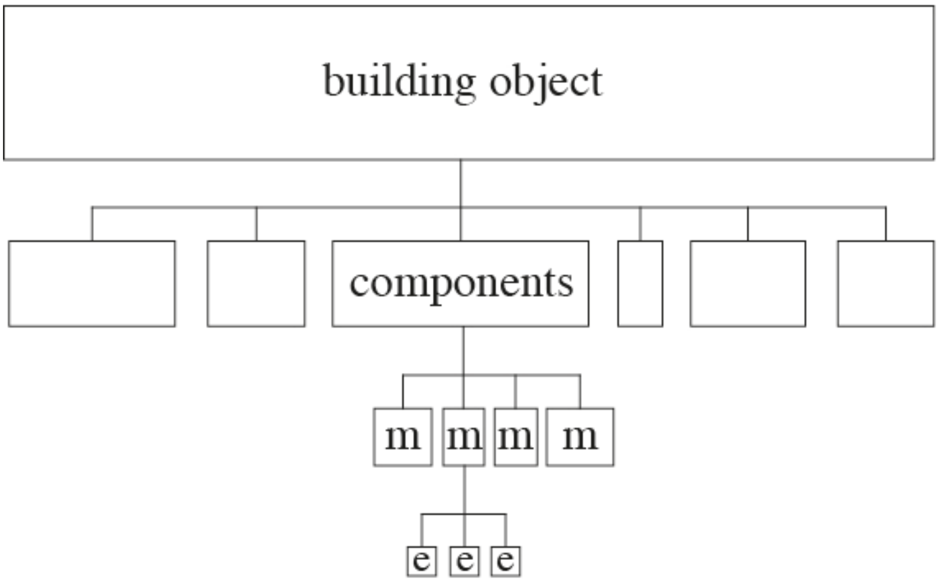


Figure 9 - Simplified scheduled wherein critical materials are miniscule element of a building object

This makes tracing of the CRMs highly difficult. Elements are usually not mentioned in product overviews and, due to sub-assemblies, information about these elements is often not available (Personal communication attachment A3, 2018; Van Beek, 2018). The elements in the above- mentioned applications, are often present in smaller amounts than 1 gram. For instance, a single mobile phone contains among others 24 mg of gold, 250 mg of silver and 9 mg of Palladium (Veit & Bernandes, 2015).
Companies who manufacture subassemblies into a final product might not know that they are using these materials. According to Van Beek (2018), most companies are not aware of what critical materials are and that they are using these materials in their own products.

"All it takes really is a significant risk to happen that embodies itself in an economic matter … and then we will see an increase in awareness and a scramble for information." (Goddin, 2018)

This moment could arrive too late for companies to adapt their design, business models or other measures to be taken to mitigate the supply risk. During the interviews, described in chapter 7, none of the invited companies were willing to collaborate, with the exception of the pilot interview. A possible cause for this unwillingness to participate is that there no interest and possibly no knowledge about critical materials in this industry.

FME, an organization for the Dutch technical industry, aims to mitigate the supply risk of critical materials. The ‘**Grondstoffenscanner’**, launched in April 2018, is an online platform is developed by among others FME and TNO for producers to examine the content of products and the criticality of its materials. The factsheets of the Grondstoffenscanner explain among others where raw materials come from and how critical they are. Also trading perspectives to limit the risk are expounded, suitable for companies with different strategies (van Beek, 2018).

3.4 Material choice

3.4.1 A complex process

The choice of material is one of the four fundamental variables to consider when designing a new product, together with the function of the object, the shape per component and the desired manufacturing process (Fairfull et al., 2016). Ashby (2005) clarifies that function, material, shape and process cannot be seen separately (Figure 10). To make the shape which is determined for the function, the material is subjected to processes that, they include primary forming processes (e.g. casting or forging), material removal processes (e.g. machining or drilling), finishing processes (e.g. polishing) and joining processes (e.g. welding).

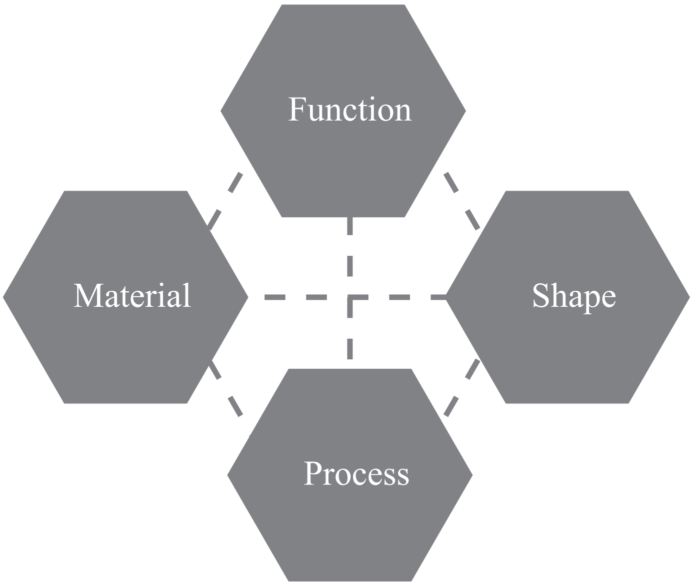


Figure 10 - Material, Function, Shape and Process cannot be seen separate (adopted from Ashby, 2005)

The choice of materials can be complex. A material can be defined by hundreds of attributes (Figure 11). Therefore, extensive knowledge of materials and their properties is required (Fairfull et al., 2016). Each material has attributes like density, strength and resistance to corrosion. A design requires a certain combination of these (Ashby, 2005). To find the most suitable material for a component, there has to be looked into at the specific function of material in the product (Kohler et al., 2010). Also, the local environment has to be taken into account due to its chemical and physical conditions (Berge, 2009). Materials can have their own individual lifecycles which evolve independently from the lifecycle of the whole product. The choice of materials also depends on the quality and performance of the component. When new technologies emerge, or existing technologies evolve, specifications for materials change. Improving the performance of components means that better materials are required (Zeph et al., 2014).

Class	Property	Symbol and units	
General	Density	ρ	(kg/m^3 or Mg/m^3)
	Price	C_m	($/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K	(GPa)
	Yield strength	σ_y	(MPa)
	Ultimate strength	σ_u	(MPa)
	Compressive strength	σ_c	(MPa)
	Failure strength	σ_f	(MPa)
	Hardness	H	(Vickers)
	Elongation	ε	(–)
	Fatigue endurance limit	σ_e	(MPa)
	Fracture toughness	K_{IC}	(MPa.m$^{1/2}$)
	Toughness	G_{IC}	(kJ/m^2)
	Loss coefficient (damping capacity)	η	(–)
Thermal	Melting point	T_m	(C or K)
	Glass temperature	T_g	(C or K)
	Maximum service temperature	T_{max}	(C or K)
	Minimum service temperature	T_{max}	(C or K)
	Thermal conductivity	λ	(W/m.K)
	Specific heat	C_p	(J/kg.K)
	Thermal expansion coefficient	α	(K^{-1})
	Thermal shock resistance	ΔT_s	(C or K)
Electrical	Electrical resistivity	ρ_e	(Ω.m or $\mu\Omega$.cm)
	Dielectric constant	ε_d	(–)
	Breakdown potential	V_b	(10^6 V/m)
	Power factor	P	(–)
Optical	Optical, transparent, translucent, opaque	Yes/No	
	Refractive index	n	(–)
Eco-properties	Energy/kg to extract material	E_f	(MJ/kg)
	CO_2/kg to extract material	CO_2	(kg/kg)
Environmental resistance	Oxidation rates	Very low, low, average,	
	Corrosion rates	high, very high	
	Wear rate constant	K_A	MPa^{-1}

Figure 11 - Design limiting material properties and their usual SI units (Ashby, 2005)

3.4.2 CES Edupack

Practical software to find materials by filtering their attributes is the material and process selection platform Cambridge Engineering Selector (CES) Edupack from Granta Design.
CES EduPack supports decision making for a large set of possible materials in engineering, science, processing and design. Besides being a rational and systematic approach for material selection, CES provides technical, economic and environmental property information about the materials. The systematic approach to materials selection helps optimizing the materials choices to maximize product performance and minimize cost. Besides finding suitable materials by properties, it can also filter on other criteria as joining, shaping and treatment processes.

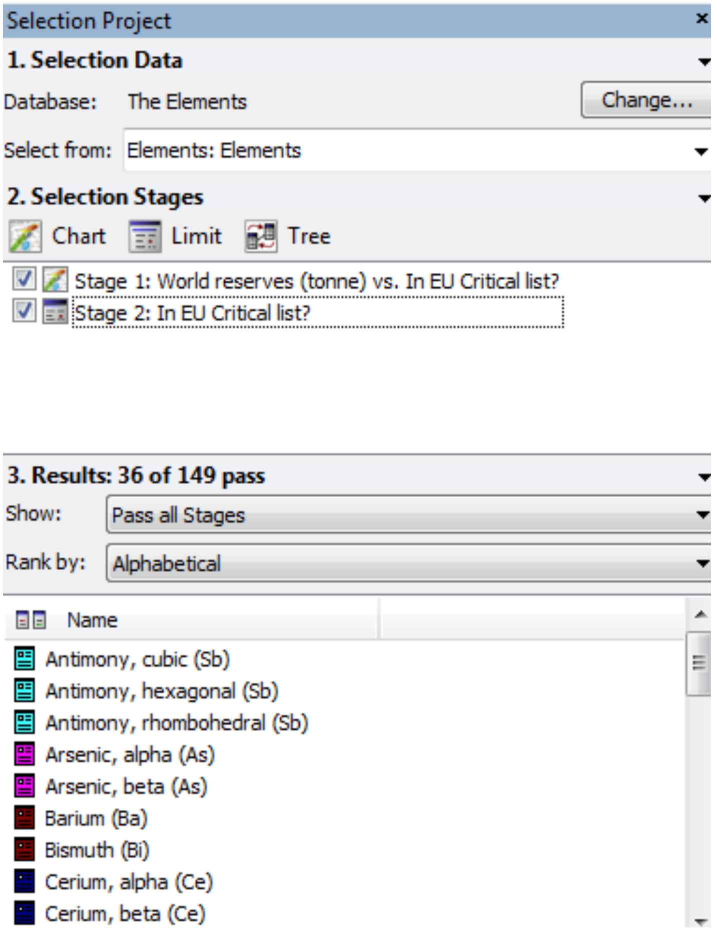


Figure 12 - Selection stages within CES Edupack (source: CES Edupack)

Different databases with about 4000 different materials can be consulted, depending on the accuracy and material types to search for. Within the selection stage there are three options which are shown in Figure 12. These options are charting attributes against each other, limiting materials by inserting values for a wide range of attributes and ‘Tree stages’. A ‘Tree stage’ can be used to filter materials in the database base on their relationship to other records. This can include the links between materials, processes and shapes. For example by excluding a material that cannot be formed into the desired shape or manufactured using a certain process. For each material and process a detailed overview can be opened to learn more about their properties, possible end-of-life treatments and corresponding manufacturing processes.

Furthermore, information on the criticality of materials can be found within CES. Substitution can be a strategy that can reduce the dependency on critical materials (Tercerco Espinoza et al., 2015). However, critical materials provide unique performance characteristics, where the product depends on (Peck, 2016). In CES those unique performances can be easily compared between all materials or elements, based on a set of properties and limits. The limiting possibilities concerning criticality of materials, differs per database. In most databases there is a limit available for materials which containing more than 5wt% (mass fraction) critical elements. In the limit selection stage of 'The Elements' more specific information is available (Figure 14). Among others; price volatility risk, sourcing and geopolitical risk level (Herfindahl-Hirschman Index (HHI)), abundance risk level and the EU and US critical material lists.

In Figure 13 the CO2 footprint of primary production is outlined next to sourcing and geopolitical risk Herfindahl-Hirschman Index (HHI), which is a measure of market concentration. Below '2. Selection Stages', the chosen limit 'In EU Critical list' is visible.

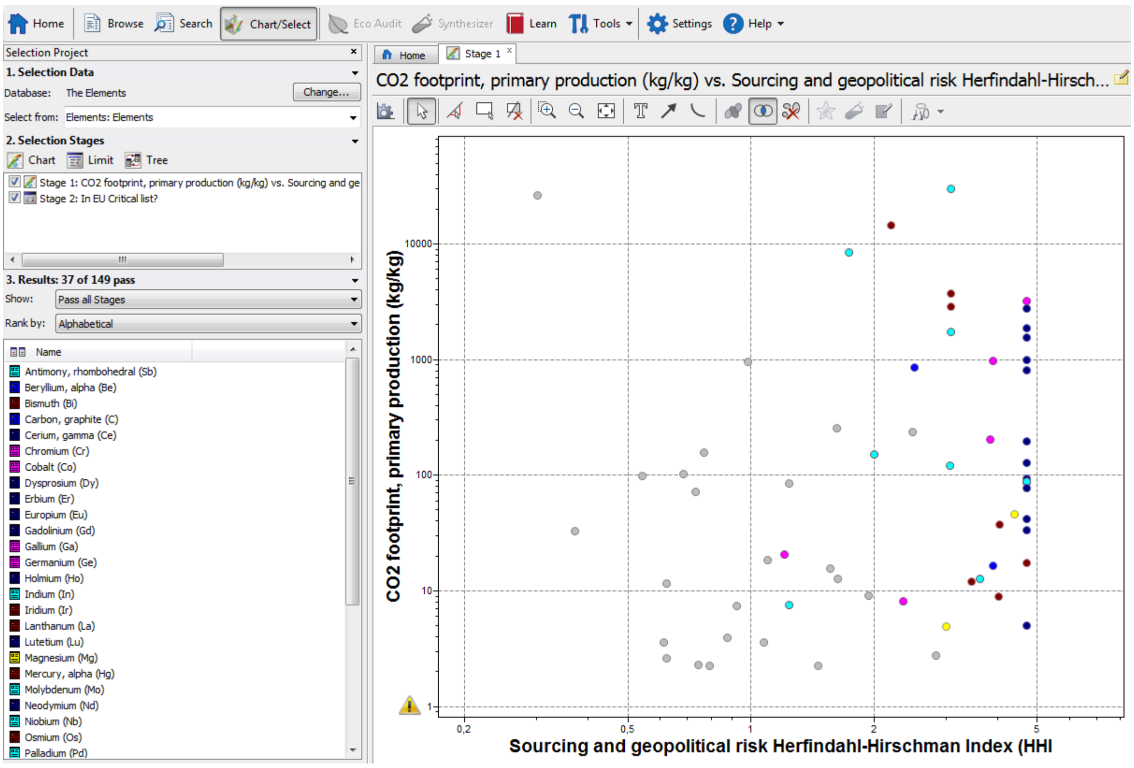
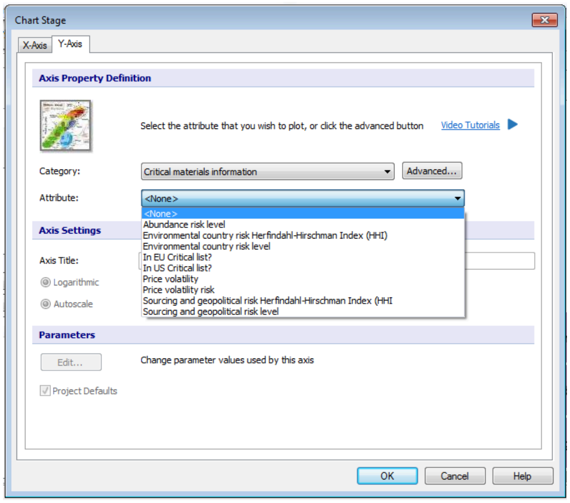


Figure 13 - CES Edupack chart and limit stage (source: CES Edupack)



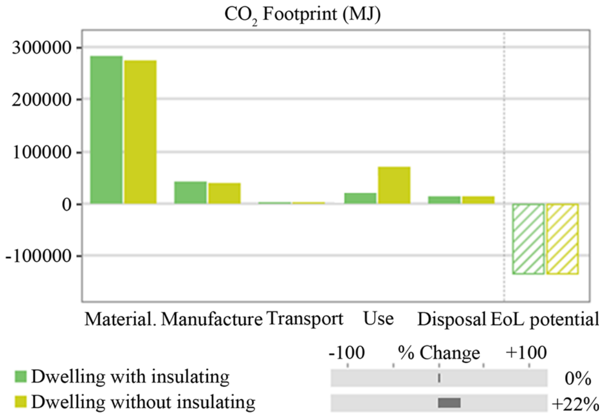


Figure 14 - CES Edupack critical materials information (source: CES Edupack)
Figure 15 – CES Edupack Eco-Audit tool summary chart (source: CES Edupack)

'The Eco Audit Tool' is a tool in CES Edupack appropriate for life cycle investigations, wherein the environmental quality can be measured. Energy use on key life phases of materials is estimated on the basis of the chosen material, manufacturing process, transport, usage and end-of-life scenarios, including circular design principles. Having performed an 'Eco-Audit', the design can be more focused on the life-phase with the greatest environmental impact. An example summary chart is given in Figure 15, also a detailed report is available.

Granta MI is another program from Granta Design which enables consolidation of corporate material information in a controlled database. This makes the data and meta-data fully traceable and it supports open access, including tools to search, report, apply and integrate data with other systems and programs such as CAD and CAE (Warde et al., 2012).

3.5 Chapter conclusion and discussion

Critical materials are becoming increasingly important in the built environment. The energy transition highly depends on them. In scientific papers about critical materials, buildings are mentioned as important consumers of critical materials. However, the knowledge and awareness of these materials in the built environment seems to be very low. A thorough paper review is conducted on both critical materials and built environment. The results from this research show significant gaps of knowledge around the topics critical materials and the built environment. Important systems for the energy transition within the built environment are mentioned in literature, while the people taking decisions about the placement of those systems might not be aware about their valuable content. Invited companies for an interview did not respond. A possible cause for no response or unwillingness to participate is that there no interest and possibly no knowledge about critical materials in this industry.

Criticality of materials seems to be a difficult issue. The miniscule amounts of CRMs used in products and a composition of sub-assemblies from a large variety of manufacturers makes the tracing of the materials difficult. Also, buildings generally exist for a long lifetime. The criticality of the used materials might change during that lifetime. This means that all materials must be documented and not just the critical materials from the last EU list at that time.

The choice of materials is of significant importance and can be very complex. Many factors have to be taken into account to provide the required quality of a product, but also many other concerns are influential such as accessible production processes, economic factors and the availability of the materials. A useful tool to make a well-informed decision is CES Edupack from Granta Design. Also, the criticality of materials can be taken into account. Not only the CRMs from the EU list, but on the basis of different factors among their availability.

Figure 16 summarizes the steps to take during the material selection process. This is the first part of the framework.

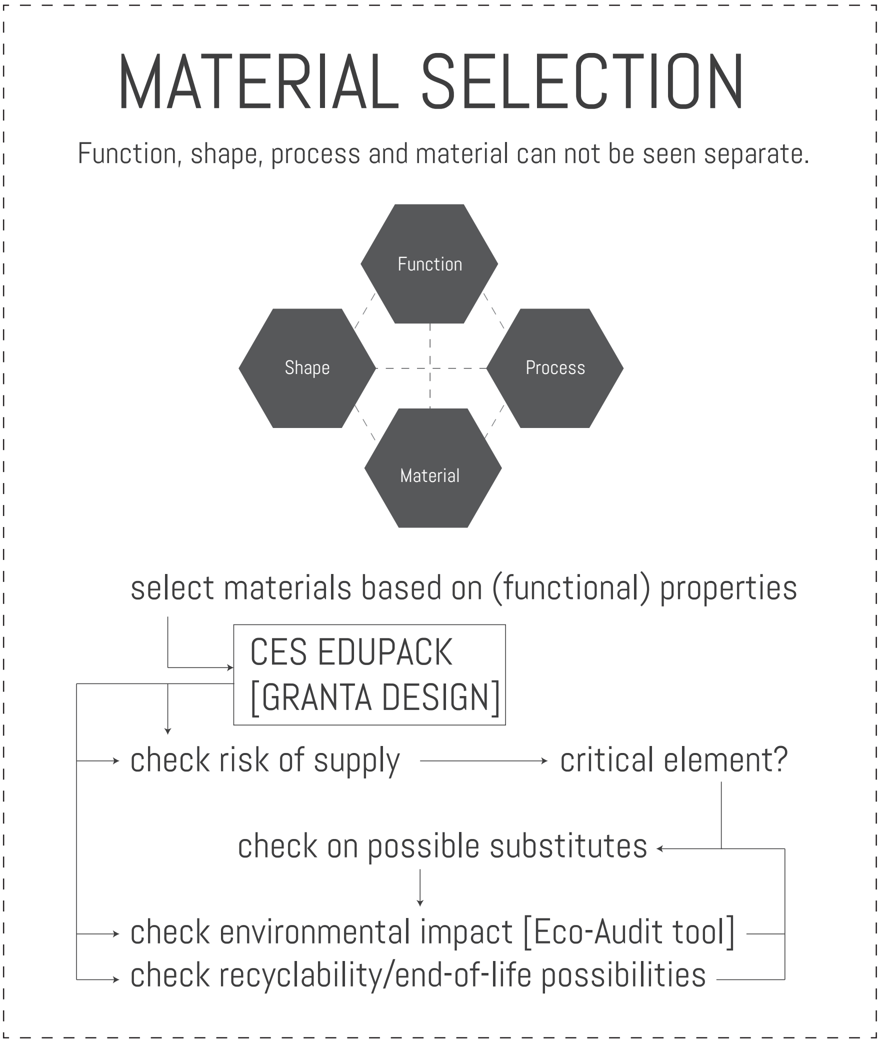


Figure 16 - Framework Part I - material selection

RESEARCH ON OPTIMIZED MATERIAL USE

WEEE man, average WEEE a UK citizen throws away in lifetime (Paul Bonomini)

4 RESEARCH ON OPTIMIZED MATERIAL USE

4.1 TOWARDS A CIRCULAR ECONOMY

4.1.1 LINEAR PROCESS

In a linear process we take, make, use and dispose. In other words a linear flow of materials from 'cradle to grave' (Figure 17). In a linear process, planned obsolescence is frequently the intention of the producer (Rau, 2015). The term 'planned obsolescence' was already mentioned in 1954 by Brooks Stevens, a product designer. Defining it as "instilling in the buyer the desire to own something a little newer, a little better, a little sooner than necessary". Planned obsolescence is the driving force in modern economy wherein many products are designed to last an estimated period. This makes the user buy a new version of the product after a certain time. Studies on planned obsolescence in architecture are very rare, according to Akyurek (2017), who did her PhD about this topic. The limited amount of available studies on obsolescence in architecture point out that economic, political, ideological and psychological reasons affect building lifetimes more than the expected life predictions of the building and construction materials.

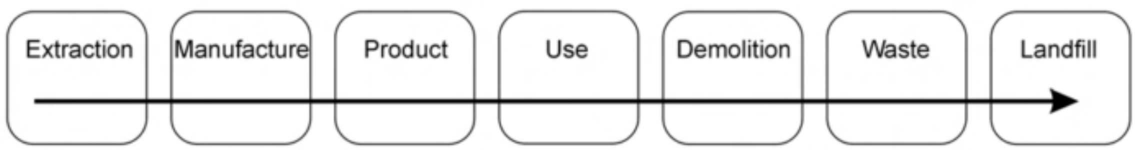


Figure 17 - Linear process materials (Addis, 2006)

4.1.2 CIRCULAR PROCESS

According to the United Nations (Dutch Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2016), the amount of raw materials that humans have extracted from the earth has tripled in the last four decades. This is likely to be caused by the rapid growth of the world-wide middle class. In a circular economy, products, materials and resources are treated within the earth's capacity to provide them in an efficient and socially responsible manner so that future generations can retain access to material prosperity (Dutch Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2016).

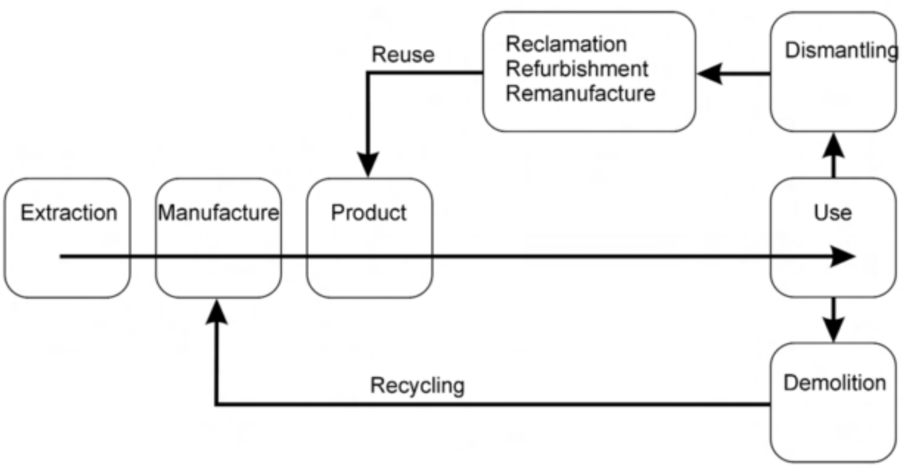


Figure 18 - Circular process, closed loop materials (Addis, 2006)

Optimizing the design of buildings for longer existence and predicting reuse and recycling are essential to create a circular economy. Nowadays, the technical lifetime of a product or building component is often not equal to the technical use time of a building component. This mismatch is caused by the integration of components into fixed assemblies; the replaceability of one component means the demolition of others. In the building industry, building components which could be re-usable end up in landfill. The end of life of buildings is often associated with demolition and waste generation (Durmisevic, 2010).

Circularity can be explained as a regenerative and waste-limited approach of using resources, based on high quality cycles and ideally without the addition of 'virgin' resources and without landfill (Figure 18) (Geldermans & Jacobson, 2015). Therefore, products and components must be designed to be disassembled and regenerated at the end of their lifetime. Similar to biological cycles, the economic system should function in closed loops. The butterfly diagram in Figure 19, from the Ellen MacArthur Foundation (2013), explains the circular system in a value circle and distinguishes between technical (blue) and biological (green) materials, which can achieve circularity in different ways. The system diagram illustrates the continuous flow of technical and biological materials through the value cycle. This is based on three principles: minimize what enters the system, maximize looping and minimize what leaves the system (landfill and incineration).

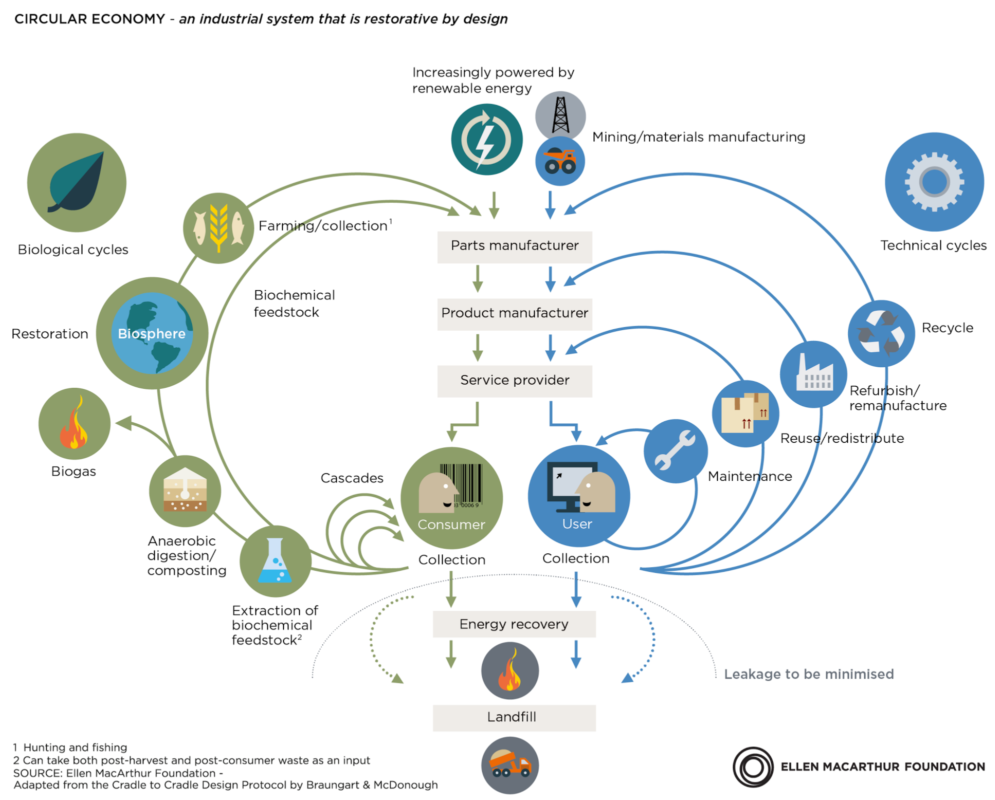


Figure 19 - Butterfly diagram (Ellen MacArthur Foundation, 2013)

An ideal case of a circular economy would be that waste streams and emissions are used to create value, by providing secure and affordable supply of materials and to reduce the pressure on the environment (Bastein et al., 2013). Another advantage of the circular economy is that reuse and recycling of secondary materials positively impacts the average emissions by typically being significantly less energy intensive than primary production (Ruuska et al., 2014). However, most electrical appliances use much more energy during their lifetime than it takes to produce them. Extending the life of a product

may save materials, but it does not necessarily save energy (Ashby, 2016), when products become less energy efficient or more energy effsicient technologies are being developed.
To optimize the circularity of a building it is important to understand their composition. A building consists of several layers or systems: the interior or mobile equipment, the space plan, the services, the skin, the structure and the site (Figure 20). The structure remains the longest time, the other layers are renewed more often. A technical separation between the layers is fundamental for efficient reuse of separate components of the whole building (Berge, 2009). The building components discussed in this research belong to the mobile equipment, which makes assembling or removing of these objects rather easy.

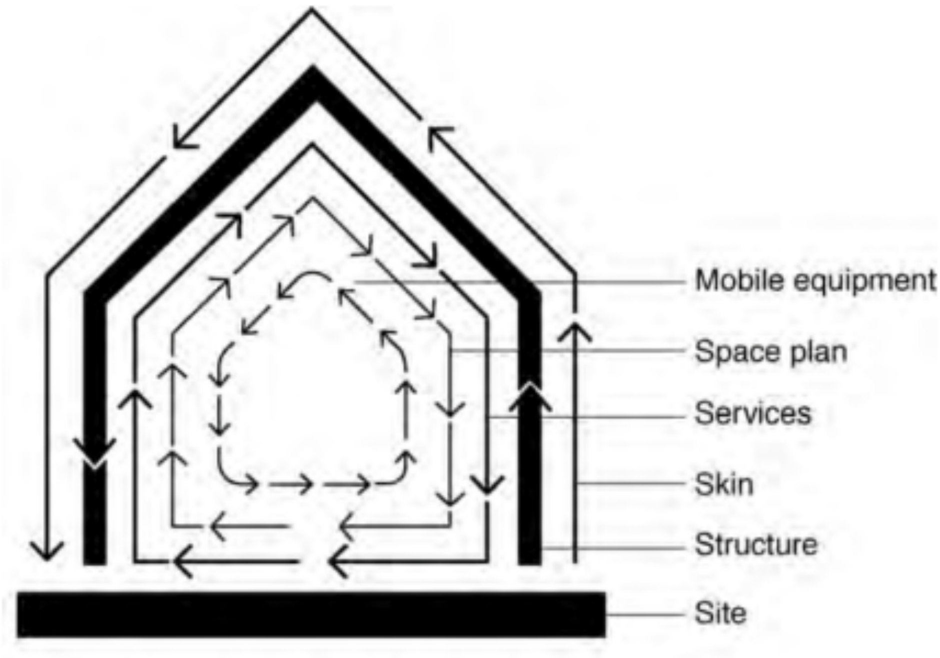


Figure 20 - Main layers of a building (Berge, 2009)

4.1.3 Material efficiency in the built environment

The building industry lacks behind on other industries when it comes to circularity. A cause is the uniqueness and high complexity of buildings compared to other manufacturing industries. More causes are the long lifetime of buildings and the split design activities among several stakeholders (Makova & Dieckmann, 2012). All building components have different life expectancies and react differently to various environmental conditions. The lifetime of building components largely depends on building usage, such as occupancy, activities and behaviour. It is difficult to objectively measure these factors, which leads to a high complexity in lifetime and status prediction of the building and its components (Akanbi et al., 2017). The Leadership in Energy Efficient Design (LEED) rating system looks, besides energy efficiency of a buildings, also at individual materials and component performances; among others where they came from and their recyclability (Weygant, 2011).

According to Thomas Rau (2015), designers have to rethink the design of products and buildings. In a full circular economy, all products should not only be demountable but also remountable; the possibility to re-assemble all elements. Therefore, redesigning products could be an important step to optimize re-usability, updateability and recyclability (Bastein et al., 2013). Materials and products need to fulfil some criteria in order facilitate circularity. According to Geldermans and Jacobson (2015) intrinsic properties and relational properties of materials can be distinguished. Intrinsic properties indicate properties about the quality (functional performance), the origin and the health (non-hazardous).

Relational properties indicate the reusability of products or components. Examples are dimensions, connections and performance time.

Material efficiency means providing more material services with less material production. This can be done amongst others by improving quality by optimizing intrinsic properties (extraction and yield) and relational properties for a longer product life. This is depending on physical, functional, technical, economic, legal and desirable conditions (Ashby, 2016). The whole lifecycle of materials is outlined in Figure 21.
A greater attention to unused resources, waste products and substitution with less limited types of resources or renewable resources, usually have a positive environmental impact. Building components which are currently made from non-renewable raw materials, sometimes have renewable alternatives. For instance, constructions could be produced from timber instead of steel and plants can be used as an alternative to plastics (Berge, 2009). However, this substitution is certainly limited in possibilities (van Beek, 2018). Materials are often chosen for specific properties and are therefore not always replaceable, especially critical materials. Another important consideration is that renewable raw materials are also limited available, they need a more economic approach to. Moreover, material losses and wastage during production and on site should be minimized. Approximately 10% of the material currently gets lost during storage, transport and installation. Primary scrap from material loss through production can still be used or recycled (Berge, 2009).
Material safety aspects in buildings have greater impact on material efficiency than in other products. If a widely used material is identified as dangerous by scientific research, but is located in building elements and structures which are not separable, other 'healthy' and reusable materials must be removed as well (Markova et al., 2013). An example asbestos which was broadly used in the building industry before discovered to be hazardous.

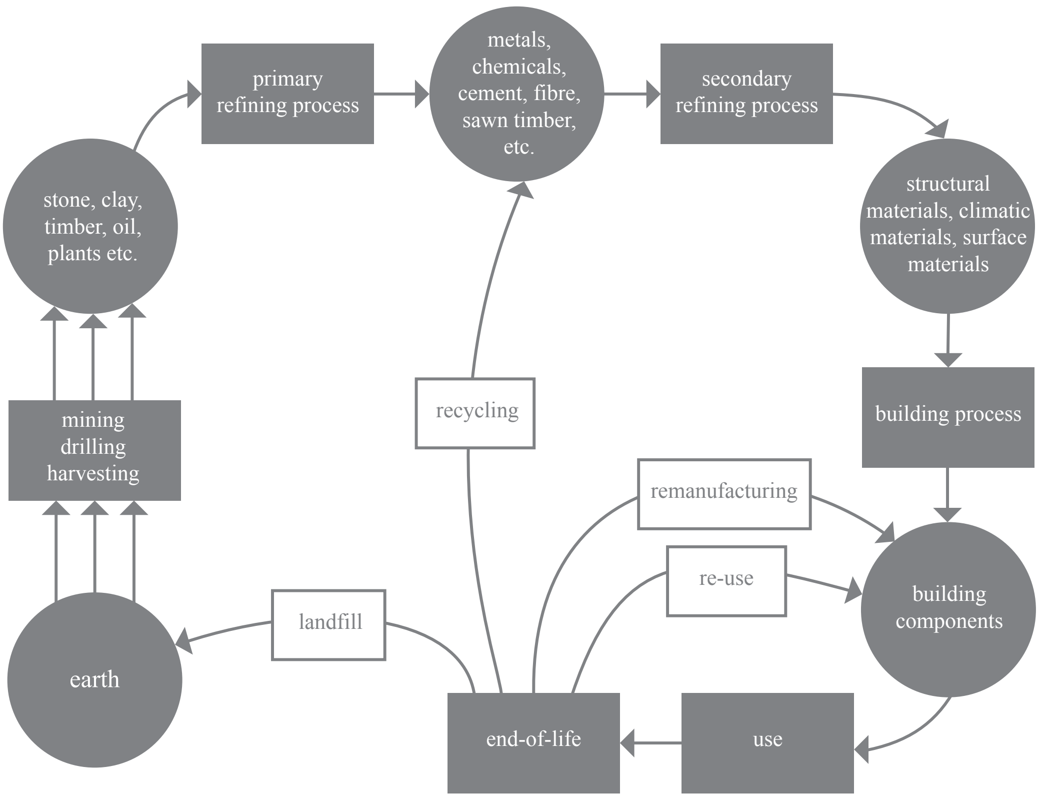


Figure 21 - Life Cycle Materials (adapted from Berge, 2009)

4.1.4 Reuse

After demolition of a building or building component, reuse is the most desired option in a circular economy. Reuse means the use of a whole component, in largely unchanged form and often for a similar function (Berge, 2009). High-value reuse within a circular economy restores products and components that have reached their end-of-use back to their original state to deliver the same function in another design or product. This way, the value of products is preserved at the highest level and the level of risk associated with resource criticality, energy demand, and environmental impact, is reduced.
Standardization is inevitable to achieve reuse of building components. Standardization of connections is found to be crucial. Particularly dry connections in the fit-out domain increase the possibilities of circularity (Geldermans & Jacobson 2015). Separation efficiency is influenced by used technology and type of connections (Caffarey, 2012). Mechanical connections such as bolt and nut joints are preferred instead of nails and gluing. Components with adhesives or mortars are challenging to disassemble and need to be cleaned afterwards (Berge, 2009). Components with low quality materials, should be easily replaceable. Durable materials should be easy to dismantle for reuse or recycling (Berge, 2009). However, in the built environment standardization is not always desirable since it limits a designer's freedom in creativity (Van Beek, 2018).

4.1.5 Repair and remanufacturing

The second loop of the 'Butterfly diagram' (Figure 19) shows repair. Herein the service life of used products or components will be extended by fixing certain broken components. Repair involves the use of new resources or energy which makes it less desirable than reuse. The reparability of a product or building component depends on the design, the level of technical expertise and the required specialized tools. The dependence on these criteria is based on the design decision made during the start of its development (Prumbohm, 2018).
Remanufacturing is another desirable option whereby parts of a product will be reused into new assemblies (Bastein et al., 2013). Remanufacturing is the third loop in the Circular Economy diagram. The aim of remanufacturing is to create products in a new condition. In the remanufacturing process components of former products will be cleaned, repaired and combined into new products. The quality and durability of the products will be the same as completely new products (Peck, 2018).

4.1.6 Recycling

Recycling is the process of recovering the materials into their initial state. By separating the components and melting or crushing it into its original constituent materials, which can re-enter the manufacturing process as raw materials (Berge, 2009). This requires more energy usage than material reuse, repair and remanufacturing (Akanbi et al., 2017). Manufacturers could avoid using combinations of materials likely to lead to recycling problems for a more efficient recycling process (Bastein et al., 2013; Reuter & van Schaik, 2012). According to Umicore (2012), materials with thermodynamic limits and difficult substance combinations should be avoided. Recycling potential is also depending on the purity of the item. Homogeneity of a material could be an important condition for a material in order to maintain quality in the next cycle. In reality recycling often comes down to downcycling, a reduction in quality whereby a part of the original value is lost because the original purity can no longer be achieved (Berge, 2009). Upcycling is processing to improve material or product quality. As mentioned before, the recycling rate of critical materials is low (EASAC, 2016). Thereby the large amount of tiny components containing critical materials makes it difficult and labour-intensive to dismantle them (Van Beek, 2018).

4.1.7 Social and economic change for a circular economy

Besides technical innovation, also social and economic processes are necessary to change existing habits towards a circular context (Bastein et al., 2013). With the transformation from a linear to a circular economy, manufacturing industries are required to take greater 'producer responsibility' for materials and the impact they may have on our environment. Rather than selling as many units as possible, wherein products are sometimes designed for obsolescence. Products can often be used more efficiently through multiple usage, by different users (Clemm et al., 2017).

This revolution should make place for a different type of ownership with new business models to increase use-intensity, such as product-as-a-service, pay-per-service or leasing (Ashby, 2016). The producers retain ownership of the product, as a result encouragement to offer durable and high-quality products that can be easily upgraded, repaired and recycled. Instead of a one-off transaction, a contractual agreement is inevitable wherein service specifications are determined. An early application of such a new business model was Philips' 'Pay-per-lux' lightning concept. The customer pays for the amount of light, while Philips stays responsible for maintaining the lightning systems and remains the owner of the material and system (Bastein et al., 2013). With such business model, it becomes more important for the producer to extend the lifetime of the product and to increase the traceability of the product. Eventually resulting in higher reusability or recycling rates. Herewith creating value based on 'use' instead of value decrease due to consumption (Het Groene Brein, 2014). With a similar service system, the producer retains ownership of the product and leases it to the consumer. The producer takes care of maintaining, repairing and upgrading if necessary, and ultimately taking it back. An added advantage for the producer is knowing the state of the product during its whole lifecycle (Addis, 2006). This allows manufacturers to learn about the performance of their product in the market and improve subsequent product versions.

"There is also the question of durability in function. How much function do you get from the material during its lifetime and how long will that lifetime be?" (Goddin, 2018)

New trends and development of new versions lead to a use lifetime that is often not equal to the technical lifetime. The building component must be wanted for a longer term by making adaption possible. Societal awareness and understanding about the value of materials should also be created to optimize the circular economy. A good example of the extension of lifetime by adaptability for an electrical product is the Fairphone. A high-resolution camera or new battery can easily be replaced by its modular design. This modular phone has a long-lasting design, consists of fair materials and all parts are reusable and recyclable. To replace the components, the user only needs to use a screwdriver to easily install new modules (Clemm, Nissen, Schischke et al., 2017).

4.2 Circularity of critical materials

For critical materials counts more or less the same as for other materials; they can only be efficiently reused or recycled if products are designed in a way that key components can be extracted at the end-of-life (Mathieux et al., 2017). The demand and duration of the use of the critical materials is dependent on the product wherein the critical materials are embodied. However, the significant smaller components lead to a far more difficult dismantling process which is labour intensive (Figure 22).

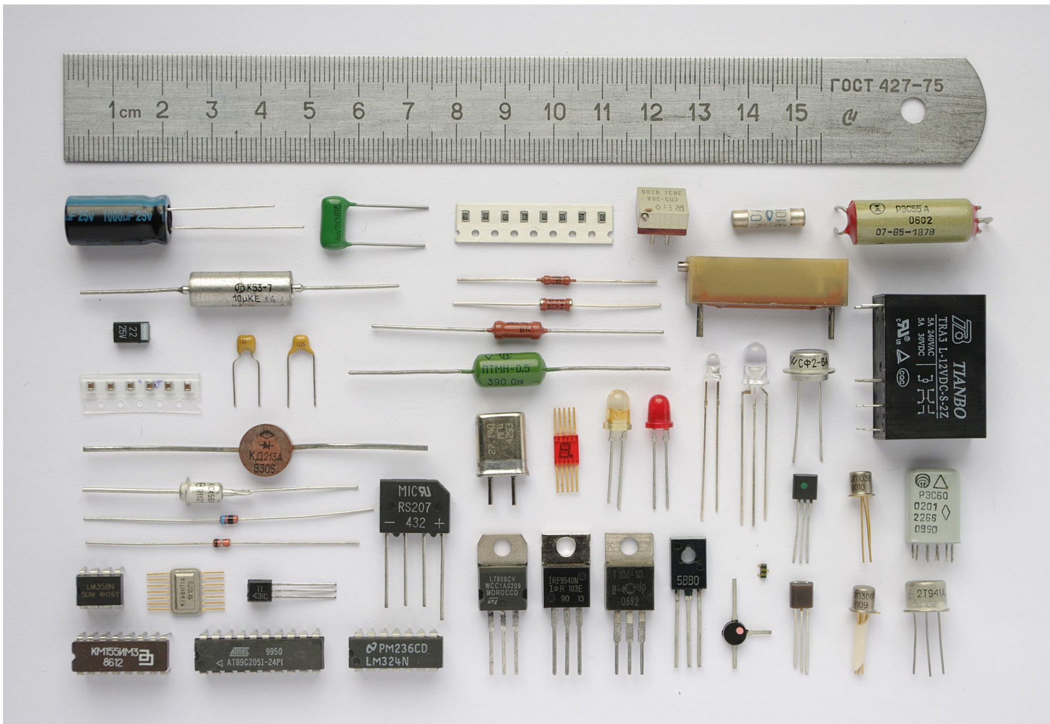


Figure 22 - General electronic components of EEE (Wikipedia)

A recycling process is not favourable as it requires a lot of energy and most critical materials are very difficult to recycle (Peck, 2016). Recovery of CRMs is often not economically viable due to very low concentrations and a complex material matrix (Schischke, 2015). Printed Circuit Boards (PCBs) are a good example of EEE with many critical materials; about 20 precious metals and other non-ferrous metals are included. The process used to recover these materials follows a complex flowchart (Veit & Bernardes, 2015).

A solution to lengthen the lifetime of the materials is to optimize the performance of the product or building component and to make its components re-usable. A way of doing so for critical materials in electrical or electronic building products is by making the product demountable. Determining factors for the ease of repair and demountability are similar to factors for regular products, for example joining techniques and standardization of elements. Dry connections for EEE components are for example modules attached to each other through screws, clips and cables rather than adhesives or solder (Figure 23).

Figure 23 - Tablet distinct of connection of main components (left dry and right soldered connections) (Schischke, 2015)

Compatibility of components between different EEE products or product generations could be stimulated by demountability and standardization in terms of form factors, electrical connectors and software (Clemm et al., 2017). According to Schischke (2015) a new circular design requirement for EEE is designing for hardware upgradability. An easy to open housing without specific tools could help to make the product repairable by the user. Standardization of components makes exchange with other products possible and allows the components of the device to get replaced, which enables upgradable.
Further separation of components to recover critical materials is often not economically viable unless the materials are separated in processes targeting at recyclable materials of high value (Schischke, 2015). Dismantling of products containing critical materials is generally labour intensive but is required to achieve recycled quality, before shredding and eventually physical separation sorting. The choice of recycling technology strongly impacts the recovery rate. Complete liberation of all particles before recycling is impossible and increasingly difficult for complex components like circuit boards. However, an overlap of properties leads to loss of selectivity and thus a less efficient recycling process. For recycling processes, determination of the exact content of a component is a key factor by enabling selection of an optimum recovery process (Caffarey, 2012).

A recent trend in product design of EEE has been towards slimmer and more integrated devices. This clearly complicates the demountability of the product. However, a contradiction is that integrated solutions require less materials. EEE products often suffer from mechanical fractures. Therefore, manufacturers often choose to design their devices for maximum robustness to extend the technical lifetime. This may end up in a compact device, designed to withstand mechanical damage, but this also means further integration of components, obstructing the demountability of a product (Clemm et al., 2017).

Durability of devices needs to be evaluated on a case-by-case basis. Each product type may have different components which fail more frequently, either for technical reasons or mechanical damage (Clemm et al., 2017). A lazy battery or a broken screen should not determine the lifetime of a product.

Concerning the reuse of critical materials used in construction, standard dimensions of construction components could be developed. For instance beams. This probably results in overdimensioned construction components within their first function, whereas the overdimensioning makes them appropriate for further reuse (Rau, 2015; Goddin, 2018).

E-scrap (Umicore)

4.3 Current policies and actions on circular economy and critical materials

4.3.1 Waste of electrical and electronic equipment

EEE disposal is a worldwide challenge. There is no structured system for reversed logistics, resulting to EEE waste often ending up in landfills. This can contaminate the soil with toxic substances of EEE. WEEE (Waste of electrical and electronic equipment, or e-waste) is often considered hazardous because it possibly contains harmful chemical compounds. This varies per product type, manufacturer, year of manufacturing and the country of origin (Vein & Bernardes, 2015). WEEE is one of the fastest growing waste streams in the EU; about 9 million tonnes of WEEE is generated in 2005 only in the EU. This is expected to increase to more than 12 million tonnes by 2020 (European Commission, 2018). In order to mitigate e-waste problems, extensive research has been done and several e-waste management tools have been developed.

4.3.2 European Commission

In 2008 the European Commission launched the **Raw Materials Initiative**. This sets out a strategy to tackle the issue of access to raw materials in the EU. It aims for resource efficiency and supply of secondary raw materials through recycling and fair and sustainable supply from global markets and within Europe. This was followed by a report with a list of CRMs once per three years (2011, 2014, 2017). Herein guidelines are presented on e.g. applications, substitution and recycling possibilities. These reports contribute among others to foster efficient use, recycling and to increase awareness of potential raw material supply risks and related opportunities among the EU (European Commission, 2017).

The EU introduces legislations through **Directives**, requiring manufacturers and other stakeholders to adopt an environmental approach to design and asses the environmental impact of their product throughout their lifecycle. Amongst others to achieve basic goals towards a circular economy and against critical materials disruption. A relevant example is the **Eco-Design Directive**, which aims to improve resource and energy efficiency by improving product design. It provides consistent rules for improving the environmental performance of products (European Commission, 2017). Herein criteria about a declarable reparability score is presented for each design and a disassembly time threshold for some key components with standard tools (Schischke, 2015).

WEEE Directives make the manufacturer responsible for collecting, recycling and disposing of waste from EEE. RoHS (Restriction of the Use of Certain Hazardous Substances) Directive prohibits the use of six hazardous substances in the manufacture of products, which does not include critical materials at this point (Cadmium (Cd), Mercury (Hg), Lead (Pb), Chromium VI (CrVI), Polybrominated biphenyls (PBB) and Polybrominated diphenyl ethers (PBDE) (Veit & Bernardes, 2015).

Horizon 2020 is an EU Research and Innovation program active from 2014 to 2020. It supports research and innovations by funding.

An accurate assessment of resources must include, besides resources available in ground (reserves), the resources in stocks within the technosphere which eventually become available for recycling. **ProSUM** (Prospecting Secondary raw materials in the Urban Mine and Mining wastes) is an EU Horizon 2020 funded project. It aims to provide data of various product groups (Mathieux et al., 2017) and better information about raw materials from secondary origins (Tukker & de Koning, 2018) in an easy accessible portal: urbanmineplatform.eu. Within the **Urban Mine Platform** (UMP), ProSUM provides a centralized database of all available information on arising, stocks, flows and treatment of WEEE and mining wastes, with a focus on CRMs (Tukker & de Koning, 2018). In Figure 24 an end of life (EoL) scheme of ProSUM is shown wherein the collection, treatment and recycling of batteries is explained. This harmonized data allows stakeholders to improve the management of the waste and enhance resource efficiency of collection, treatment and recycling. It aims to support Europe's position on raw material supply, with the ability to accommodate more waste and resources in the future. To maintain and expand the UMP, standards and recommendations for statistics and improved reporting on CRMs in waste flows have been developed (Downes et al., 2017).

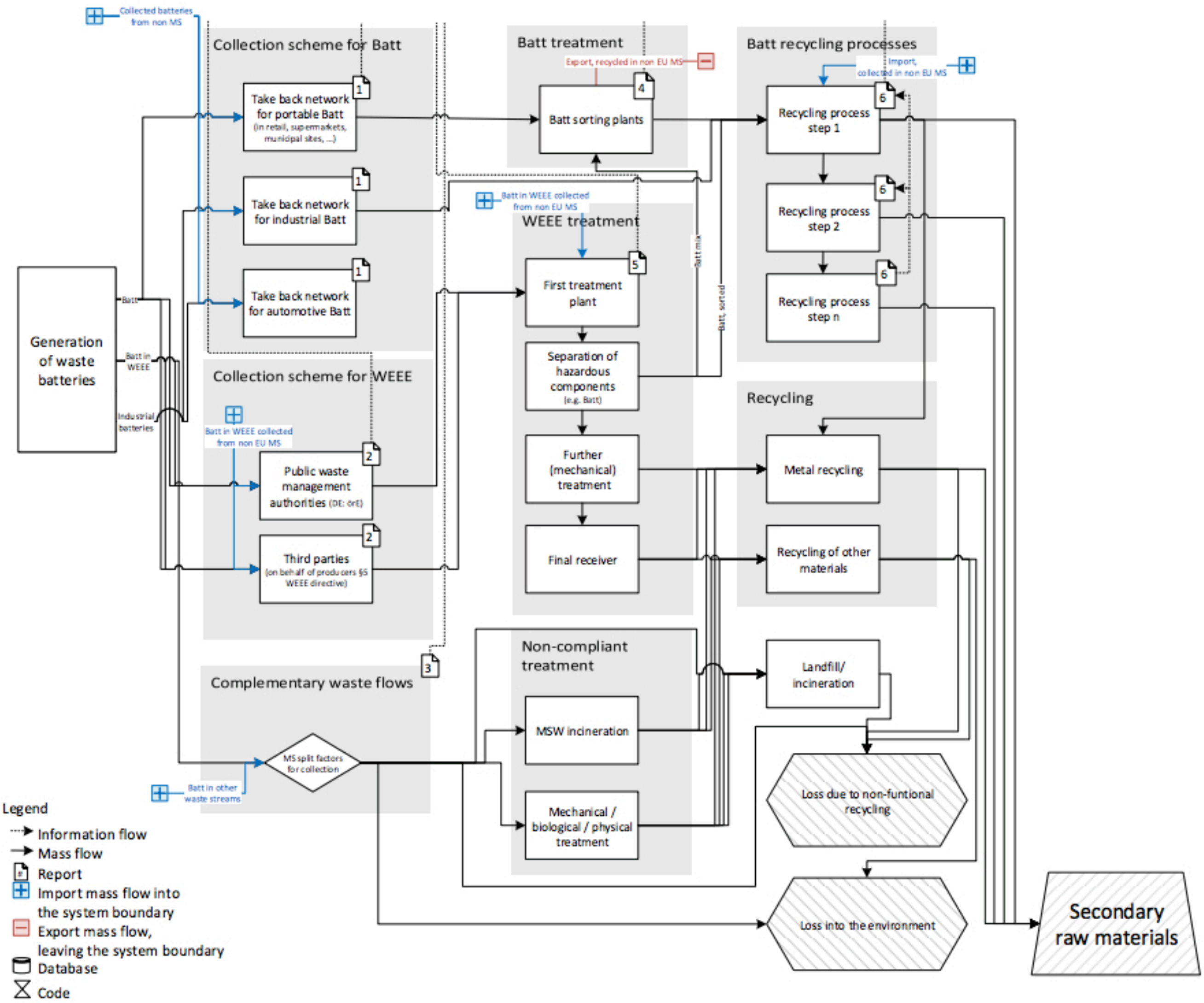


Figure 24 - End-of-Life treatment batteries by ProSUM(2018)

Successful implementation of the policies of the European Union in this field requires identification of the raw materials that are key for the European Economy (the critical materials) and detailed knowledge about the flows of these materials in Europe (Deloitte, 2015).

LCA (Life Cycle Assessment), MFA (Material Flow Analysis), MCA (Multi Criteria Analysis) and EPR (Extended Producer Responsibility) are techniques that could help to improve the disposal of electronic waste by optimizing recycling, reusing secondary scrap and reducing environmental impacts.

Another important source of background information to design for security of supply is the Material System Analysis (MSA) . In 2015 the European Commission published a report on MSA, which investigates the flows and stocks of critical materials (European Commission, 2015). Data from

extraction to primary supply is used to estimate concentrations of the use per sector and embodiments in product (Tukker & de Konings, 2018).
The outcome is a map of the flows of material through the EU economy across the entire life cycle, presented in Sankey diagrams (Figure 25Figure 26Figure 27). Additional information is presented about security of supply, substitutes, future supply and demand changes of materials. This system can help to quantify potential primary and secondary sources and to improve the level of circularity (European Commission, 2018; Deloitte, 2015).

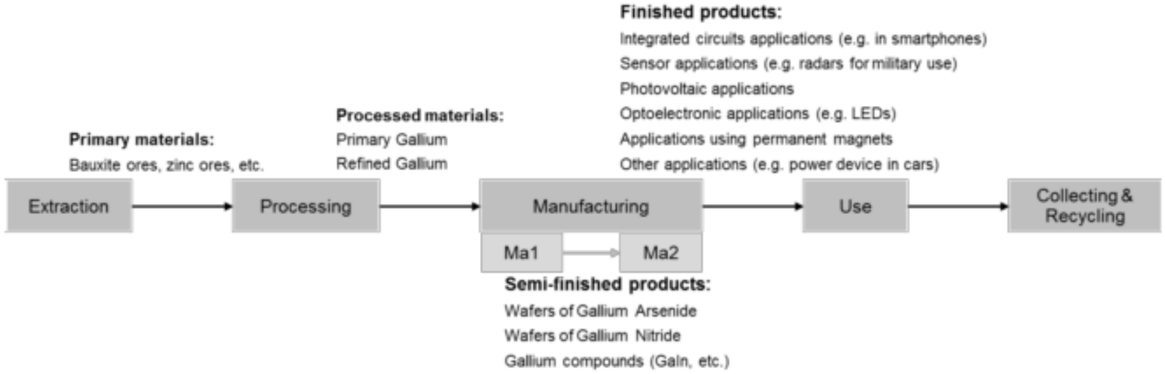


Figure 25 - Value chain of Gallium (Deloitte, 2015)

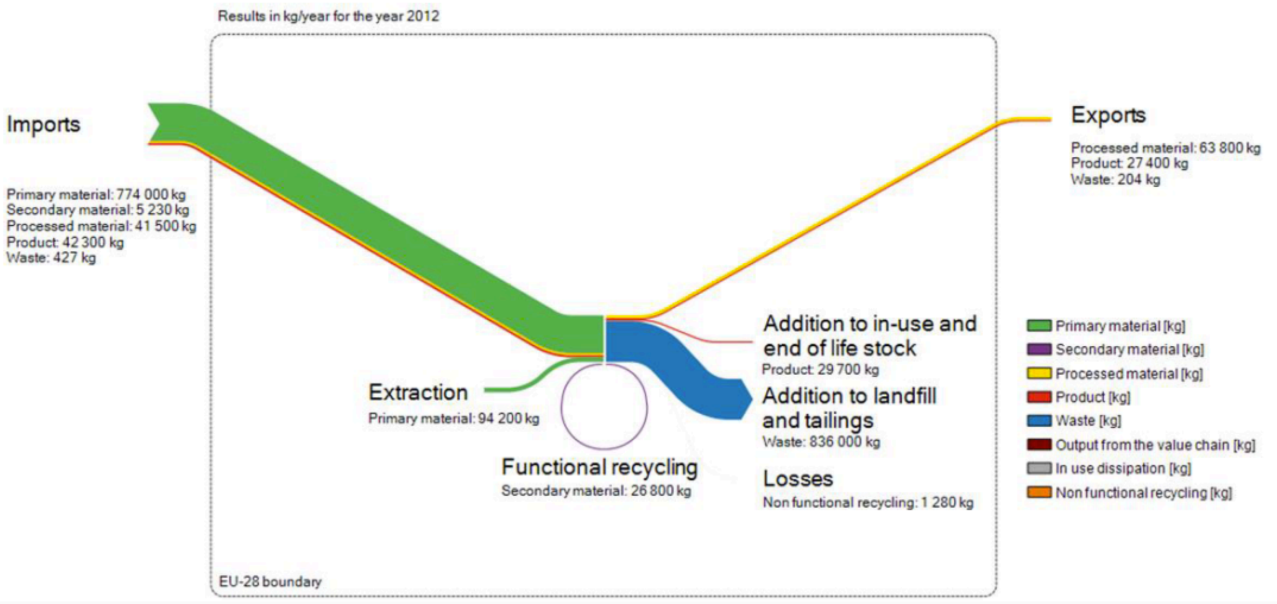


Figure 26 - Sankey diagram for Gallium (Deloitte, 2015)

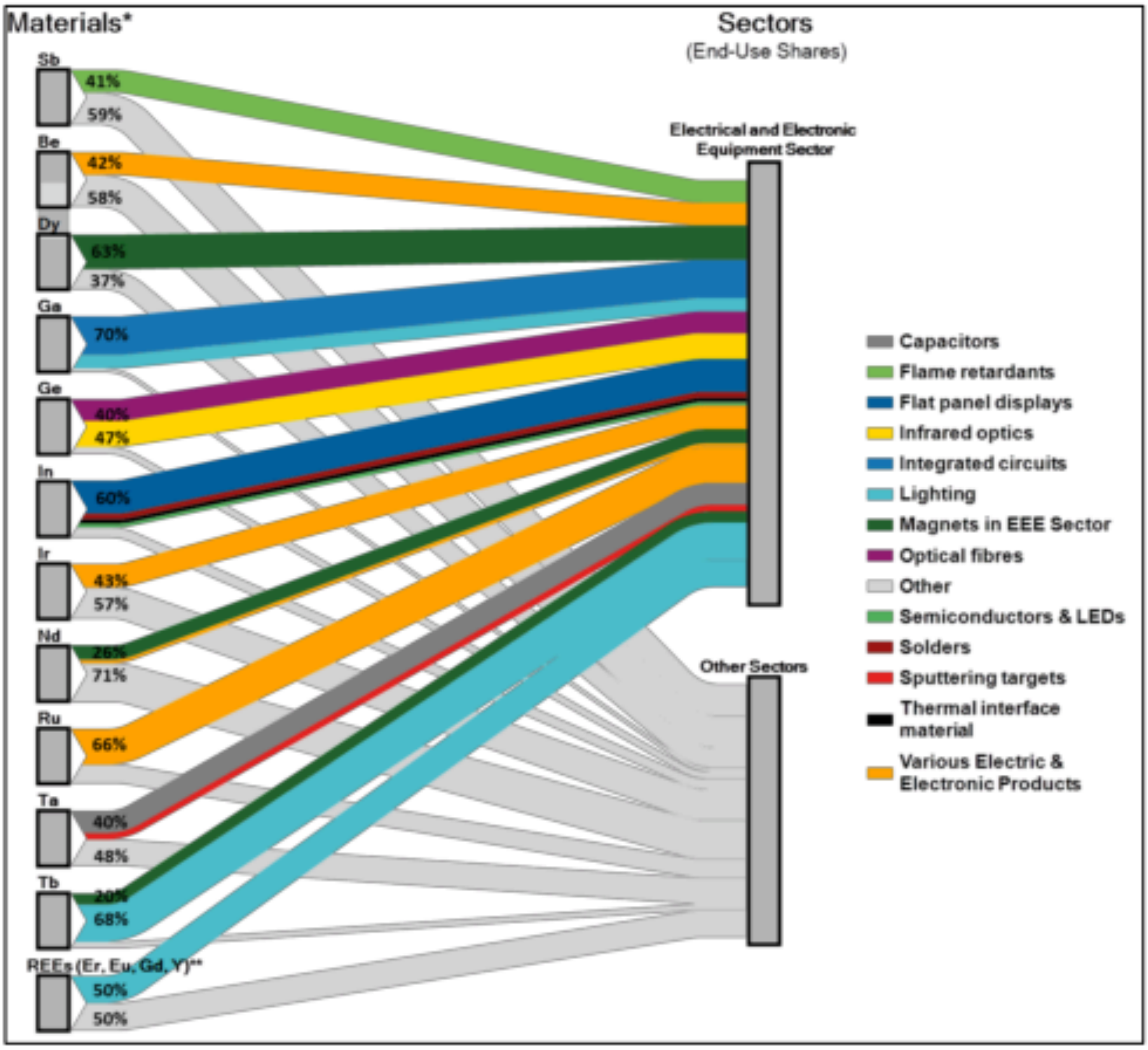


Figure 27 - CRMs used in EEE (European Commission, 2017)

4.3.4 The Netherlands

The Dutch government has formulated a resource agreement on circular economy (Grondstoffenakkoord), which is signed by a wide range of organizations. This agreement, titled ‘Nederland Circulair in 2050’, describes the aim to transform the Dutch economy into a circular economy (Nederland Circulair in 2050, 2016). It describes the reduction targets for five groups of materials: biomass, building materials, plastics, raw materials for manufacturing sector and domestic waste. The aim is to halve the demand of raw material by 2030 and to have an fully circular economy by 2050.

4.3.5 More initiatives

The high goals set out by the European Union and their policies concerning critical materials and circularity have created an open market for initiatives from various parties.

Many initiatives received funding from the European Commission (EC). An example is **SustainablySMART**, which aims for sustainable smart mobile devices lifecycles through advances re-design, reliability, reuse and remanufacturing technologies. The Fairphone, the modular phone which is discussed before, is a SustainablySMART project (Schischke, 2015).

SusCritMat is also funded by the EC and provides education about important aspects of critical materials. It aims to understand the role of CRM in the whole value chain and to share this knowledge with current and future decision makers in the industry. The project is EU funded and supported by the European Institute of Innovation and Technology (suscritmat.eu, 2018).

CloseWEEE has the main goal to increase the range and yield of recovered materials from WEEE streams materials which can be reused. They provide integrated solutions for pre-processing electronic equipment. CloseWEEE describes recovery processes for critical metals from batteries, and advanced sensor-based plastic sorting and separation technology. CloseWEEE outlines the full value chain from secondary raw material recovery to WEEE to manufacturing of new products.
CloseWEEE collaborates with iFixit and D.R.Z. (Dismantling and Recycling-Centre), who together developed an online Recycler Information Center platform. **iFixit** provides service manuals for EEE products. Their scorecard grades the level of difficulty to disassemble and repair a product (Dender & Rifer, 2015). **The Recycler Information Center**, funded by the European Union's Horizon 2020 research and innovation program, constitutes a centralized source of visually illustrated information, regarding safe, fast and efficient procedures for treating WEEE. It includes information about the presence of hazardous substances and disassembly procedures (CloseWEEE, 2018).

Basel Action Network (BAN) is an organization that tracks the flow of toxic waste in the world. According to BAN a large part of electronic waste (8 out of 10 computers in the USA) end up in Asian countries, where recycling costs are lower (Veit & Bernardes, 2015). **Closing the Loop** from Amsterdam buys broken mobile phones with local partners in Africa and Asia and ensures that the devices are recycled responsibly. Various types of electrical and electronic waste are processed by large recycling companies. Mainly in order to recover precious metals, **Umicore, Noranda, Boliden** and **Cimélia** have published papers on the process of refining metals.

European Recycling Platform (ERP) collect WEEE, batteries and packaging worldwide. By providing take-back services, they organize, sort and recycle the materials. With an interactive guide 'What happens to your waste', ERP explains the basics of recycling processes for different product types (ERP recycling, 2018).

Figure 28 describes the initiatives and policies mentioned in this research.

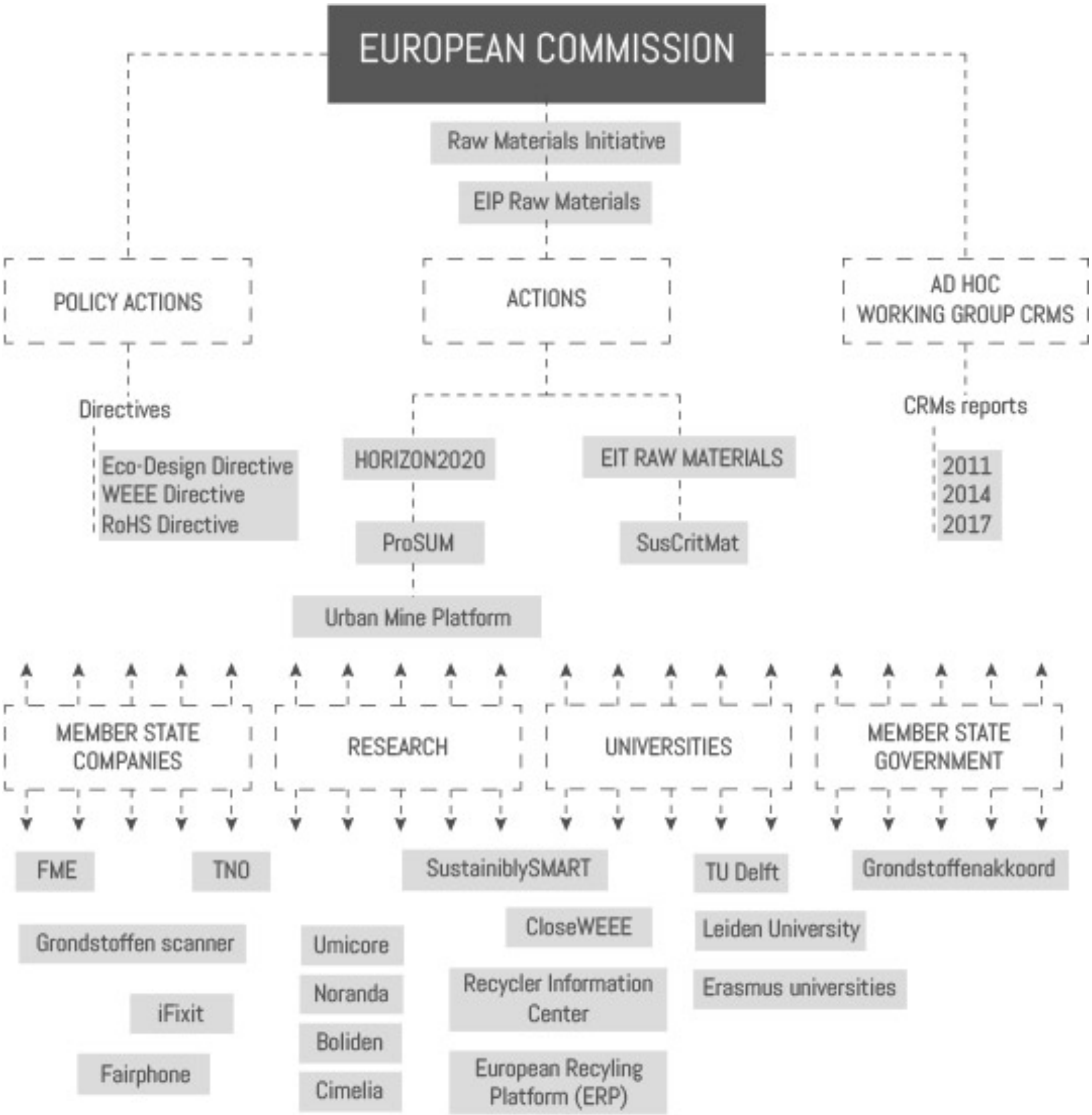


Figure 28 - Initiatives and policies mentioned in this research

4.4 Chapter conclusion and discussion

The circularity of products containing critical materials seems to be more difficult than for most other products. The large amounts of tiny components makes efficient dismantling of the materials labour intensive. Thereby the recycling rate of critical materials is low. To make recycling more efficient, material selection should be done carefully. Hence, products and components containing critical materials need priority to be reused or re-manufactured. Modularity of products is favourable by targeting reparability, upgradability and better materials separation at the end-of-life. This needs to be integrated from the conceptual design phase. Standardization of components of those objects and demountability through dry connections will contribute to this. Within EEE, general components seem to be used frequently, it should be made easier to dismantle them to make them reusable.

Besides the technical changes, also changes concerning policies, business models and social aspects are important to realize a circular economy and thereby optimized material use. More responsibilities for the manufacturers lead to new business models, wherein they stay owner of the product. Leasing of products containing CRMs can be interesting since the companies stay owner of their product and thereby the contained critical materials.

Policies of the EU have led to many initiatives to optimize resource efficiency. Mapping resources, research on new possibilities and defining policies have a positive impact on the circular economy and raise awareness about critical materials.

Summarized, the following steps in Part II of the framework in Figure 29, must be considered to optimize the use of materials, both critical and non-critical.

OPTIMIZE LIFETIME MATERIALS

design for longer lifetime;
- physical, functional, technical, economic, legal and desirable.

technical;
- durable/high quality materials,
- modularity: updateble, repairable,
- maintenance.

re-usable components;
- standardized components,
- dry connections.

recyclable materials;
- combination of materials.

social and economical change;
- business model, responsibilities, maintenance and awareness.

Figure 29 - Framework part II - application of critical and non-critical materials / material efficiency

RESEARCH ON MATERIAL INFORMATION TECHNOLOGY

5 RESEARCH ON MATERIAL INFORMATION TECHNOLOGY

5.1 Harmonization of material data

Specification of recoverable materials during the building design and construction phase is a major factor that determines the level of re-usability of recoverable materials at the end-of-life of a building (Akanbi et al., 2017). A strategic approach to share and compare materials information requires consistent material information wherever relevant decisions are taken; during research, design, production, but also in-service and end-of-life (Warde et al., 2012). However, managing material information is challenging. Many factors make materials information specific. The range and types of material data differ, thereby not all material information is always relevant and needs to be mentioned. The method of documentation in the building industry varies strongly depending on respective product and manufacturer. Different layers and parts of the building are designed by different sub-contractors and are documented in a data format of their own choice (Markova & Dieckmann, 2012). An wide variety of design systems and data formats make information exchange challenging. The language of specialist differs. Classes and properties of materials have their own conventions, units and measurement techniques (Warde et al., 2012). Standardized object libraries for materials could provide a solution (Markova, Dieckmann & Russell, 2013). Without harmonization in material data, comparing data gets more difficult. Standardized code lists and protocols are being developed and researchers, engaged in producing data on the composition of products, are encouraged to use them to achieve data harmonization (Downes et al., 2017). An example are lists and codes developed by ProSUM.
According to the International Organization for Standardization (ISO) “a standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose” (BAMB2020, 2017).
Another advantage of data harmonization is the possibility to reuse data sets, which could save a lot of time and help making better informed decisions by analysing previous design decisions (Warde et al., 2012).

Traceability and related data of materials are the key requirements to easily recover their full context (Warde et al., 2012). A suitable method for extracting the exact localization and complete documentation of substances is necessary for circular purposes. Physical properties of the material consist of geometrical data and location parameters. Those can be defined in material property sets. Materials should be checked for recyclability in correlation with existing recycling technologies, allowing for recycling and reuse without downgrading (Markova & Dieckmann, 2012). Knowledge about the exact combination of materials in a product or its component, can lead to a more efficient recycling process. If specific material properties are known, separating can be done more efficiently, based on these properties.
Regulatory information about materials is important for many manufacturers since it is restricted to substance regulations as the European Union’s REACH. The right material information at the right time can be substantial to mitigate the risk (Warde et al., 2012).

It also needs to be clear where to find specific data, thereby all information needs to be accessible for all involved stakeholders (Warde et al., 2012). It is important to take into account what logical search criteria are for finding specific elements (Fairfull et al., 2016). Searching for critical materials could be done per element, e.g. Gallium or Ga, or simply per critical material.

For modelling tools, the program could give a warning when a designer switches to a materials grade with an associated risk (Warde et al., 2012), e.g. critical or hazardous materials. The aim is to develop universal, securely managed access and use of the digital representation of product definition information. A corporate database may record several hundreds of attributes per material. Specific information, which is not needed in the model in order to track and trace within the models or schedules, can be linked to the model through linked documents or multimedia in hyperlinks. This way, live links can be updated, as material information can change during the lifecycle (Fairfull et al., 2016).

In a report of Granta Design (Fairfull et al., 2016), the requirements for best practice material information management are described; capture (import information), analyse (compare materials), deploy (available when needed) and maintain. The data must be updated throughout the lifecycle and users must be able to modify schemes without specialist programming skills (Fairfull et al., 2016).

5.2 Material passports

“Materials passports are (digital) sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse” (BAMB, 2017).

According to Thomas Rau (2015), material passports are essential to know the exact content of a building. Giving the materials an identity aids reuse and recycling after demolition. This way buildings become material depots. It is possible to link a material passport to the Building Information Model internally in the software or externally via an add-in. Different types of information about materials are important throughout the lifecycle of a building or product. Information can be about different attributes; among others about engineering properties, processing, costs, environmental impact and availability (Warde et al., 2012). As mentioned before, not all information about materials is always relevant. To improve computational speed of the model, relevant information needs to be selected carefully and remaining information can be enclosed via external links.

To increase the circularity of a building component, relevant information for disassembly, recycling or disposal must be presented at the end of life (Mathieux et al., 2017). It requires detailed constructions for the manual disassembly, especially for the parts wherein critical materials are used (Mathieux, Ardente, Bobba et al., 2017).
A material passport is about designing and ensuring the reusability of components and materials by providing information on different levels. Recently BAMB2020 (Building As Material Banks, 2017), published a framework for material passports. According to them material passports consist of qualitative and quantitative information. The qualitative information consists of circular qualities; design for reversibility. The quantitative information consists of the number of building components within a building, the amount of reusable building component, weight, volume of recoverable materials and their locations. BAMB2020 (2017) also distinguishes structured and unstructured data. Structured data is for instance “yes”/”no” or a number. Unstructured data could be maintenance instructions or other guides. According to Luscuere (2016), a material passport provides guidance, but does not necessarily make the product suitable for the circular economy. If the product has potential within the circular economy, the passport is an enabler to fulfil that potential.

Different sources, all with a prospect of extending the lifetime of materials by providing relevant data, mention different types of information to be registered within a material passport or database:

- General information;
  - Product description (type or family) [3, 4];
    - Identification code/Article number [1, 9];
    - Intended use [1, 9];
  - Production year [3];
  - Manufacturer information [1, 3, 4, 9];
  - Installation instruction [1, 9];
  - Exact location of the building [1];
  - Number of building elements (within building) [1];
  - Responsibilities [1];
    - Business model/take back agreement [1];
    - Ownership [1];
  - Operation and functionality [1, 9];

    - Use guide [1, 9];
    - Maintenance [1, 9];
  - Environmental impact for each phase / LCA (extraction, production, use, end-of-life) [1];

- Composition of building component/product;
  - Product components [7];
  - Bill of Materials (description of material content and composition of a product) [2, 4];
    - List and weight [2, 4, 5];
    - Identification of hazardous substances and critical materials (or scarcity prospects) [1, 2, 4, 5];
  - Description physical structure of product and their elements [1, 2, 5];
  - Processing information (how are materials constructed, joined, treated, coated) [5];
  - Elements of the product design specification relating to environmental design aspect [3, 5];
  - Relevant legislation (for example RoHS) [2, 5];
  - The origin of the materials used in the product [2, 5];
  - Reason to choose this material; relevant studies and tests [3, 5];

- Circularity;
  - Expected lifetime [..];
  - Description of the end-of-life possibilities [2, 4, 5, 6];
    - Recyclability/reuse rate or potential [4];
      - Next opportunities or previous application [1];
    - Recycled/reused components;
  - Disassembly/removal manual [1, 2, 4, 5, 6, 8];
    - Joining techniques used [4, 8];
    - Guidelines EoL treatment [4];
  - Maintenance [8];
  - Replaced parts during use [8];
  - CRM parameter [7];

1. BAMB2020 (2016)
2. Damen (2012)
3. European Council (2009)
4. CENELEC (2017)
5. Warde et al. - Granta Design (2012)
6. Mathieux et al., (2017)
7. ProSUM
    a. Scheepens et al. (2015)
    b. Van Straalen et al., (2015)
8. Luscuere (2016)
9. Weygant (2011)

For structural or load-bearing components other information might be important to secure the safety in case of reusing the building components (van Beek, 2018).

5.3 Transparency

A large amount of data needs to be shared among stakeholders to realize optimized use of the materials and their circularity. The manufacturers need to provide technical documentation about their products. Usually this information is only available on the level of the product itself. This often includes functional aspects and certifications of the product and general information about materials. Information about its components and their sub-manufacturers is generally not given. This information could be translated to material and element composition to get to know the exact content (Tukker & de Koning, 2018).
Within a circular economy, all information is intended to be accessible by diverse stakeholders who have distinct objectives. Confidentiality of data from a manufacturer's side could be a problem to realize a transparent dataset. Also, the complexity of the whole supply chain makes it challenging to receive this information. Data on element level of all components needs to be transferred among different phases and stakeholders until it comes together at the final manufacturer to realize full transparency.
A material passport should allow confidential data to only be accessible to specific users in the platform. The provider of confidential data, often the manufacturer, should be able to define who has access to this information (BAMB2020, 2017). Material databases need to be accessible by parties which are capable of connecting it to action. Confidentiality is a bottleneck. There are cases where information is important, but does not need to be fully transparent to all stakeholders, as long as the evaluation of the information can be presented transparently (Luscuere, 2016).

Mesbah Sabur, founder of '**Circularise**' (Circularise, 2015), found a solution for the communication barrier between product manufacturers, end users and recyclers. Manufacturers are not always able to share all product information, just like Coca-Cola will not share their recipe. *Circularise* found the solution for this: A platform wherein details about the materials are gathered and the data is locked in time, without sharing it with third parties. This creates a system in blockchain, wherein stakeholders can communicate about products without having to share sensitive information by smart-questioning (Figure 30) (Sabur, 2016). Another Dutch company '**Excess Material Exchange**' also works with blockchain technology to ensure the safe exchange of proprietary data, aiming for circular use of materials. By making use of their service, companies remain owner of their data while materials will be traced anonymously. The blockchain also ensures non-corruptibility and traceability of supply chains, which will help to prevent frauds.

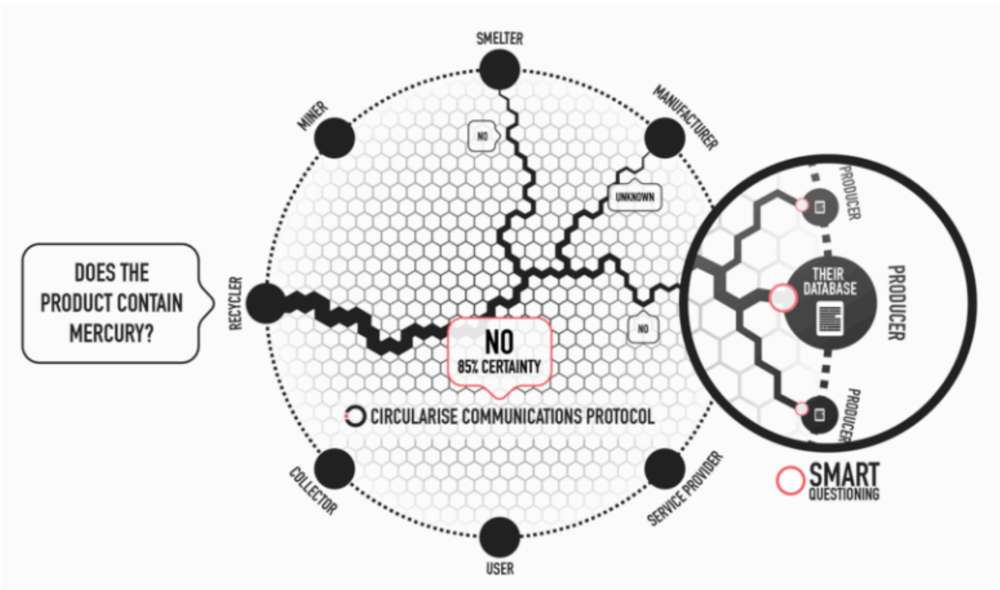


Figure 30 - Smart questioning (Circularise, 2018)

5.5 Building Information Modelling

5.5.1 Introduction

To obtain a full circular process it is important to get to know the full life cycle of the building, its components and their materials. Such a Life Cycle Analysis (LCA) of a building need new type of information compared to traditional building process. Because of the abundance of required information, there is need for efficient information-technological solutions. Besides the required functional an physical information, an overall change of process is required to obtain a circular process. A useful approach to implement this life cycle analysis and concurrently share all information is Building Information Modelling; BIM.

“Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” (National Institute of Building Sciences, 2015).

A BIM process relies on technical and social factors (Figure 31). The integrated process involves collaboratively developing and using a computer generated parametric 3D model of a building (Akanbi, Oyedele & Akinade, 2017). Within this model, all involved stakeholders share information during the whole life cycle of the building. This means that the static hierarchy of decision making, where each phase has to deliver specifics, makes place for a dynamic decision-making process (Figure 32) (Durmisevic, 2010). This leads to a better integrated design due to efficient collaboration and continuous availability of highly accurate, consistent and reliable building information.

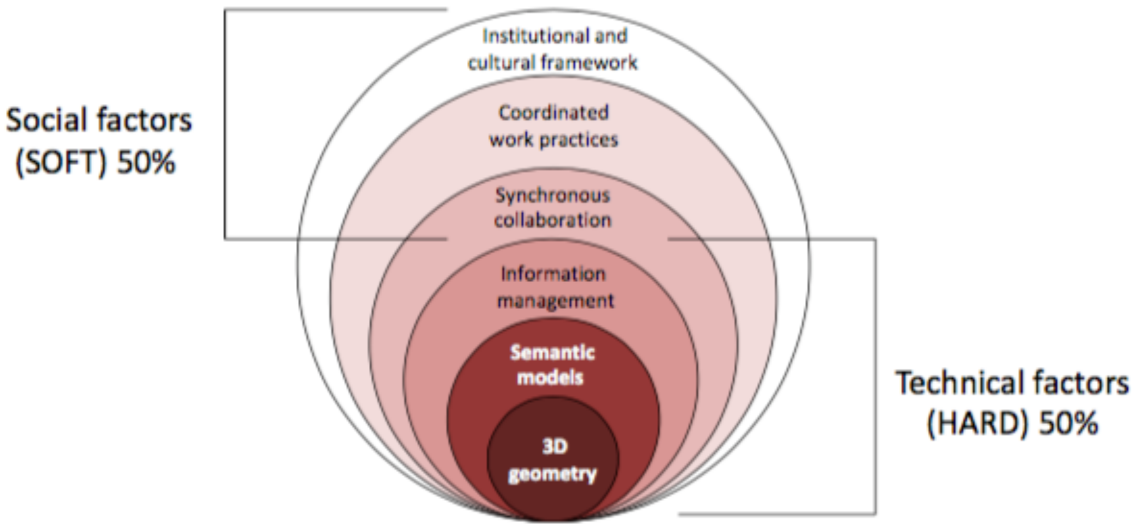


Figure 31 - Social and technical factors BIM process (Bähre, 2017)

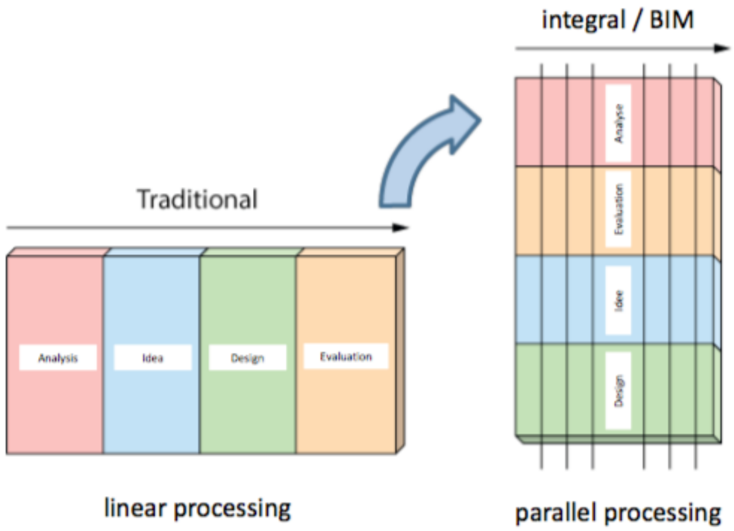


Figure 32 - BIM parallel processing (Bähre, 2017)

BIM is mostly used in countries where its use is mandated in public projects, among others the United Kingdom, the United States, France, South-Korea and Norway (Figure 33) (Audier et al., 2017).

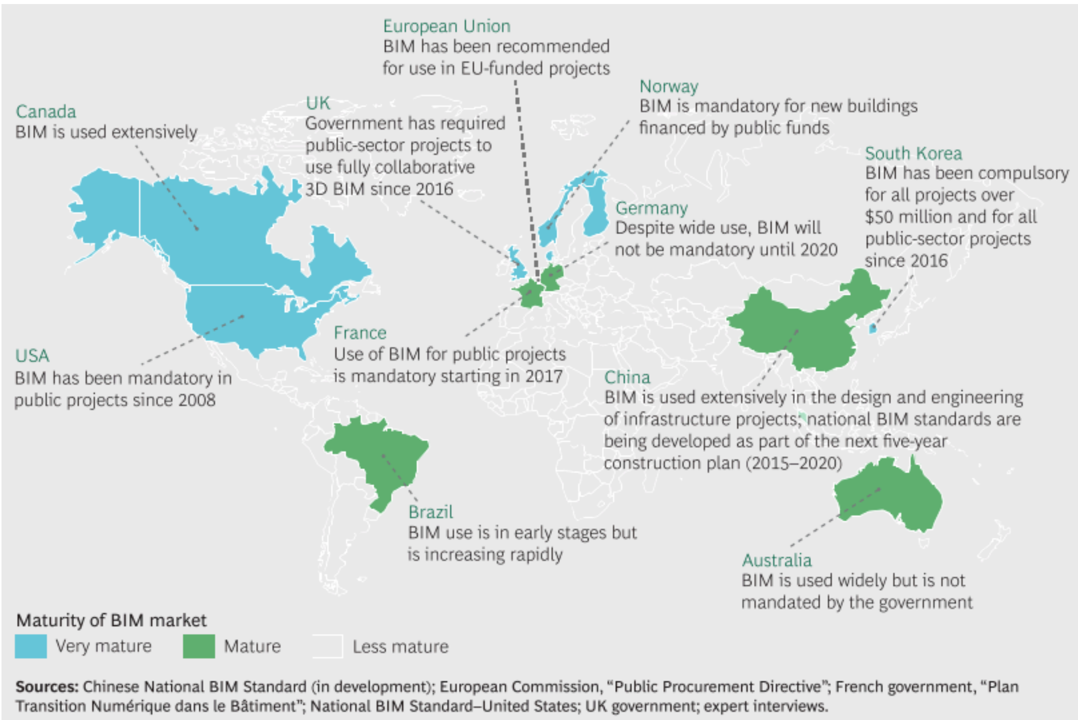


Figure 33 - BIM use over the world (Audier et al., 2017)

The frequently used BIM life cycle consists of the following phases: idea, design, analysis and optimization, fabrication, construction, logistics, operation and demolition. This clearly shows similarities with a circular life cycle. The capability to acquire lifecycle information makes BIM suitable for a circular economy process (Akanbi et al., 2017). However, most important phases for this research are not taken into account in the BIM lifecycle; the extraction and processing of resources and their end-of-life possibilities (Figure 34).

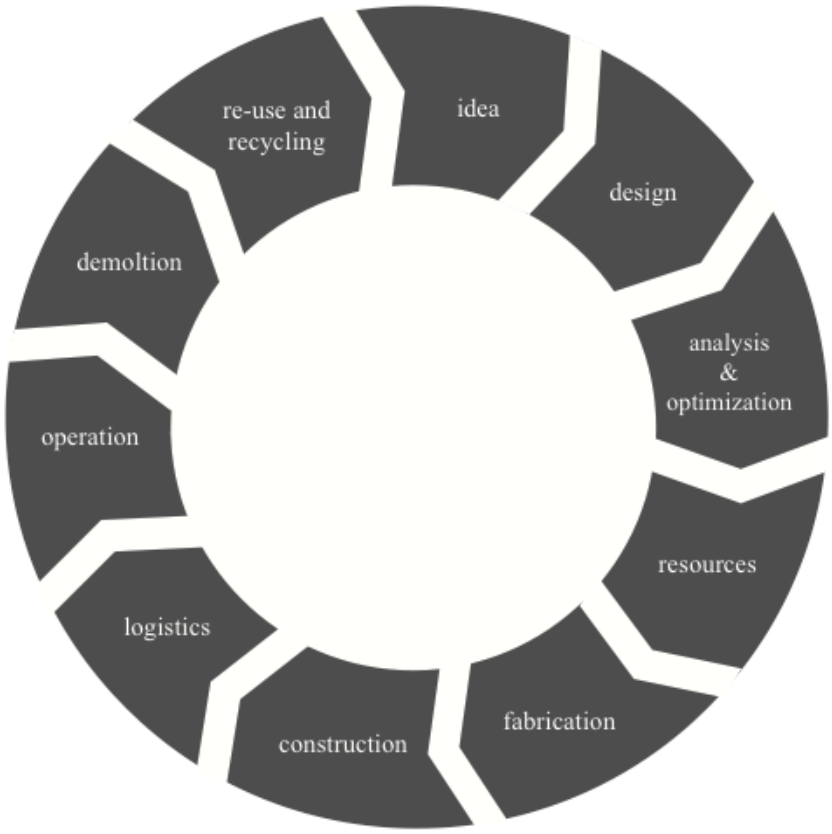


Figure 34 - BIM life cycle phases

Within a BIM approach, the whole life cycle is taken into account from the beginning of the design phase. This provides many advantages. The development from a schematic model to a detailed building model allows for a more careful evaluation to determine whether it meets the building's functional and sustainable requirements. Thereby early evaluation of design alternatives is available using analysis and simulation tools to increase the overall quality of the building. The automatization of a parametric model and data sharing increases consistency and design speed (Panaitescu, 2014). This could eventually lead to more integrated design solutions and prevent clashes. Besides optimizing the design for the lifetime and making circular economy possible with BIM, life span information also indicates when maintenance activities are necessary (Rwelamila, 1996). The main feature of BIM that makes it suitable for the circular economy is its capability to accumulate lifecycle information about everything within a building (Akanbi et al., 2017).

Within BIM implementation, stakeholders are able to use several software programs. Data can be exchanged between different formats and software, e.g. Revit Autodesk (available for Windows) and ArchiCAD (available for Windows and iOS). The model is based on the setup of building components which can be parameterized. This can automate the design process partly and decrease the duration of design changes.
An important benefit of using it during the whole life cycle of a building, is that it permits everyone in the process to have a clear understanding of the design by providing an earlier and more accurate visualization. Stakeholders with less technical knowledge have a better possibility to understand the process and the principles.
The generation of accurate and consistent 2D drawings, which are updated automatically, are easily extractable at any time and at any specified view of the project. This significantly reduces the time and number of errors associated with generating construction drawings at any time for all disciplines (Eastman, 2011). Though, it not the main goal of BIM.

5.5.2 Stakeholders

As mentioned before, during the whole life cycle of the building, many different stakeholders are involved. Some will make decisions about the use of critical materials. In an integrated process stakeholders from later phases are involved from the beginning of the design phase (Figure 32). Participation of stakeholders from later phases lead new requirements. Involving stakeholders such as facility managers, occupants, installers, leads to optimized building use.

In the design phase, the most important stakeholders are the project manager, the design team, which consists of architects, (construction) engineers and design specialists (Weygant, 2011). This team decides how the building will perform and makes decisions about which materials and products go in (Goddin, 2018). The same team will be involved during the analysis and optimization, together with consultants, manufacturers and fabricators. Most important stakeholders during the fabrication, construction and logistics phase are a general contractor, subcontractors and manufacturers (Weygant, 2011; Eastman, 2011). The contractors and building manager are responsible for daily coordination with e.g. subcontractors, installers and suppliers. A logistics manager takes care of transportation, distribution and storage of building components during construction and end-of-life phase (BAMB2020, 2017). During the use of the building, owners, facility users and facility managers are involved (Weygant, 2011; Eastman, 2011). They will decide about technological changes during the occupancy of the building, thus on the use of critical materials. According to Weygant (2011), a BIM model is a gold mine of data for facility managers and owners. The finalized model can be utilized for information for facility management, maintenance, forecasting and budgeting. The model can be imported into control systems for different purposes with a 3D interface, for example HVAC, security and fire protection.
Within a circular economy, more stakeholders are involved in the end-of-life phase for the collection of materials to realize circular possibilities; examples are the de-constructor, collector and recycling companies (BAMB2020, 2017). More incorporates, less involved in the design but definitely important to take into account, are outside organizations: the government and municipality, the community and financial agencies (Weygant, 2011; Eastman, 2011). Also, a developer who oversees the entire process and lifetime of a building is involved (BAMB2020, 2017). This person could play an important role in reviewing data exchange. Governing bodies and policy makers establish regulations and guidelines related to development permits, manufacturing, construction and resource management and re-utilization. They are responsible for controlling and approving projects in the built environment according to building standards (BAMB2020, 2017). The implementation of information about (critical) materials involves new groups of stakeholders. Governments were already involved for different

purposes, Furthermore mining companies and recycling companies will be key users of material data (Tukker & de Koning, 2018).

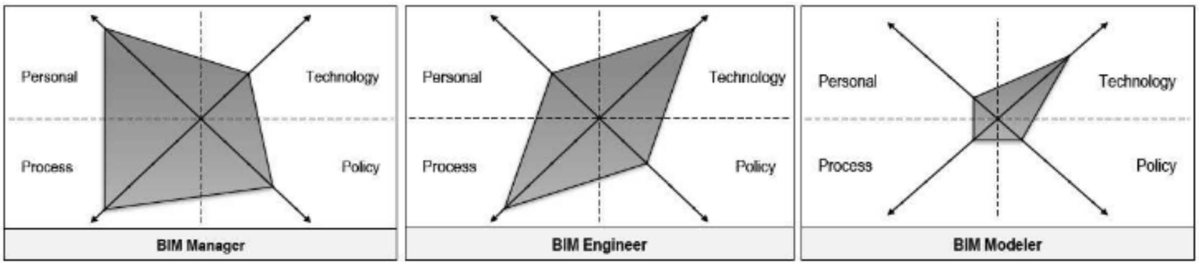


Figure 35 - New roles within BIM approach (Bähre, 2015)

In case of a BIM practice: a team of modellers, BIM managers and BIM engineers are involved. Their tasks differ per project and are flexible and constantly changing in relation with adaptive processes (Figure 35) (Bähre, 2015). To make sure the BIM model is usable during the whole lifetime of the building, the model needs to be updated as soon as anything changes. In most organizations a facility manager, owner or operator lacks BIM knowledge. Therefore an extra person is required for updating the BIM model (BAMB2020, 2017). An overview of all stakeholders is given in Figure 36.

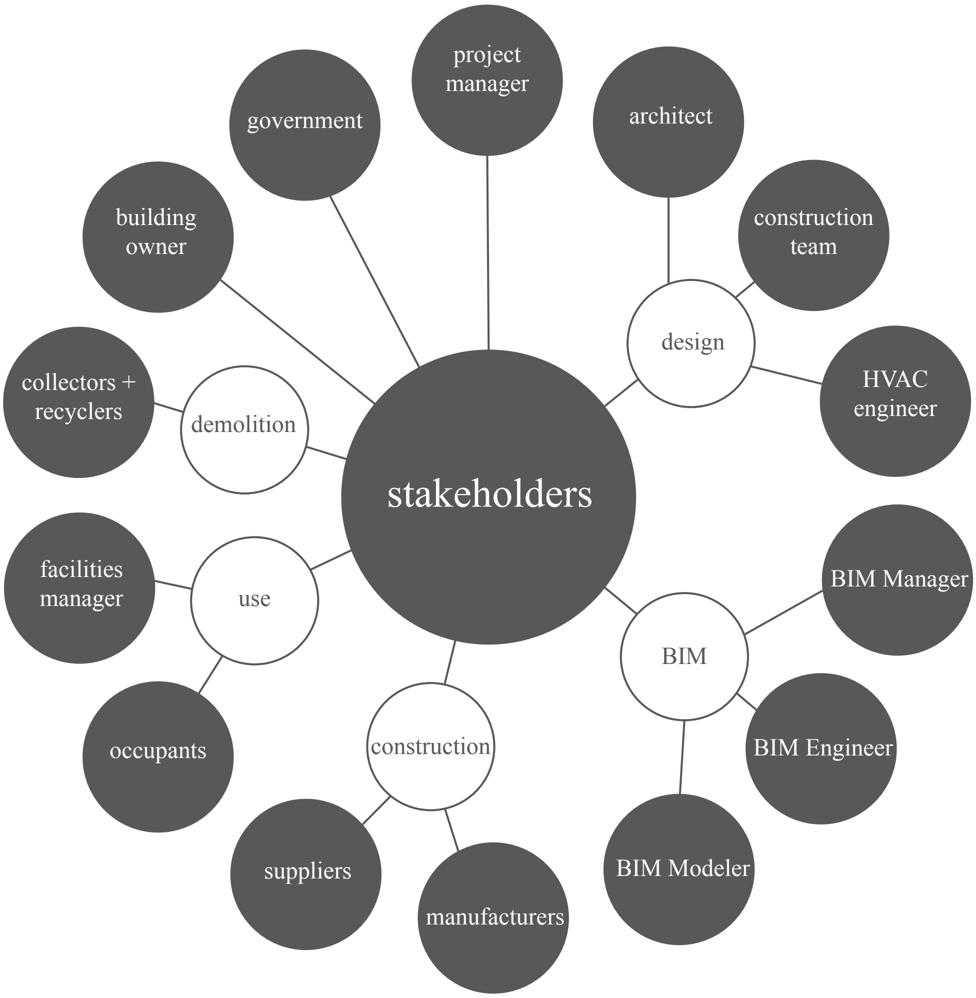


Figure 36 - Stakeholders building life cycle

5.5.4 Level of Detail

Level of Detail, LOD or also referred to as Level of Development, is a way to describe the level of detail of a BIM model at various stages. Per stage there will be agreed upon a LOD to determine responsibilities (Figure 37).

According to Eastman (2011) the level of detail can be described as following:
LOD100: Approximate graphical representation with symbol or other generic representation.
LOD200: Generic system or object with approximate quantities, size, shape, location and orientation.
LOD300: Specific system or object in terms of quantity, size, shape, location and orientation.
LOD350: Specific system or object in terms of quantity, size, shape, location, orientation and interfaces with other building systems.
LOD400: Specific system or object in terms of quantity, size, shape, location and orientation with detailing, fabrication, assembly and installation information.
LOD500: Verified representation in terms of size, shape, location, quantity and orientation.

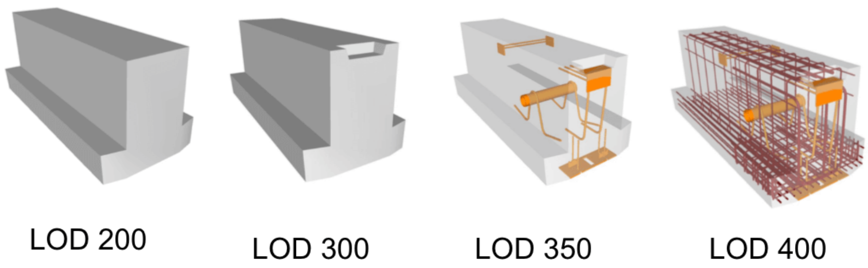


Figure 37 - Level of Detail (LOD) for BIM (BuildingSMART, 2016)

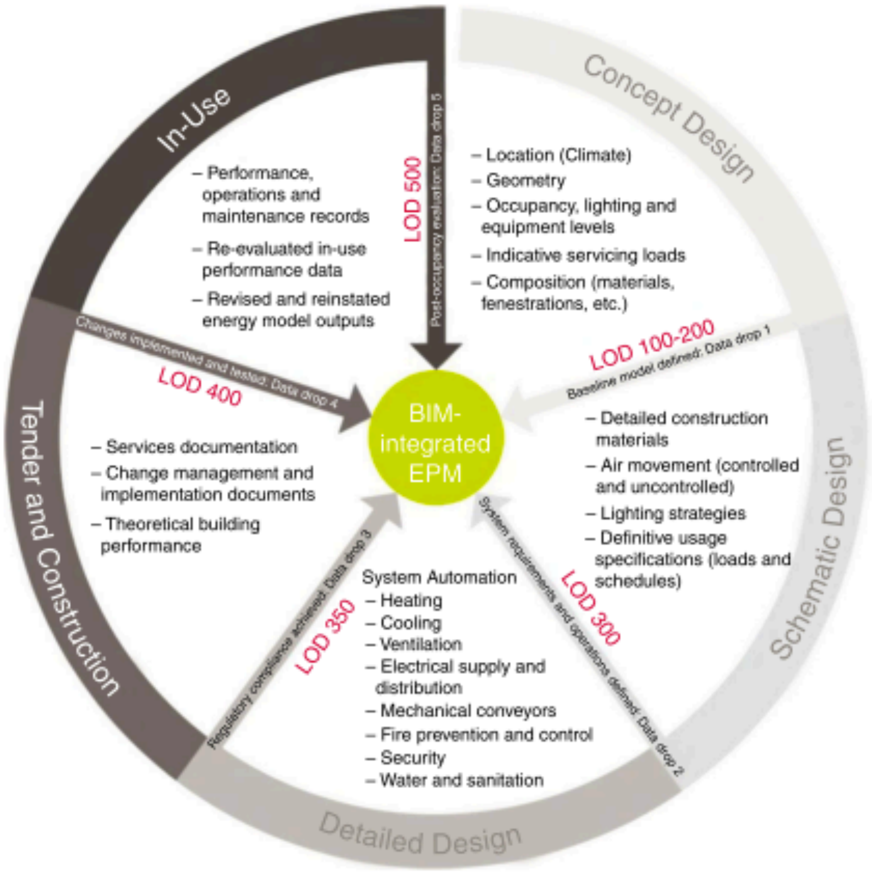


Figure 38 - LOD integration BIM (Gerrish, Ruikar and Cook, 2017)

The Level Of Detail is affected by the size of the model and the items that need to be communicated (Figure 38). Planners can use a single component to represent multiple activities guarantee computational speed (Eastman, 2011). LOD is only related to the physical BIM model and not to other deliverables and responsibilities.

It is recommended that only relevant information identifying an object will be entered into the BIM model to avoid information overload. This allows the model to operate faster (Weygant, 2011). All information on the unique characteristics of the element can be kept in a separate database which can be easily linked to the model (Luscere, 2016).

Within different LODs, especially during the design and optimization phase, the evolution of material definition through the lifecycle plays an important role; the level of detail evolves from conceptual generic material definition to a very specific grade. For example, at first a material can be described as 'strong, stiff plastic', later the specific type will be further defined; 'glass-filled nylon', in the next phase; 'PA66 20-25% glass fibre, flame-retarded' and eventually; 'Du Pont Zytel 70G20HSL in Aurora Red' (Fairfull et al., 2016).

5.5.5 Material data in BIM

A Building Information Model can consist of a large number of objects, representing physical and functional information. The objects contain information about their geometry, location, relation to other objects and a number of other different attributes relevant for the object. A Building Information Model is able to contain all available and relevant information about every single component of a building (BAMB2020, 2017). Elements that have the same function can be linked into groups with identical or similar physical properties and often a similar life duration (Markova & Dieckmann, 2012).

Weygant (2011) states that material data is often the most important information in the specification of an object. Taking the time to develop a high-quality set of a material early on, facilitates to use this set for diverse objects, requiring little or no effort to maintain them.

General material information in BIM is easy to link to an object, but the standard available types of material are imprecise (BAMB2020, 2017), such as 'Wood' or 'Glass'. Each graphic solid has a material assigned that details its appearance in the model, render view and associated information about its properties. Attributes may be added to materials which allow them to be categorized. An important possibility of adding attributes into materials is to offer the ability to explain why it was selected (Weygant, 2011). Names of manufacturers, material classifications and performance values make the materials searchable within the model. In ArchiCAD, this can be done with the 'Find & Select' tool, which will be defined later. Objects that are assemblies of components, consist of series of materials. In BIM, those are specified as a single unit, rather than a sum of manufactured parts. This makes it more challenging to trace the exact location of the material.

It is possible to add, or change, material information per object. In Figure 39, general options for material selection are shown. It is possible to create a new building material. However, no detailed information can be entered here; in the 'ID', a name or description with more information can be added (Figure 40 and Figure 41). Weygant (2011) advises to avoid using special characters in naming materials, as they can cause errors when importing and exporting information of the model to other formats.

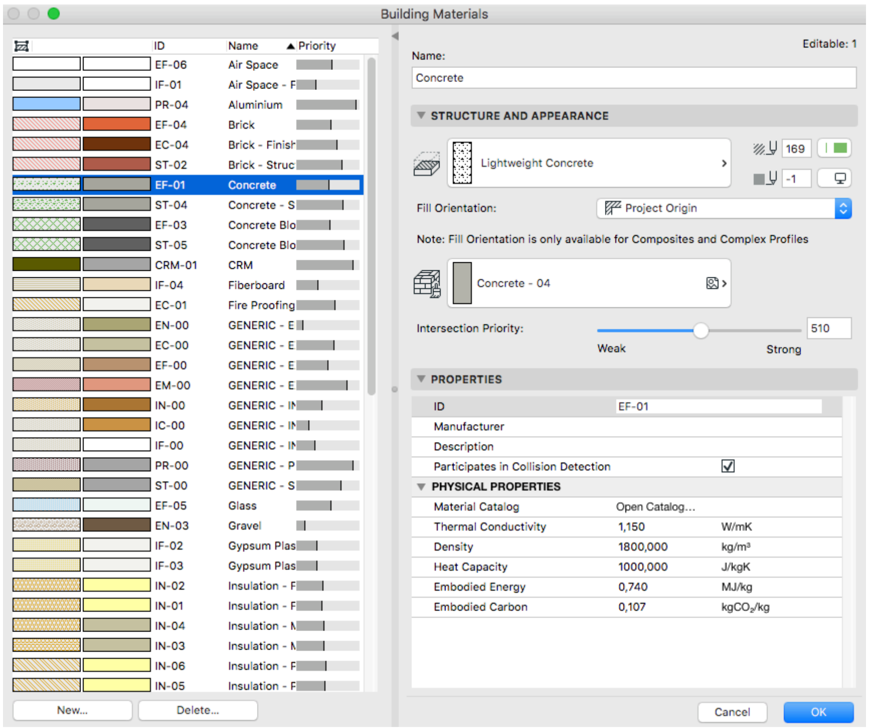


Figure 39 - Building material in ArchiCAD (source: ArchiCAD)

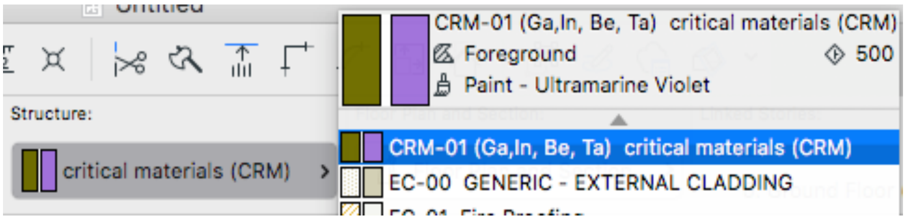


Figure 40 - CRM is manually added to Building Materials Library in ArchiCAD (source: ArchiCAD)

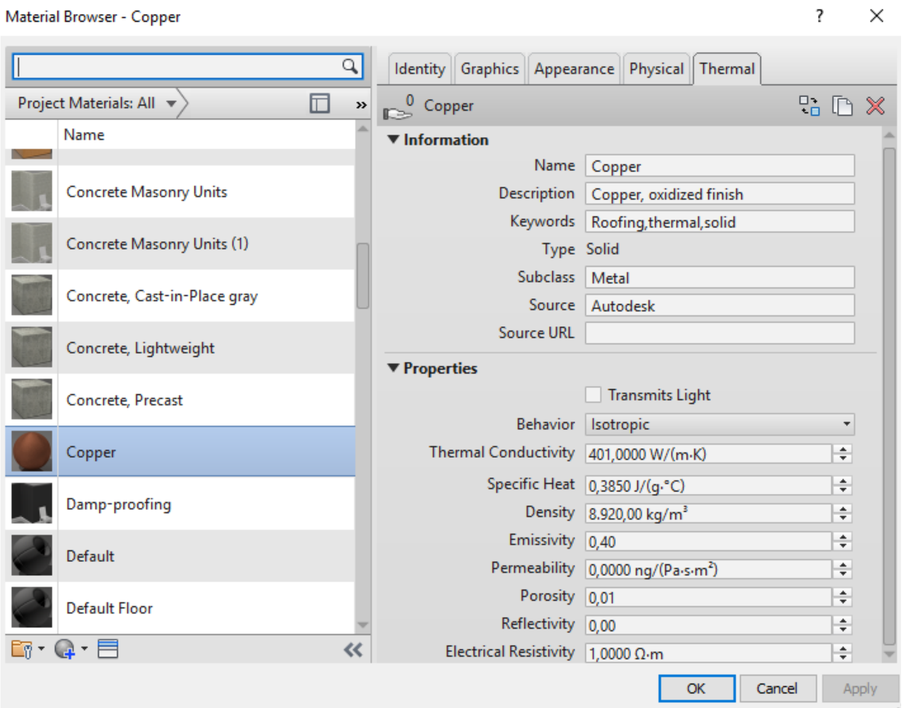


Figure 41 - Material information in Revit (source: Revit)

5.6 Industry Foundation Class

5.6.1 Introduction

A dedicated material information system may become isolated information; it needs to be easily available for everyone who needs it. Integration must ensure that data can flow between different engineering software programs (Warde et al., 2012).
One of the standards developed for BIM is IFC. BuildingSMART develops and maintains IFC (Industry Foundation Classes). IFC is an open and international standard for exchanging BIM data to facilitate interoperability in the architecture, engineering and construction (AEC) industry. An '.ifc' file is a physical file that directly can be embedded in the BIM model. IFC is widely used to exchange data and represents 3D objects and related information. However, for modelling purposes, IFC does have flaws in processing parameters, which causes imperfections in exporting the exact physical representation of an object.
The data representations of building information are exchangeable for different AEC software applications (Eastman, 2011). Over 150 software applications support import and export of IFC data. Besides modelling programs, these formats are available within construction management, building services, facility management, simulation and model viewer programs (BuildingSMART, 2018). Figure 42 shows a single IFC file in three different applications.

NBS (National Building Specification) is an organization that defines BIM Object Standard requirements to obtain quality and enable collaboration and efficient information exchange. It is essential to use consistent information to make data comparable and interoperable. The NBS National BIM Library developed an industry standard that gives every object a core property set to adopt a consistent approach for classification, standard naming for the ease of use and standardized approaches to the level of detail and object presentation (NBS, 2018).

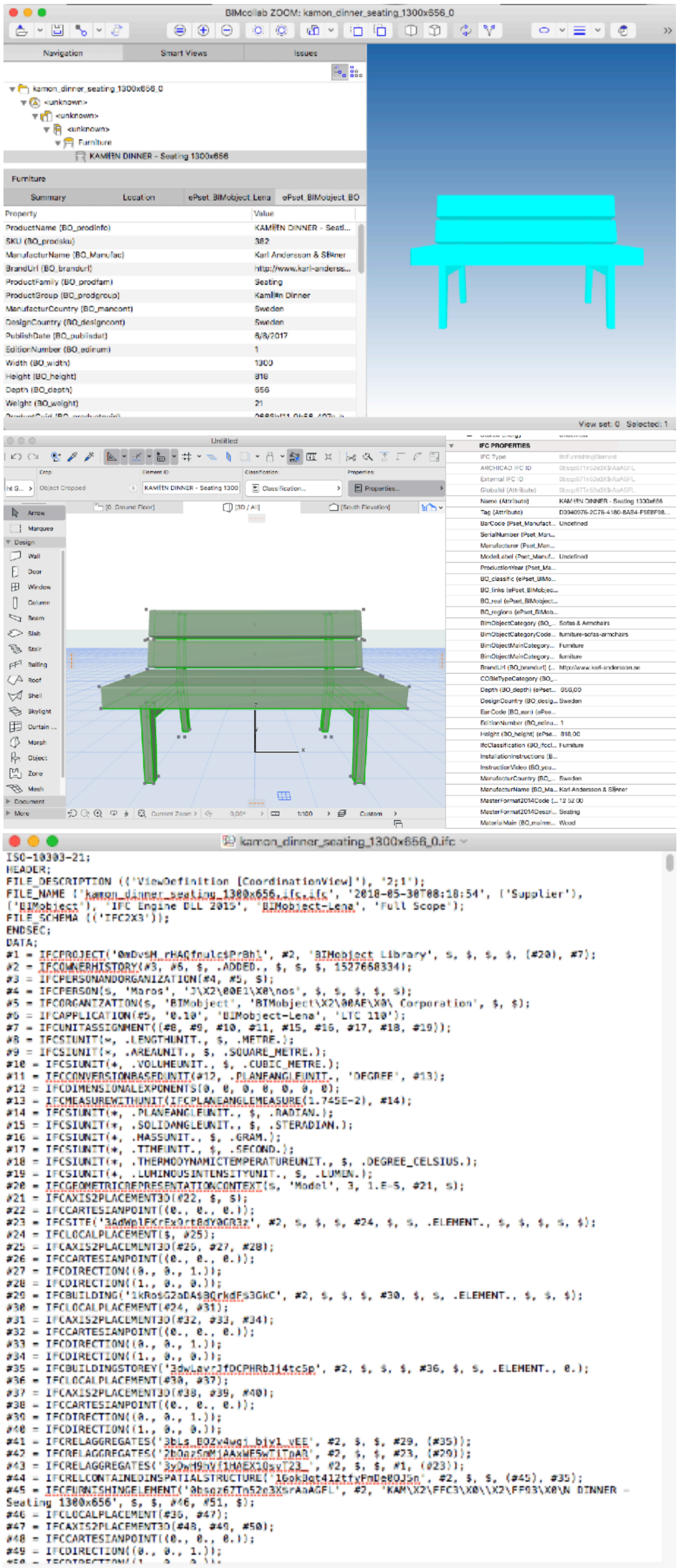


Figure 42 - IFC file in three different AEC applications (source: BIM viewer, ArchiCAD and Text editor)

5.6.2 Structure IFC

In an IFC model, the project information is represented as a set of **IFC entities**, built up in a hierarchical order. IFC Entities can for instance be objects, surfaces and their relationships. In Figure 44, a standard set of IFC Entities within ArchiCAD is shown. Each entity includes a number of **IFC attributes** and additional **IFC properties**. A few hundred entities are available, including building elements, properties and relationships. An **IFC Container** is an IFC entity that does not have its own geometry, but geometry is captured in its components. An example is a window that consist of the components glass and window frame. A particular style of type of a product can be defined by **IFC Type Product** (BuildingSMART, 2018). The structure of an IFC file is shown in Figure 43.

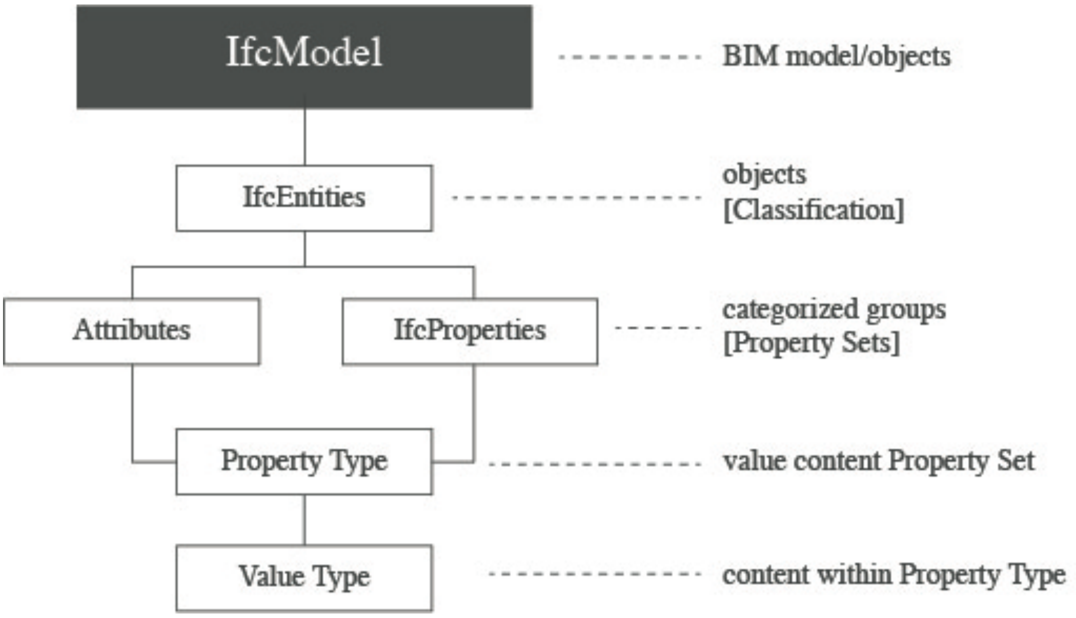


Figure 43 - Structure IFC file

NBS describes standard information on IFC formats. Within the BuildingSMART library, many IFC 'Property Sets' are available that can be added to an object. If a required property set is not available, a new one can be created. To standardize the name for this property set, it is recommended to use 'Pset_xxxxxCommon', where 'xxxxx' describes the required property set (BuildingSMART, 2018). Furthermore, it is recommended that property names are entered as 'PascalCase'. When a parent-child relationship occurs, the child should be prefixed with the corresponding parent property so that they are sorted logically within the hierarchical order. Property names should not include units. In Revit IFC properties are named 'IFC Parameters' in among others ArchiCAD and Vectorworks 'Pset_xxxxx' (NBS, 2018).

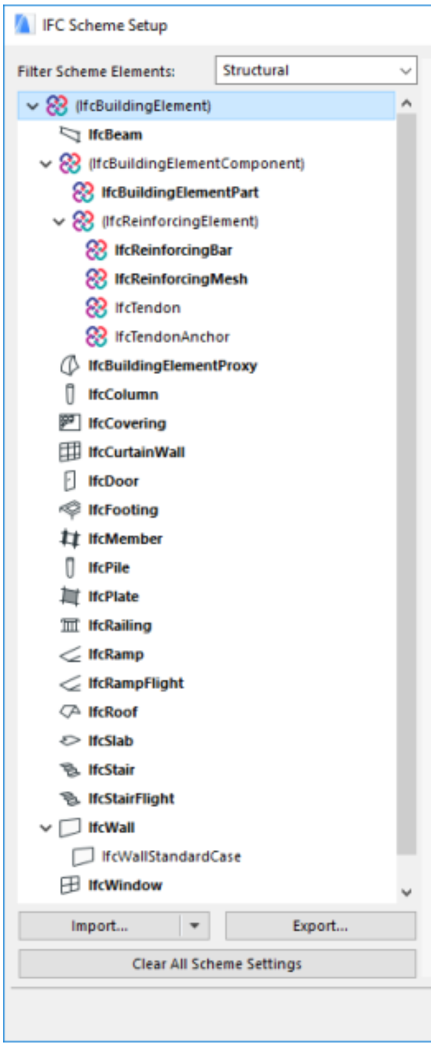


Figure 44 – Standard IFC Entities in ArchiCAD (source: ArchiCAD)

IFC Attributes are the main identifiers of IFC entities. Their names are fixed as part of the IFC standard code, defined by Building SMART. The Value of the entity is open depending on a specific type.

IFC Properties are stored in property sets, whose names begin with the prefix 'Pset_' in most BIM environments. This is a container class that holds properties and that can be assigned to an object. The same 'property set' can be applied to more objects. 'Property sets' consists of minimal one property, defined by a Property name and a property type. The '**Property type**' has a value for the content of the property. Mostly used values are 'Single Value', 'Enumerated Value', 'Bounded Value', 'Table Value', 'List Value' and 'Reference Value'. Their definitions can be found in Table 3 (BuildingSMART, 2018).

Table 3: Property types defined by Helpcenter Graphisoft (2018)

Property type	Definition
Single Value	A property object which has a single (numeric or descriptive) value assigned.
Enumerated Value	A property object whose value is chosen from an enumeration.
Bounded Value	A property object which has a maximum of two (numeric or descriptive) values assigned, the first value specifies the upper limit and the second value specifies the lower limit.
Table Value	A property object which has two lists of (numeric or descriptive) values assignes, corresponding to a table with two columns.
List Value	A property that has serveral (numeric or descriptive) values assigned, corresponding to an ordered list.
Reference Value	A property object which references to calendar date-type entity (day/month/year)

Besides the 'Property Type', a '**Value Type'** must be defined. The 'Value Type' defines the possible content within the 'Property Type'. Value types can be among others; 'IfcLabel', 'IfcIdentifier', 'IfcText'. 'IfcTimeMeasure', 'IfcBoolean', 'IfcLengthMeasure' and 'IfcInteger'. The value type limits the possible content of the entity, the mostly used Value types are described in Table 4. Properties with a value Boolean, which requires a 'Yes' or 'No', need to be named so that they clearly imply that they require such an answer (BuildingSMART, 2018).

Table 4: Value types defined by Helpcenter Graphisoft (2018)

Value Type	Definition
IfcBoolean	A defined data type value is TRUE or FALSE (YES or NO in some environments).
IfcIdentifier	Max. 255 characters which allows an individual thing to be identified.
IfcInteger	A defined data type of a number of bits, the number is unrestricted.
IfcLabel	A label is the term by which something may be referred to, max. 255 characters.
IfcLengthMeasure	Real type value of distance, set in meters, recalculated at export based on Length Unit settings.
IfcLogical	A defined data type; TRUE, FALSE or UNKNOWN.
IfcMonetaryMeasure	Real type value of an amount of money without regard to its currency (can be set at Currency Unit settings.
IfcRatioMeasure	Real type value of relation between two physical quantities that are of the same kind, expressed as a decimal value.
IfcReal	A defined data type of simple real type; numbers.
IfcText	Alphanumeric string of characters which is intended to be read and understood by a human being, for information purposes, no character number limitation.
IfcTimeMeasure	Real type of duration of time periods, time unit can be set at Time Unit settings.
IfcVolumeMeasure	Real type of value of the solid content of a body, set in cubic meters, but recalculated at export based on Volume Unit settings.

The structure of the text version file is openable in a text editor. Herein all data is available, although more difficult to understand. The file is divided in a header and a data section. The header contains information about the used IFC version, the application that exported the file, the date and time when the export was done, the name, the company and the authorizing person of the file (Liebich, 2009). Afterwards an unlimited number of lines is set. These define the physical and functional properties of the model.

Structure of an IFC file in text format:

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION (('ViewDefinition [CoordinationView]'), '2;1');
FILE_NAME ( ‘filename.ifc’,
     ‘2018-04-09T20:55:36',
     (‘user’),
     (‘company’),
     ‘name and version of IFC preprocessor',
     ‘name of originating software system',
     ‘name of authorizing person’);
FILE_SCHEMA ((‘IFC2x3’));
ENDSEC;
DATA;
     #1 = …;
     #2 = …;
     #3 = …;
     etc.
ENDSEC;
END-ISO-10303-21;
```

The data within the text version of an IFC file, is more difficult to understand, but openable in most simple text editors. Herein it is still possible to search for specific terms or names, such as critical materials, Gallium or Ga.

5.6.3 IFC Material Properties

The following entities from BuildingSMART are available concerning materials:

- IfcMaterial
- IfcMaterialClassificationRelationship
- IfcMaterialDefinitionRepresentation
- IfcMaterialLayer
- IfcMaterialLayerSet
- IfcMaterialLayerSetUsage
- IfcMaterialList
- IfcMaterialProperties

‘IfcMaterial’ can be a homogeneous or inhomogeneous substance that can be used to form elements. This is the basic entity for material designation and definition; it includes a name and classification, as well as an association of material properties defined by ‘IfcMaterialProperties’.

'IfcMaterialProperties' assigns a set of material properties to associated material definitions. The set may be identified by a 'Name' and 'Description'. Subtypes are used to express the individual material properties by name, description, value and unit.
A set of material properties can be assigned to an individual 'IfcMaterial', to a set or composite of materials; 'IfcMaterialConstituent', 'IfcMaterialConstituentSet', to a set or individual material layer; 'IfcMaterialLayer', 'IfcMaterialLayerSet' or a set or individual material profile; 'IfcMaterialProfile', 'IfcMaterialProfileSet' (BuildingSMART, 2018).

5.6.4 Custom Property Sets

If the required property does not exist, it is possible to create a new one. In the 'IFC Scheme Setup' new attributes can be defined by clicking 'New Property/Classification'. An existing property set can be selected or a new one can be created, starting with "Pset_" (Figure 45).

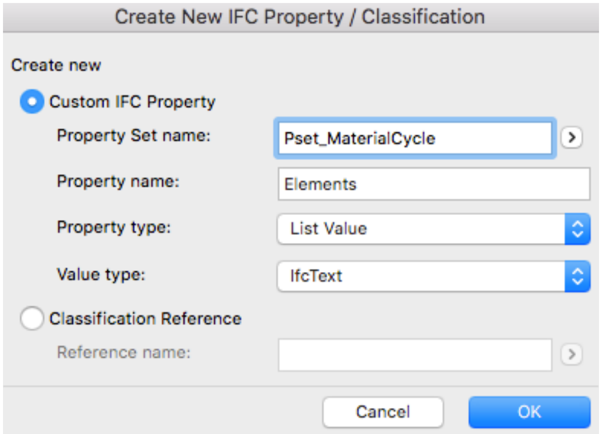


Figure 45 - Create new Property Set in ArchiCAD

Markova & Dieckmann (2012) describe new type of property sets concerning material efficiency: 'Pset_SubstanceCommon' gives information about the contained substances and 'Pset_MaterialCycle' about the circularity of the material (Figure 46).

TABLE 1. PropertySet Name: Pset_SubstanceCommon.

Name	Data Type	Definition
Reference	IfcIdentifier	ReferenceID for the specific type in the project
Listed	IfcBoolean	Indicates whether the substance is marked as listed according to current safety classifications
Composition Rating	IfcBoolean	Indicates if the substance is identified as an "impurity" with regard to the containing material and will therefore cause a downgrade in the recycling process

TABLE 2. PropertySet Name: Pset_MaterialCycle.

Name	Data Type	Definition
Reference	IfcIdentifier	ReferenceID for the specific type in the project
Composite	IfcBoolean	Identifies if the material is a composed material (according to manufacturer data sheets)
Recycled	IfcBoolean	Identifies if the material is a recycled material
Recyclable	IfcBoolean	Identifies if the material is recyclable

Figure 46 - Custom 'Property Sets' concerning materials (Markova and Dieckmann, 2012)

5.6.5 Required data in IFC

The required data for a material passport mentioned in 5.2 is converted in Table 5 into possible IFC properties. Also general properties are given which are standard contained in a dataset.

Table 5: Required data converted to possible IFC properties

	Data	Property Set	Content	Type	Value
General	IFC Type	Attributes	IfcType to specify		
	Fixed ID	Attributes	GlobalID (fixed: derived from project)	Single Value	IfcGlobally UniqueId
	OwnerHistory of IFC object	Attributes	OwnerHistory (fixed: derived from project)	Single Value	-
	Name	Attributes	text	Single Value	IfcLabel
	Description	Attributes	text	Single Value	IfcText
	Object type	Attributes	type or family	Single Value	IfcLabel
	Article number	Attributes	text	Single Value	IfcIdentifier
	Product information	Attributes	hyperlink	Single Value	IfcText
	Importance	Attributes	Contains material of high importance!	Single Value	IfcText
	Production year	Pset_Manufacturer	YYYY	Reference Value	IfcLabel
	Service life	Pset_RenovationAnd Phasing	YYYY	Reference Value	IfcLabel
	Use guide	Pset_Operation	hyperlink	Single Value	IfcText
	Installation guide	Pset_Operation	hyperlink	Single Value	IfcText
	Maintenance guide	Pset_Operation	hyperlink	Single Value	IfcText
	Legislation	Pset_Legislation	certificates	Single Value	IfcText
Manufacturer	Barcode	Pset_Manufacturer	text	Single Value	IfcIdentifier
	Serial number	Pset_Manufacturer	text	Single Value	IfcIdentifier
	Manufacturer	Pset_Manufacturer	text	Single Value	IfcIdentifier
	Sub-manufacturers	Pset_Manufacturer	text	List Value; Tabel Value	IfcList; IfcText
	Production year	Pset_Manufacturer	YYYY	Reference Value	IfcLabel
	Ownership	Pset_BusinessModel	text	Single Value	
	Business model	Pset_BusinessModel	text or link	Single Value	
	Environmental impact		hyperlink	Single Value	IfcText
Circularity Composition	Replaced parts during operation	Pset_Operation / Pset_MaterialCycle	list of replaced parts	List Value	IfcText
	Components list	Pset_MaterialCycle	list of all components	List Value	IfcText
	Re-usable components?	Pset_MaterialCycle	TRUE/FALSE	Single Value	IfcBoolean
	List reusable components	Pset_MaterialCycle	list of reusable components	List Value	IfcText
	References re-usability	Pset_MaterialCycle	hyperlink	Single Value	IfcText
	Reused components?	Pset_MaterialCycle	TRUE/FALSE	Single Value	IfcBoolean
	List reused components	Pset_MaterialCycle		List Value	IfcText
	Processing	Pset_MaterialCycle	hyperlink/text	Single Value	IfctText
	Guidelines EOL treatment	Pset_MaterialCycle	hyperlink	Single Value	IfcText
	Bill of Materials (BOM)	Pset_MaterialCycle	Table or hyperlink (overview amount per material, origin, reason of choice per material)	Table Value; Single Value	IfcText
	Elements	Pset_SubstanceCom mon	List of all elements	List Value	IfcText

Critical materials?	Pset_SubstanceCommon	TRUE/FALSE	Single Value	IfcBoolean
CRM factor	Pset_SubstanceCommon	ProSUM factor	Single Value	
Hazardous elements?	Pset_SubstanceCommon	TRUE/FALSE	Single Value	IfcBoolean
List Hazardous elements	Pset_SubstanceCommon	List of hazardous elements	List Value	IfcText
Material history (recycled materials)	Pset_SubstanceCommon	Hyperlink/text	Single Value	IfcText
Recyclable materials	Pset_SubstanceCommon	List of recyclable materials	List Value	IfcText

The exact location and number of components can be easily find via the 'Project Manager', 'Find & Select' tool or 'Schedules', which are discussed later. Hyperlinks could be made only accessible for certain parties via a hyperlink with a password, however this is not desirable. This makes the information not available anymore for all stakeholders and it hinders the traceability of data.

5.6.6 Find & Select

To make objects easily findable by their content, it is important to consider how they are organized within the AEC industry and how they will be searched for. This could be for instance by category, classification and specific type (Weygant, 2011). The 'Find & Select tool' (in ArchiCAD) is useful to find objects on specific properties or other given information (Figure 47). Open the tool at 'Edit' > 'Find & Select'. Click bottom arrow next to 'Add…' > 'IFC Properties …' > 'List IFC Properties from 'Project''.

Select types or find types by filtering the list and adding values for the defined criteria. Add as many criteria as needed. Deselect all objects and click 'Selection +' to find the delegated objects.

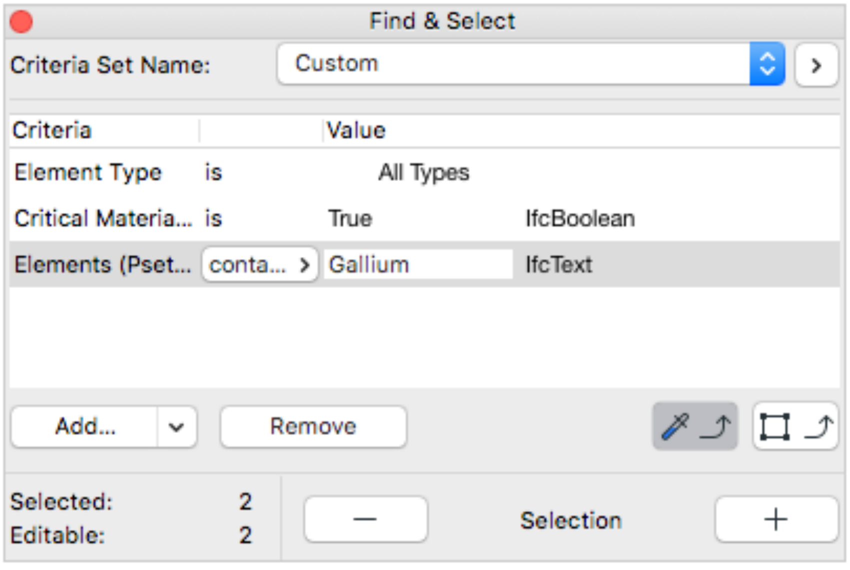
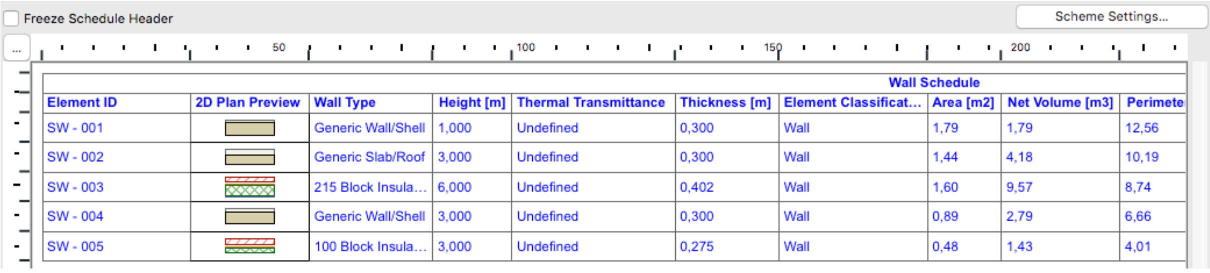


Figure 47 - 'Find & Select' tool in ArchiCAD (source: ArchiCAD)

5.6.7 IFC Schemes

In ArchiCAD, IFC Attributes, Properties and Classification Reference data can be stored in schemes, which are '.xml' files (Figure 48). An **IFC Scheme** is a collection of IFC Properties that can be defined and used in a project for certain or all IFC element types. These can be used to manage IFC data and assign rules to IFC data.
Schedules or schemes can be find by clicking 'Document' > 'Schedules'. Here the required schedule can be selected, viewed and exported to XML file. From this window, or via 'Document' > 'Schedules' > 'Scheme Settings', the Scheme Settings can be opened. In the scheme settings can be defined, which properties will be visible in the selected scheme.



Element ID	2D Plan Preview	Wall Type	Height [m]	Thermal Transmittance	Thickness [m]	Element Classificat...	Area [m2]	Net Volume [m3]	Perimete
SW - 001		Generic Wall/Shell	1,000	Undefined	0,300	Wall	1,79	1,79	12,56
SW - 002		Generic Slab/Roof	3,000	Undefined	0,300	Wall	1,44	4,18	10,19
SW - 003		215 Block Insula...	6,000	Undefined	0,402	Wall	1,60	9,57	8,74
SW - 004		Generic Wall/Shell	3,000	Undefined	0,300	Wall	0,89	2,79	6,66
SW - 005		100 Block Insula...	3,000	Undefined	0,275	Wall	0,48	1,43	4,01

Figure 48 - Schedule in ArchiCAD (source: ArchiCAD)

The Schedules can be easily exported into XML formats which is openable in Excel. This can be done from the Schedule window, 'File' > 'Export as' > 'Excel Workbook' or 'PDF'.

5.7 Chapter conclusion and discussion

To be able to create one large BIM-model of all IFC standards, it is important that the required data has been acquired and that the necessary knowledge and skills to put the models together are available.
The information must be collected from the very first beginning of the supply chain, consistently available and exchanged amongst all stakeholders, on a 24/7 hour basis. This requires full collaboration and complete transparency. It must be defined by an agreement amongst all, which information must be delivered from the beginning of the supply chain in order to receive required data and to prevent miscommunication and uncertainties.
At the moment it seems almost impossible to achieve this transparency. Confidentiality of data from manufacturer's side could be a problem to realize a transparent dataset. Also the complexity of the whole supply chain makes it challenging to receive this information. There are possibilities in BIM to keep this data confidential. This can be done by adding a hyperlink in an 'IfcText' element, and make the hyperlink only available for certain stakeholders by entering credentials. This is certainly not beneficial for the required transparency of information. BIM is meant to be an open process.

IFC files seems to be appropriate to process the required information on critical materials and their circularity. Many different 'Property Sets' are available and new ones can be created easily, to which information can be linked in groups. On the basis of chapter 3 and 4, the following groups are created: general information, materials, optimize lifetime, circularity and manufacturer.
Because one object can consist of many sub-components which do not exist in the model separately, documentation of all sub-components are brought together into one dataset. This makes it more difficult to trace the exact location of the material within the object. An 'IfcTable' makes it possible to link all materials to sub-components. Another possibility is to link external overviews with this information via a hyperlink in 'IfcText'.

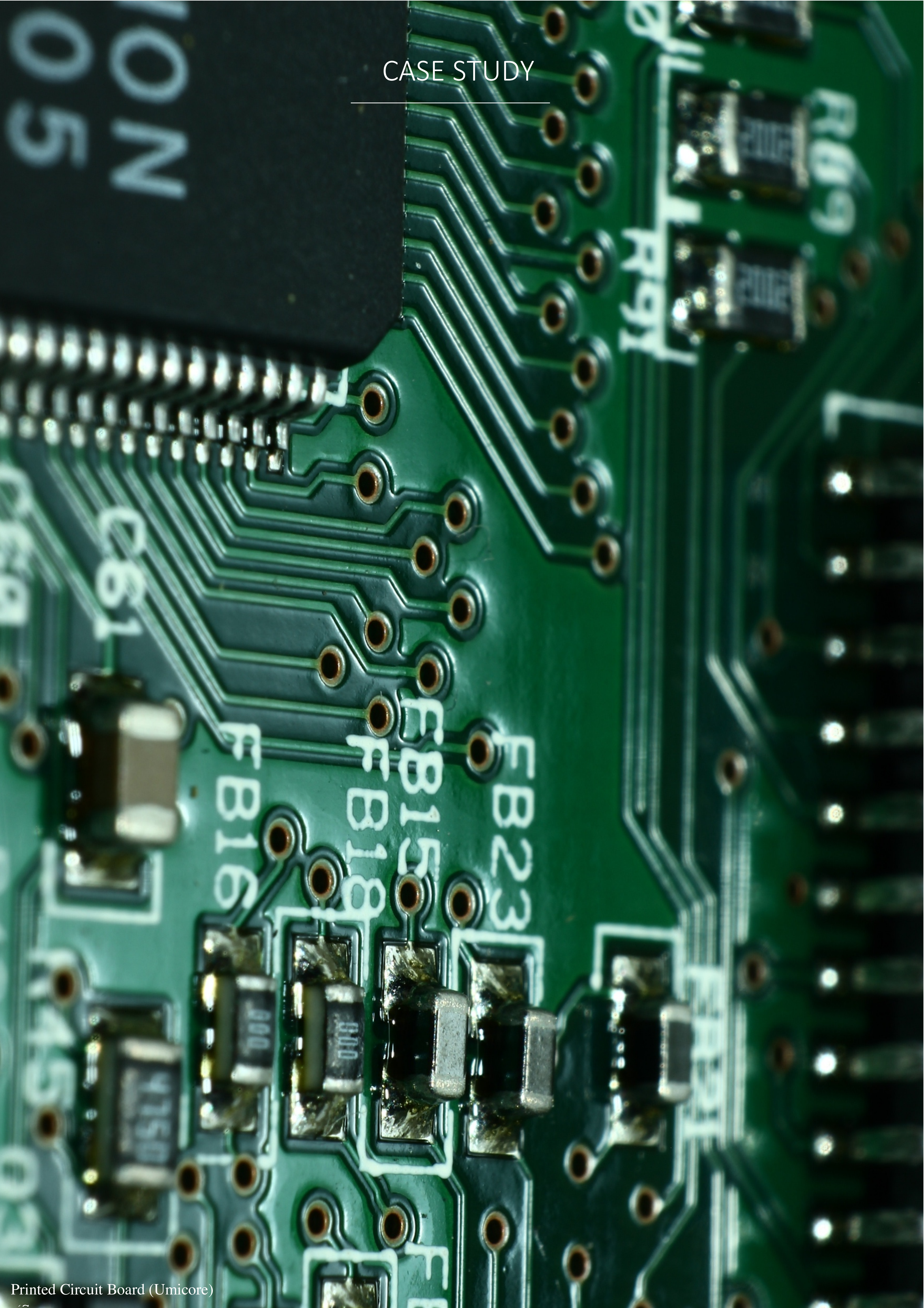
IFC files are complex files which require advanced skills to enter and process specific information in very specified format. Based on the complexity of BIM, A BIM specialist is therefore required to process all data in a very accurate way. To obtain standardized datasets, specification of the required content is necessary. There is a tremendous need to easier connect data between all platforms to be fully exchangeable and available. This needs to be researched further. For example to the Urban Mining Platform from ProSUM or other economic models of the EU.

In Part III of the framework in Figure 49, the groups and connected 'Property Sets' and 'Values' are described to process the required information.

	content	Property Set	Value + Type
general information	name	Attributes	IfcLabel; Single Value
	description	Attributes	IfcText; Single Value
	type	Attributes	IfcText; Single Value
	article number	Attributes	IfcLabel; Single Value
	installation date	Pset_Manufacturer	IfcLabel; Reference Value
	product description	Pset_Manufacturer	IfcText; Single Value;
materials	Bill of Materials list, weight and origin	Pset_MaterialCycle	IfcText;Single Value; hyperlink
	list of all elements	Pset_SubstanceCommon	IfcText; List Value
	critical materials EU 2017	Pset_SubstanceCommon	IfcBoolean; Single Value
	CRM factor	Pset_SubstanceCommon	IfcBoolean; Single Value
	hazardous substances	Pset_SubstanceCommon	IfcBoolean; Single Value
	conflict materials	Pset_SubstanceCommon	IfcBoolean; Single Value
optimize lifetime	production year	Pset_Manufacturer	IfcLabel; Reference Value
	expected lifetime	Pset_Manufacturer	IfcLText; Single Value
	use guide	Pset_Operation	IfcText; Single Value; hyperlink
	maintenance guide	Pset_Operation	IfcText; Single Value; hyperlink
	installation guide	Pset_Operation	IfcText; Single Value; hyperlink
circularity	list of components	Pset_MaterialCycle	IfcText; List Value
	reusable components	Pset_MaterialCycle	IfcText; List Value
	reference reusability	Pset_MaterialCycle	IfcText; Single Value; hyperlink
	reused components	Pset_MaterialCycle	IfcText; List Value
	joining techniques	Pset_MaterialCycle	IfcText; Single Value; (hyperlink)
	guideliness EoL treatment	Pset_Manufacturer	IfcText; Single Value;
manufacture	manufacturer	Pset_Manufacturer	IfcLText; Single Value
	sub-manufacturers	Pset_Manufacturer	IfcLText; List Value
	ownership	Pset_BusinessModel	IfcText; SingleValue
	businessmodel	Pset_BusinessModel	IfcText; SingleValue; hyperlink

Figure 49 - Framework part III - required data converted in IFC ‘Property Sets’

CASE STUDY



Printed Circuit Board (Umicore)

6 CASE STUDY

As a case study, a building component is chosen to analyse and to find relevant information for documentation. Looking at building components containing critical materials in the current tendency in the built environment towards smart buildings, a sensor is a logical choice. Sensors are broadly implemented into new and existing buildings to procure energy efficiency.

6.1 SENSOR HISTORY

Like many other technologies, the origin of sensors is found in military. The first wireless sensor with similarities to the modern sensor is the Sound Surveillance System, a network of acoustic sensors spread in the Atlantic and Pacific oceans developed by the US Military in the 1950's to detect and track Soviet submarines (Silabs, 2013).
The first thermostat which is considered as the first modern manmade sensor, came to market in 1883. First infrared sensor in the late 1940s. The first motion sensor came early 1950s, used for an alarm system (Wilson, 2005). Nowadays sensors play an increasing role in our daily lives; in our homes, offices and cars. The devices continue to get smaller, better and cheaper, which opens new ways for more applications.

6.2SENSOR APPLICATIONS

Sensors are devices that detect types of physical occurrences. Measurements of those occurrences will be converted into a signal. In the built environment they are used for a variety of applications. Physical occurrences are for example pressure, light, movement, temperature, humidity.
Converting physical occurrences into an electrical signal, makes sensors the link between the physical world and the world of electrical devices. Sensors are generally part of a larger system, which could be for example a system for measurement, data acquisition or process control (Wilson, 2005).

With the availability of inexpensive and extremely small microprocessors, an opportunity has come for the use of sensors in a wide variety of products (Wilson, 2005). Currently different types of sensors play an important role in the built environment. Motion sensors emit radio energy into a room and monitors the reflection pattern. Passive Infrared (PIR) measures infrared (IR) light and detects changes in the amount of infrared radiation. Those are commonly used in burglar alarms and automatically-activated lightning systems. The sensor converts the resulting change of temperature difference with environment in the output voltage and the infrared emission pattern of the object, which triggers detection.

Internet of Things

The Internet of Things (IoT) is a network of physical devices based on sensor use which enables objects to connect and exchange data. The devices generate all kinds of information and connect those devices and locations for instant data analysis and eventually 'smart' action. IoT facilitates a complete information value loop; an act is monitored by a sensor that creates information (different types of sensors), the information passes through a network so that it can be communicated and collected across time and space. Sensors, therefore, are key elements in the Internet of Things. The obtained information can be analyzed using different tools to develop insights for building operations. Different types of sensors are able to track different features; motion, pressure, light and temperature (Deloitte, 2016).

The Edge

As part of the case study, the applications of sensors were analyzed within 'The Edge' (Figure 50), which is known as the most sustainable office in the world, with a BREEAM qualification 'Outstanding' and a score of 98,36%. The surface area is 41.000 m2 office and 10.000 m2 parking. By means of 28.000 sensors, which means approximately 0.7 sensor per square meter, the smart building tracks different activities in and around the building (Crone, 2015).

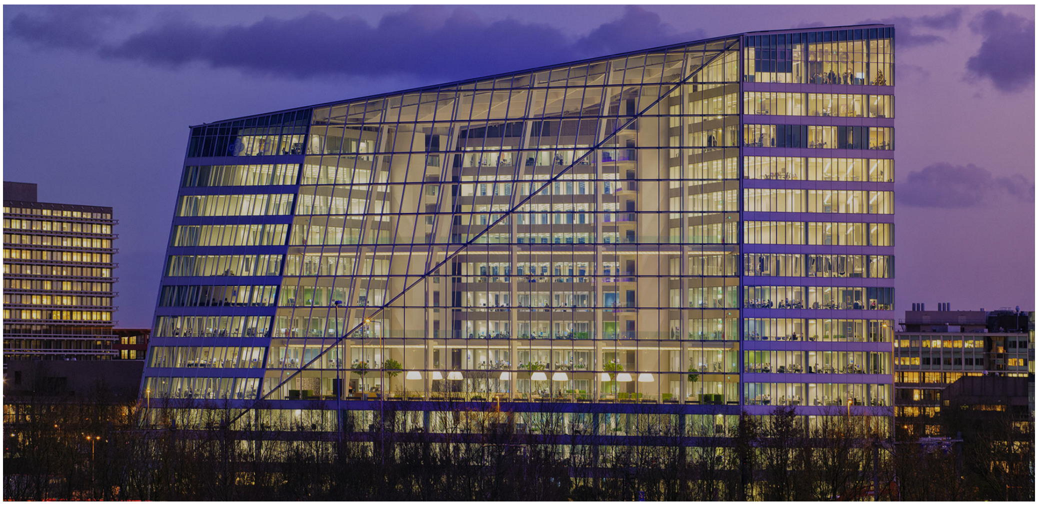


Figure 50 - The Edge 'Most sustainable and smartest office in the world' (OVG Real Estate)

Articles about The Edge (Bloomberg, 2015; OVG Real Estate, 2017) describe smart applications of the sensors. Central dashboards are able to track diverse occurrences; energy use, occupancy and also coffee machines that need to be refilled. On days when fewer employees are expected, an entire section could be shut down. Sensors in LED armatures measure natural daylight, movement and temperature. For smart cleaning, activity is tracked by sensors built into light panels; people and robots responsible for cleaning can focus on the areas that have been used most heavily (Figure 51). An application for the employees suggests desk locations, based on their temperature preferences and meeting locations through-out the day. The on-site gym encourages the employees by tracking their progress when checking in from their phones. Moreover, the gym sends watts back to the grid. The towel dispenser in the bathrooms is connected to the internet and lets cleaning staff know when a bathroom is probably ready for a clean-up. Per individual working space (18 m2) the lightning system is adjustable by the employees with an application on their smartphone. Facility Managers can use information obtained by sensors to make more efficient use of energy, lightning, cleaning, heating and cooling.
These high tech possibilities to make the systems and the workspaces for the employees more efficient sound very impressive. However, according to an employee of Deloitte, many of the data acquired from these systems are not used for optimization yet, since this is in conflict with privacy or other policies.

Also the sensor attached to the working spaces are hardly used, since the system is not up to date and employees have to check in via an application on their phone. The sensor in the coffee machines give a signal to facility manager if it needs to be refilled, but according to the national Deloitte policies, these machines have to be filled every morning, which makes the sensors useless.

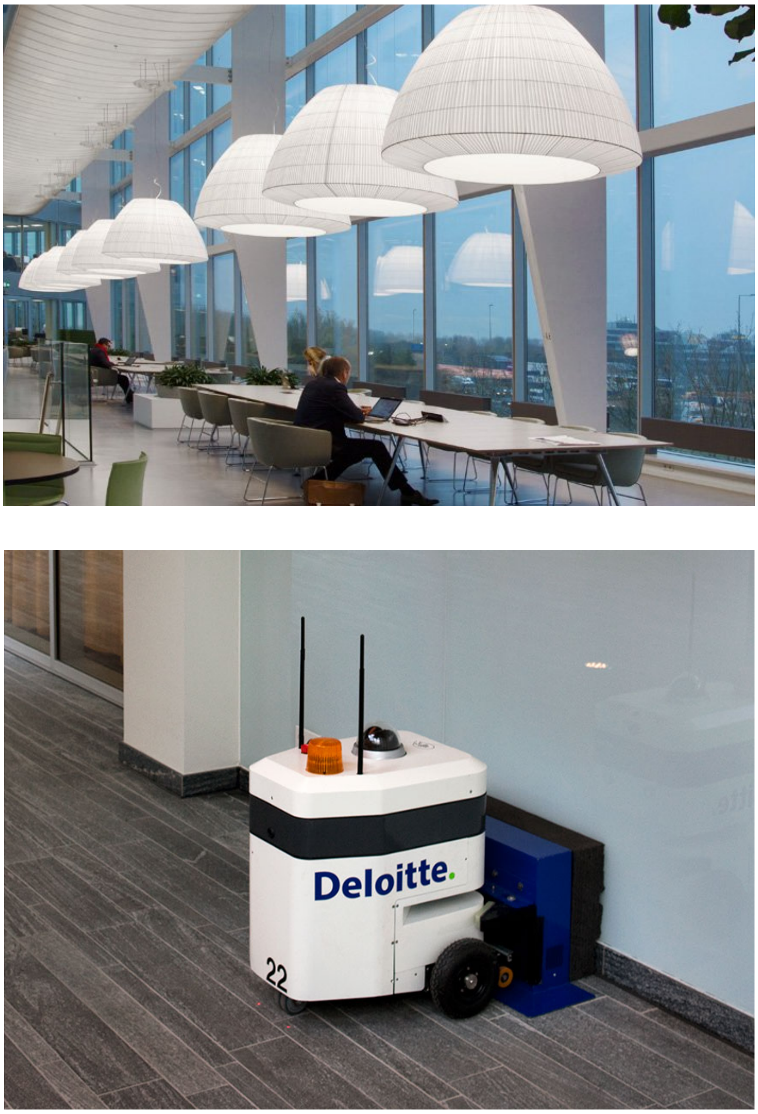


Figure 51 – Robotics and LED armatures with motion sensors (Raimond Wouda)

Atrium of The Edge; known as the most sustainable office of the world (Raimond Wouda)

6.3 Sensor composition and documentation

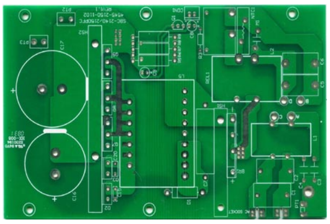
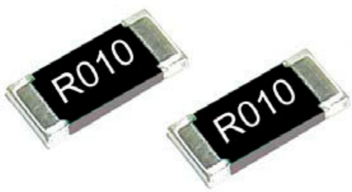
Exact composition of sensors differs per type. For this analysis a motion sensor is taken to analyse. The objective of this analysis is to find the already mentioned data and process this into BIM. A printed circuit board forms the basis of the sub-components (Figure 52).

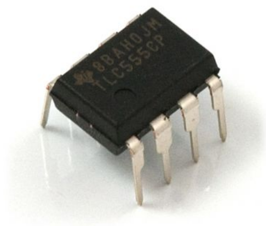
Figure 52 - PIR motion sensor examples (Kiwi-electronics)

The exact content of sensor is not mentioned in product descriptions, neither the components of which the sensor consists. The housing of the sensor is commonly plastic with a plastic window covering which are Fresnel lenses. Some PIR sensors are manufactured with internal, segmented parabolic mirrors to focus the infrared energy. According to Cuchiella et al., (2015), an average of 21% by weight of the WEEE are plastics. Although the cover is for EEE products certainly not the most precious part, this seems often to be the biggest obsolescence driver. The external part suffers from mechanical force and if placed outside, it may suffer from environmental impact (Fischer, Achterberg & Ballester, 2017). This means the internal part with precious elements is reusable; it should be made clear that this part will get back to the manufacturer to remanufacture the sensor.

The exact content per component is not traceable, however a better understanding of the amount of subassemblies and an estimation of the content is given in Table 6. The critical materials are indicated in bold.

Table 6: Sensor sub-components and their content

Image	Name	q	Estimation of the content
	printed circuit board (PCB)	1	Generally Nickel (Ni), Copper (Cu) and Gold (Au). Sometimes **Palladium** (Pd).
	connector	2	**Palladium** (Pd), **Ruthenium** (Ru), **Beryllium** (Be)
	large capacitor	1	**Gallium** Nitride (GaN)
	schottky diode	3	**Indium** (In); **Gallium** (Ga), Zinc (Zn); Oxide (O), **Silicon** (Si), Aluminium (Al), Carbon (C), Chromium (Cr), **Cobalt** (Co), Iron (Fe), Manganese (Mn)
	tactile switch	2	Brass (Copper (Co)+ Zinc(Zn)); Silver (Ag); **Phosphor** (P) bronze; PA; Stainless steel; PPA
	resistor	32	**Ruthium** (Ru), Chromium (Cr), **Tantalum** (Ta)
	capacitor SMD	23	Silver (Ag), **Palladium** (Pd), Tin (Sn), **Tantalum** (Ta), **Niobium** (Nb)
	microcontroller	1	**Gallium** (Ga)

	LED	3	AlIInGaP + InGaN Aluminium (Al), **Indium** (In), **Gallium** (Ga); **Phosphorus** (P), Nitrogen (N)
	transistor/ amplifier	10	**Silicon** (Si), **Germanium** (Ge), **Gallium** (Ga), Arsenide (As)
	inductor	1	FeNiMo, FeSiAl Iron (Fe), Nickel (Ni), Molybdenum (Mo), **Silicon** (Si), Alumium (Al)

(content of sub-components: CRMInnonet (2013); images: kiwi-electronics.com)
* The mentioned materials are estimations.

Detailed information about the exact content of one of the sub-components was found on the product specification website of Nexperia (2018). Namely of the ‘Schottky diode’ or ‘BAT54’. The total mass of this sub-component is 7,5 mg. It contains gives substances from the current list of critical materials defined by the EU (European Commission, 2017). An overview of the complete content of this sub-component can be found in Figure 53.

Subpart	Material group	Substances	CAS number	Mass(mg)	Mass(%) of subpart	Mass(%) of total product
Die	Doped silicon	Silicon (Si)	7440-21-3	0.03000	100.00000	0.40117
		subTotal		*0.03000*	*100.00000*	*0.40117*
Lead Frame	Iron-nickel alloy	Aluminium (Al)	7429-90-5	0.00220	0.08980	0.02942
		Carbon (C)	7440-44-0	0.00098	0.04000	0.01310
		Chromium (Cr)	7440-47-3	0.00539	0.22000	0.07208
		Cobalt (Co)	7440-48-4	0.01054	0.43021	0.14094
		Iron (Fe)	7439-89-6	1.17551	47.98019	15.71920
		Manganese (Mn)	7439-96-5	0.02107	0.86000	0.28175
		Misc. Phosphor compounds [1]	7723-14-0	0.00049	0.02000	0.00655
		Misc. Sulfur compounds [1]	7704-34-9	0.00049	0.02000	0.00655
		Nickel (Ni)	7440-02-0	0.88543	36.14015	11.84018
		Silicon (Si)	7440-21-3	0.00637	0.26000	0.08518
	Pure metal layer	Copper (Cu)	7440-50-8	0.27856	11.36984	3.72497
		Silver (Ag)	7440-22-4	0.06296	2.56981	0.84192
		subTotal		*2.44999*	*100.00000*	*32.76184*
Mould Compound	Additive	Non hazardous	Proprietary	0.09560	2.00000	1.27839
		Triphenylphosphine	603-35-0	0.02390	0.50000	0.31960
	Filler	Silica -amorphous-	7631-86-9	3.44160	72.00000	46.02189
	Pigment	Carbon black	1333-86-4	0.02390	0.50000	0.31960
	Polymer	Epoxy resin system	Proprietary	0.71700	15.00000	9.58789
		Phenol Formaldehyde resin [1]	9003-35-4	0.47800	10.00000	6.39193
		subTotal		*4.78000*	*100.00000*	*63.91930*
Post-plating	Impurity	Antimony (Sb)	7440-36-0	0.00002	0.00952	0.00027
		Bismuth (Bi)	7440-69-9	0.00004	0.01905	0.00053
		Iron (Fe)	7439-89-6	0.00002	0.00952	0.00027
		Lead (Pb)	7439-92-1	0.00002	0.00952	0.00027
	Tin solder	Tin (Sn)	7440-31-5	0.20989	99.95239	2.80670
		subTotal		*0.20999*	*100.00000*	*2.80804*
Wire	Pure metal	Copper (Cu)	7440-50-8	0.00820	100.00000	0.10965
		subTotal		*0.00820*	*100.00000*	*0.10965*

Figure 53 - Substances of a Schottky diode or BAT54 (Nexperia, 2018)

To get a better understanding of the total amount of critical material in a sensor, similar products of which more information is available, have been analyzed. According to Veit & Bernardes (2015), a single mobile phone contains among others 24 mg of gold, 250 mg of silver and 9 mg of Palladium. In literature about WEEE schemes are given with the content of EEE products. In Table 7 the metal concentration of printed circuit boards is given in mass fraction (wt%), in Appendix A6 a detailed overview is given on the content of several EEE products in gram per unit.

Table 7 - Metal concentraction (wt%) of printed circuit boards reported in different studies (Veit & Bernardes, 2015)

wt%	Sum [52]	Guo et al. [53]	Yang et al. [54]	Park and Fray [55]	Yamane et al. [56]	Tuncuk et al. [57]
Gold	0.1	0.008	–	0.025	0.00	0.035
Silver	0.2	0.33	–	0.100	0.21	0.138
Copper	20	26.8	25.06	16.0	34.49	13
Nickel	2	0.47	0.0024	1	2.63	0.1
Tin	4	1.0	–	3.0	3.39	0.5

The exact amount per material in a sensor seem to be extremely difficult to trace. The analyzed sensor consists of approximately 84 components of which 16 different types. Except for the case, all components contain precious materials of which many are critical.

6.5 Sensors in BIM

Most EEE components belong to the group of mechanical, electrical and plumbing (MEP) components. In general, MEP components require fewer graphics and a considerable amount of information (Weygant, 2011). A sensor belongs to the category MEP components. From open access platforms such as http://www.bimobject.com and http://www.nationalbimlibrary.com, different types of building components and products are available to download. This has been done for a few sensors, to analyse the given information. Information in the downloaded BIM objects are organized in the following property sets:

- Phasing (Created; Demolished)
- Construction (Sensor Option, Coverage Area)
- Material and Finishes (Device Materials; Product Material; Material main; Material secondary)
- Electrical Engineering (Apparent Load; Power Factor; Connector Description; Load Classification; Number of Poles; Voltage)
- Identity Data (EAN code; Installation instruction, Assembly description; Product guide; Product certification; Product data Url; Comments; Technical description; Provide Feedback; Model; Manufacturer; OmniClass Number; OmniClass Type)
- General (Brand url; Data of publishing; Design country; Edition number; Manufacturer country; Manufacturer name; Nominal height; Nominal Width; Product family; Product group; QR code)
- Model properties (Weight; Time Delay; Storage Temperature; Sensitivity; Operating Temperature; Humidity; Coverage)

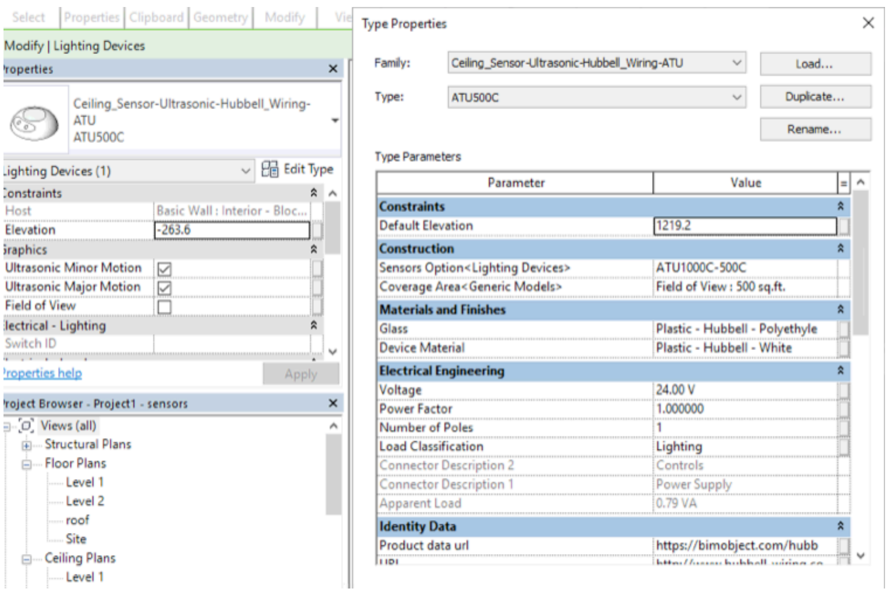


Figure 54 - Sensor information in Revit, downloaded from BIM object (source: Revit)

In all the available BIM object of a sensor, no information about the components nor materials was available, except for mentioning the plastic cover (Polyethyle) (Figure 54).

Within ArchiCAD an morph (solid shape) is created which will become the sensor of this case study. By giving the object an existing classification (Figure 55), it already contains standard data in IFC datasets, connected to the function of the object. In this case the object becomes an 'IfcDistributionControlElement' and an 'IfcSensor' (Figure 56 and 57).

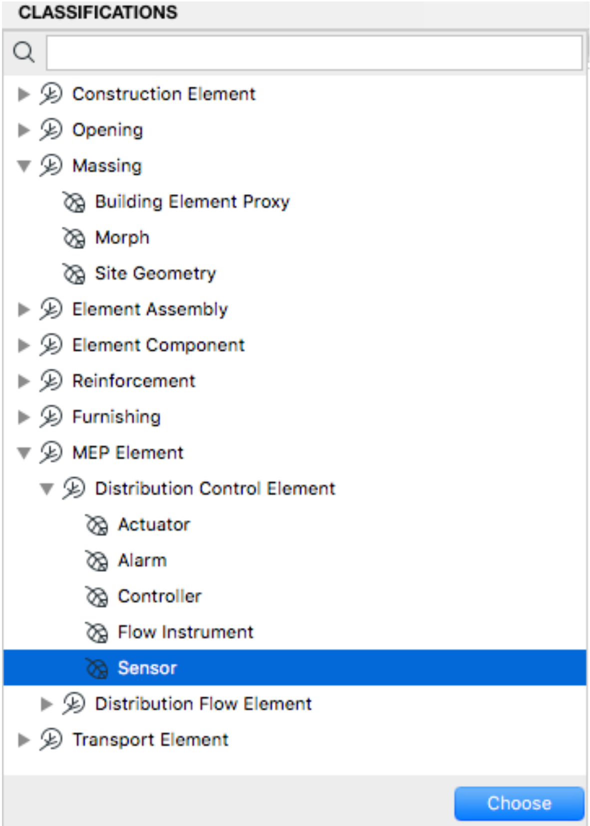
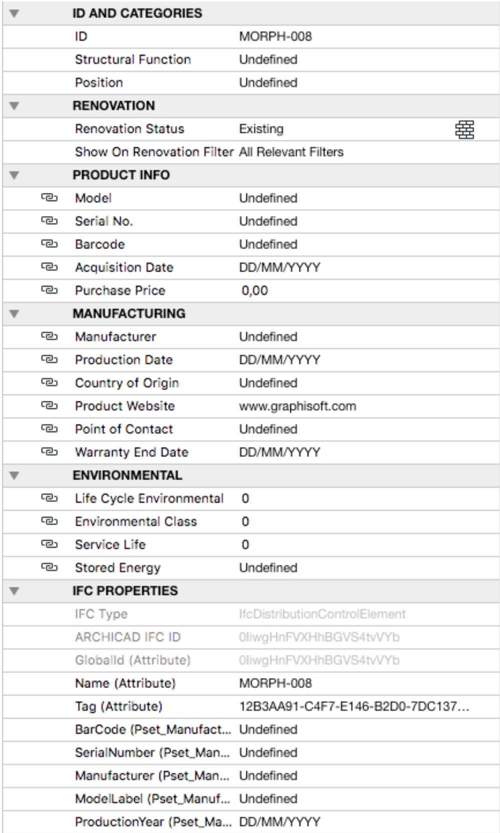


Figure 55 - ArchiCAD standard classifications (source: ArchiCAD)



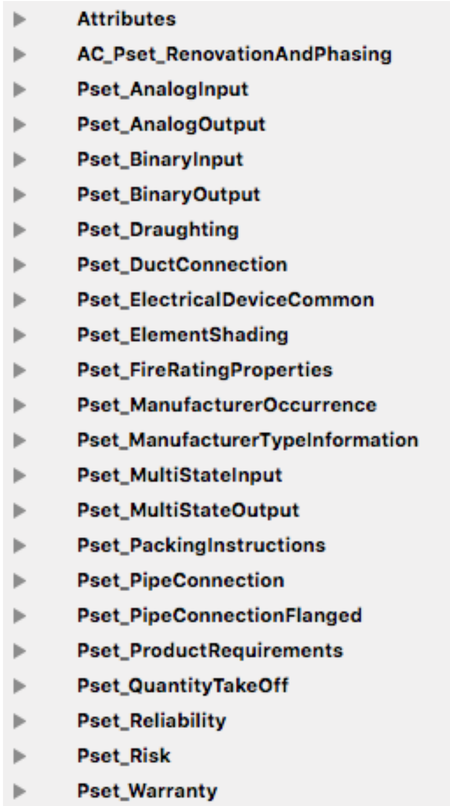
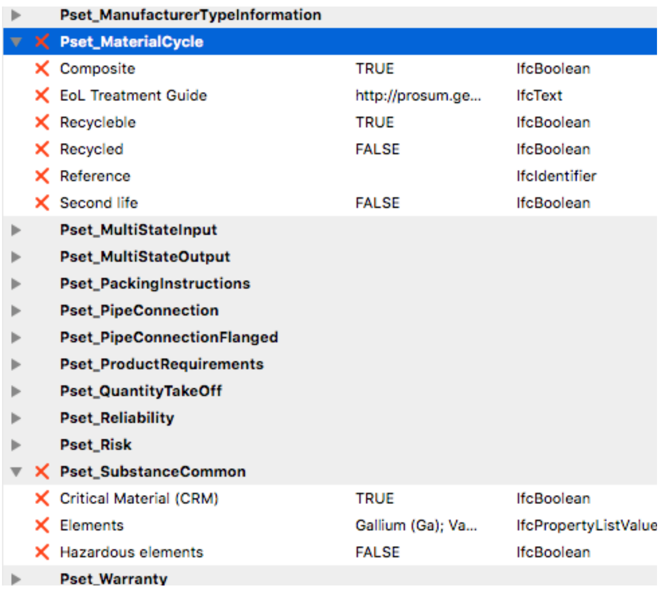


Figure 56 - ArchiCAD standard properties to be specified (source: ArchiCAD)
Figure 57 - Linked Property Sets to IfcSensor (source: ArchiCAD)

In the Project Browser the Property Sets linked to an 'IfcSensor' appear. New Property Sets are created to process the discussed data (Figure 58) wherein all elements can be easily added via 'IfcLists' (Figure 59). Next, all materials can be found within the model by the 'Find & Select' tool.



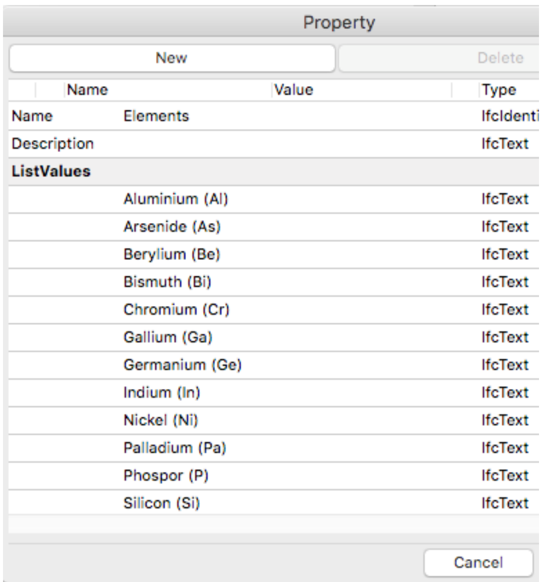


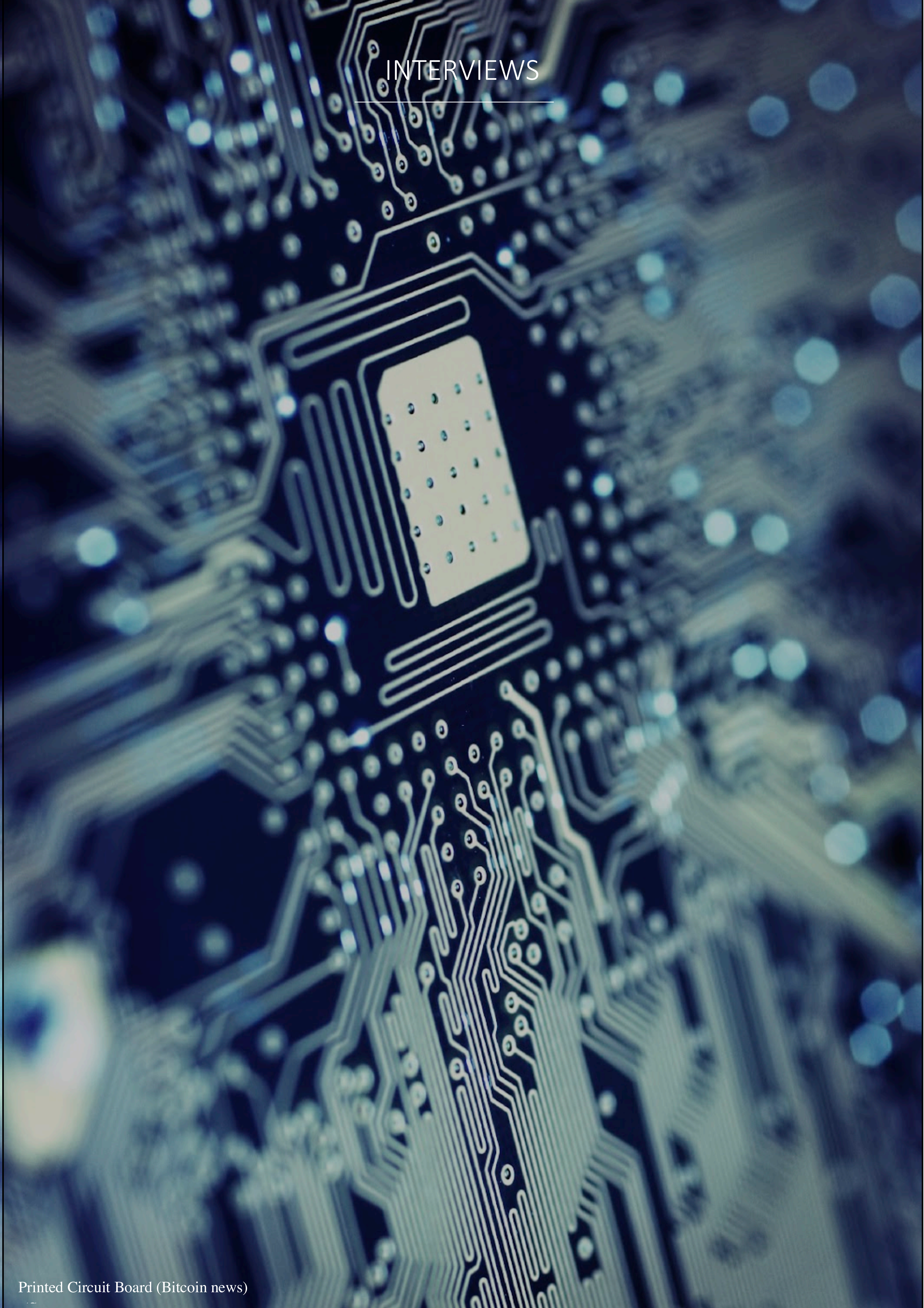
Figure 58 – New Property Sets (source: ArchiCAD)
Figure 59 - Process elements in an IfcList (source: ArchiCAD)

6.6 Chapter conclusion and discussion

The focus of this chapter was to determine the needed data for the case object, to convert this data into standardized datasets and to export it into BIM. Finding the exact composition of a simple sensor seem to be extremely difficult. The aim of looking for this information was to get a better understanding of the amount of subassemblies, sub-manufacturers and the critical materials within the object. This process indicated the difficulty of receiving this information. For the large amount of sub-assemblies some product information was available, but mostly about the use, limits and certifications of not using hazardous materials (RoHS compliant). Several product specifications of sensors have been analyzed, neither components nor materials were ever available. Contact with companies led to a better idea about the composition of sub-components of a sensor. A detailed product specification of one sub-component shows the large amount of substances of a sub-component of only 7,5 mg. This overview gives a good idea about the complex content of a sensor, taking into account that the information in this overview consists of only 1 of the 84 sub-components.

Standard IFC data sets give the possibility for a lot of building objects to process corresponding data. An 'IfcSensor' can be chosen from the list of 'IfcDistributionControlElement'. The pre-set data of the 'IfcSensor' corresponds with product specifications of a sensor.

INTERVIEWS



Printed Circuit Board (Bitcoin news)

7. INTERVIEWS

7.1 Interview I: Industry

The first interview has been developed for the industry and is linked to the case study to question the sensor producers. The goal of these interviews was to get response from industry on critical materials and to gain insight into their knowledge of critical materials within their own product and the documentation of the sensor and its materials. Hereby the main questions are: which resources do they use, where does it go to after demolition and how do they document all this information.
Before composing the interview questions, questionnaires and their outcomes have been analyzed on a similar topic. The analyzed examples were a Master Thesis Research of Industrial Design from Moerland-Masic (2012) and a PhD research from Peck (2016). The outcomes of this analysis is describes in Appendix A1. The reviewed interviews have the same objective; namely to show the awareness and knowledge of the industry on critical materials. This way the outcomes could be compared with each other to find conceivable changes of the industry herein.
The interview questions are in depth and structured. A pilot interview has been conducted with a start-up company to test the relevancy of the questions and to get an insight on the knowledge within this industry. Pilot studies for an interview are important to test out the chosen research method. Thereby it is useful to investigate if the answers are useful for answering the research questions (Peck, 2016). The outcomes of this pilot interview is described in attachment A3.
After this pilot and re-consideration changes have been made to the questions. The questions about BIM have been removed, to not give possible answers within the question and push them immediately towards this method of documentation.

Removed questions after re-consideration:

BIM

5.1 Is your company already involved with BIM? If not, why not?
5.2 If yes, does a library of the sensor already exist? Is there information about the materials presented in the BIM model? Are IFC formats included?
5.3 Is your company willing to share all information needed to optimize the quality and life expectancy of the sensor?
5.4 If not, why not?
5.5 If yes, what possibilities do you see to share this information?
5.6 Do you have recommendation to facilitate information in the future? What are the requirements to realize this?

On the next page the full interview for sensor producers is presented.

Interview questions industry

Knowledge Critical Materials

1.1 Can you name all of the critical materials contained in the sensor?
1.2 Which elements from the table are used within the sensor? (checklist)
1.3 In which parts of the sensor are the aforementioned critical materials used?

Supply

2.1 Do you know which companies supply the critical materials?
2.2 Do you know the origin of the critical materials? (where do the materials come from)

Life cycle analysis

3.1 What is the life expectancy of the sensor?
- 3.1.1 What does the life expectancy depend on?

3.2 Is specific maintenance of the sensor required?
- 3.2.1 If yes, what and who takes care of this?

3.3 Is the sensor demountable; if the sensor needs to be repaired or updated, can parts be taken out and replaced easily?
- 3.3.1 Who takes care of the this?

3.4 What happens to the sensors components and materials after demolition of the sensor?

Documentation

4.1 Is information about (parts of) the sensor regarding the following phases presented to the associated stakeholders?
- 4.1.1 Installation
- 4.1.2 Maintenance
- 4.1.3 Repair
- 4.1.4 Demolition
- 4.1.5 Collection
- 4.1.6 Reuse or Recycling

4.2 How is the information about the sensor and its elements presented? (e.g. brochure, website, BIM model)
4.3 What information is presented to the stakeholders about the critical materials?
4.4 What can be done better in the documentation and facilitation of knowledge towards the stakeholder?
4.5 Is your company willing to share all information needed to optimize the quality and life expectancy of the sensor?
- 4.5.1 If not, why?
- 4.5.2 If yes, what possibilities do you see to share this information?

4.6 Do you have recommendations to facilitate information in the future?

None of the invited companies seemed willing to collaborate, with the exception of the pilot interview. A possible cause for this unwillingness to participate is that there no interest and possibly no knowledge about critical materials in this industry. Most companies did not respond at all. Some companies mentioned they did not see the relevance of this topic for their company. In compliance with professors David Peck and Boris Bähre (TU Delft) an estimated guess is that there is not much interest and possibly no knowledge about critical materials, leading to no participation in this research.

7.2 Interview II: Experts

The second interview was conducted after re-consideration since the industry seem not to be willing to collaborate on this research. Experts concerning critical materials and circularity with different backgrounds were interviewed to get their perspective on critical materials in the built environment and their documentation.

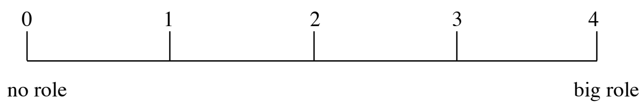
The invited experts for this interview are all working on different aspects of a circular economy, critical materials or both. Two of the asked respondents were able to participate to this interview. Both interviews have been conducted over a phone call.

This part has been done in the end phase of the research and serves mainly as a validation of this research. The interviewees and outcomes of this interview are mentioned in the previous chapters, sourced as Van Beek (2018) and Goddin (2018). The complete interview including lay-out and transcripts can be found in Attachments A4 and A5.

Interview questions experts

Critical Materials in the built environment

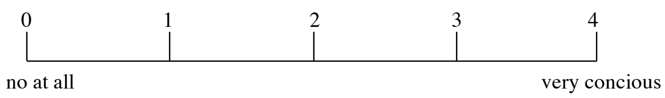
1. Tick on the scale, shown below, to what extent you think critical materials play a role in the built environment, concerning energy efficient buildings?



Explanation:

2. Do you think this will change in the next 3-5 years? (Yes/No)
Explanation:

3. Tick on the scale, shown below, to what extent you think the built environment consciously approaches critical materials.



Explanation:

4. Do you think this will change in the next 3-5 years? (Yes/No)
   Explanation:

5. Which measurements can we take concerning critical materials in the built environment? (more answers possible)
   - Decrease the use of building components which contain critical materials
   - Raise awareness within the built environment
   - Other, namely …

   Explanation:

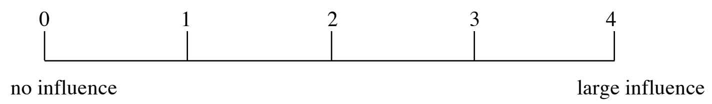
6. How do you think more awareness can be raised in the built environment according to critical materials?

Circularity of critical materials

7. Which measurements producers of building elements containing critical materials could take to increase circularity and optimize use of the materials?

Documentation of critical materials

8. Tick on the scale, shown below, to what extent you think the documentation of critical materials can affect their circularity?



   Explanation:

9. Which information do you think is needed to increase circularity of critical materials?

10. Which information concerning critical materials and the building components containing them, do you consider relevant during the whole lifetime of a building to communicate to concerning stakeholders to optimize use of the critical materials?

Do you have additional comments, relevant for my research but not discussed?

Light Emitting Diodes (Umicore)

8. CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

CONCLUSION

SUB-RESEARCH QUESTIONS

1) *What is the level of knowledge about critical materials in the building industry?*

[Chapter 3] While critical materials are becoming increasingly important in the built environment and its energy transition highly depends on them, the knowledge and awareness of these materials seem to be very low. Buildings are identified as heavy consumers of critical materials. In literature, sustainable systems are mentioned to be of significant importance for the energy transition of the built environment. However, a conflicting conclusion is that people who take decisions about the placement of those systems might not be aware about their value. Active building components such as a sensor, are broadly implemented into buildings at the moment. Most of the sensor companies invited for an interview did not reply or did not see the relevance. A tentative guess can be made that their slowness in response is because they did not understand what I was asking or that they were unwilling to acknowledge their lack in knowledge. The results from this research show significant gaps in awareness and understanding around the topics critical materials and the built environment.

2) *What strategies are available to mitigate critical material problems?*
    - *What are critical materials in the European Union?*

[Chapter 3 and 4] In this research the definition of critical materials of the European Commission is considered. The main parameters used to determine the criticality of materials are their economic importance and risk of supply. The supply risk of these materials is concerning while they seem to be indispensable to achieve sustainable development goals. In 2011, 2011 and 2017 the European Commission released a report on critical materials with a list of critical materials according to their parameters. The latest list from 2017, consists of 27 elements and compounds wherefrom three groups (HREE's, LREE's and PGM's).
The EU aspires to reduce the import dependency of critical materials and recently came up with research and programs on this topic. This is leading to more initiatives and strategies to mitigate critical material problems in the EU. Mapping resources, research on new possibilities and defining policies have a positive impact on the circular economy.
In the built environment, critical materials can be mainly found in EEE building components. Circular use of these materials is of significant importance. Recycling of the materials is challenging since dismantling of these products is labour intensive and not all materials are recyclable. Extending the lifetime of critical materials by easing repair, remanufacturing and reuse appears to be the best options for components containing critical materials. This requires technical changes of the design. Standardization of general components with dry connections seems to be the key. Besides technical changes, also changes in policies, business models and social aspects become evident in a circular economy. Leasing of products containing CRMs can be interesting for companies since they stay owner of the product and thus the critical materials. This gives to manufacturers more responsibilities, which could lead to higher quality products.

The choice of materials is depending on varied sets of required properties. Extensive research on materials should be done at the beginning of a design to optimize the object and to mitigate the risk of disruption of supply of the materials. Programs and online platforms such as 'CES Edupack', the 'Urban Mine Platform' or the Dutch 'Grondstoffenscanner' can support this research. The criticality of materials changes continuously. As a result, pure focus on the EU list is not appropriate for business specific decisions. The criticality of used materials might change in the lifetime of buildings.

3) *What data of critical materials should be disclosed per phase of the life cycle?*

[Chapter 3,4 and 5] The relevant data about critical materials does not differ much from general material datasets for optimized material use. The building components need to be designed for circularity, which starts in the design phase wherein the choice of materials is made. Stakeholders should be aware of the value and criticality of materials. Maintenance, reparability and updatability are of high importance to optimize the lifetime. Changes will be made during a buildings' lifetime which requires certain information. If objects containing CRMs are discarded because they are broken or not used, they need to be brought to a collection point or returned to the manufacturer. This makes information about the manufacturer and the business model type important to mention. Demolition is the most important phase concerning data about critical materials. All objects must be documented accurately to make reuse of objects or components and recycling of materials possible. To connect the BIM model to material stocks and flows of other economic models, exact information about the bill of materials, including the amount of material per product and the location is required.

4) *What role can BIM play to facilitate knowledge and solutions for critical materials?*
    - *What is the role of material parameters in Building Information Modelling processes?*

[Chapter 5] Material parameters play an important role in the current BIM environment, since they specify objects. The current role of the standard material parameters in BIM is not meant for substances as critical materials. However, there are possibilities to change names, settings and descriptions to include more in depth information.

To provide usable information and make the information wider applicable, standardized datasets are required which can be imported and exported via different BIM environments. IFC datasets could be a possible solution. Within 'Property Sets', harmonized data sets can be created wherein a wide range of data can be processed. Within one 'Property Set', lists of all elements can be processed as an 'IfcList'. Herein all elements are separately traceable. Search terms must be defined; there are multiple possibilities. If the data is inserted correctly, a component containing Gallium can be found by searching for the keywords; critical materials, Gallium or Ga.

In a BIM model, components such as sensors, are integrated into one object which is the building component. Sub-components and materials are integrated into one object and are not separately accessible and visible. This makes it challenging to trace the exact location of the material within the component. A solution can be to use an 'IfcTable' to connect critical materials to a certain sub-component or to insert a hyperlink as an external dataset.

Main research question

Is BIM as an approach compatible to facilitate knowledge and solutions for critical materials in the built environment?

The EU aspires to reduce the import dependency of critical materials. Data about the stocks and flows of critical materials is therefore considered as highly important to the European Commission. New possibilities need to be developed to link information to datasets of dynamic economic models. Improved application is required in a circular context. The minuscule amounts of critical materials makes them difficult to trace. To optimize the lifetime of critical materials and realize their circular use, a lot of detailed information is required. Information that should be shared amongst many stakeholders during the whole lifetime of a building.
BIM is increasingly used in the architecture, engineering and construction sector and already mandatory in some countries for public projects. BIM is capable of holding and processing much information amongst many stakeholders. This makes BIM a very qualified platform to facilitate knowledge of and solutions about critical materials. When using IFC files, information can be processed into standardized datasets and exported to many different applications. The nature of BIM being a database, facilitates the connection to other databases.
Information can be grouped in Ifc 'Property Sets' and linked to certain phases if required. By standardizing data among critical materials and circular use, this information could eventually be linked to other databases such as the 'Urban Mine Platform'. All the objects of a building can be stored within a BIM model. This includes construction, envelope and systems. The wide range of applications and materials make BIM a compatible approach to facilitate knowledge and solutions for critical materials in the built environment.

The framework in Figure 60 is created on the basis of this research, to support material selection, application and finally, BIM-based documentation.

BIM BASED DOCUMENTATION OF CRITICAL MATERIALS IN THE BUILT ENVIRONMENT

This framework is part of a Thesis research of the Master track Building Technology at Delft University of Technology.

Goals of this framework:

- Facilitate knowledge and solutions of critical materials in the built environment.
- Optimize material selection processes and application of materials for building products.
- Provide a standardized dataset which can be linked to large scale stocks and flow projects.
- Inform stakholders during the whole life time of a building about critical materials.

CRITICAL MATERIALS
List European Commission 2017

Antimony	Hafnium	Phosphorus
Baryte	Helium	Scandium
Beryllium	HREE and	Silicon metal
Bismuth	LREEs (16)	Tantalum
Borate	Indium	Tungsten
Cobalt	Magnesium	Vanadium
Coking coals	Natural graphite	
Fluorspar	Natural rubber	
Gallium	Niobium	
Germanium	PGMs (6)	

Parameters:
- Economic importance (end-use applications and manufacturing industries)
- Supply risk (risk of disruption in EU supply based on concentraties primarly supply)

note:
- criticality might change during building lifetime; take more into account than only the EU list.

MATERIAL SELECTION

Function, shape, process and material can not be seen separate.

select materials based on (functional) properties

CES EDUPACK [GRANTA DESIGN]

→ check risk of supply → critical element?

check on possible substitutes

→ check environmental impact [Eco-Audit tool]

→ check recyclability/end-of-life possibilities

OPTIMIZE LIFETIME MATERIALS

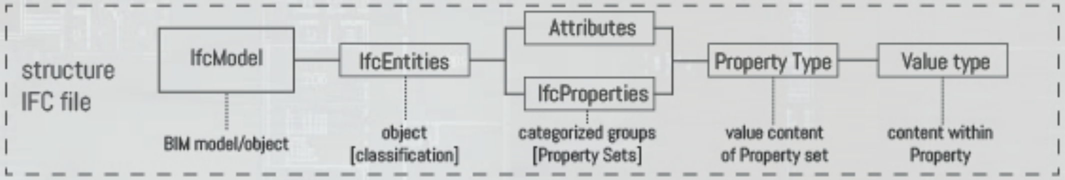
design for longer lifetime
physical, functional, technical, economic, legal and desirable

technical;
durable/high quality materials, modularity: updateble, repairable and remanufacturable
re-usable components;
standardized components, dry connections
recyclable materials;
combination of materials

social and economical change;
business model, responsibilities, maintenance, raise awareness

BIM-BASED DOCUMENTATION

This overview presents a standardized data set in Industry Foundation Class (IFC), which is available for all BIM applications. The acquired data and linked Property Sets aim to optimize the lifetime of materials and facilitate knowledge of critical materials.



	content	Property Set	Value + Type
general information	name	Attributes	IfcLabel; Single Value
	description	Attributes	IfcText; Single Value
	type	Attributes	IfcText; Single Value
	article number	Attributes	IfcLabel; Single Value
	installation date	Pset_Manufacturer	IfcLabel; Reference Value
	product description	Pset_Manufacturer	IfcText; Single Value;
materials	Bill of Materials list, weight and origin	Pset_MaterialCycle	IfcText;Single Value; hyperlink
	list of all elements	Pset_SubstanceCommon	IfcText; List Value
	critical materials EU 2017	Pset_SubstanceCommon	IfcBoolean; Single Value
	CRM factor	Pset_SubstanceCommon	IfcBoolean; Single Value
	hazardous substances	Pset_SubstanceCommon	IfcBoolean; Single Value
	conflict materials	Pset_SubstanceCommon	IfcBoolean; Single Value
optimize lifetime	production year	Pset_Manufacturer	IfcLabel; Reference Value
	expected lifetime	Pset_Manufacturer	IfcLText; Single Value
	use guide	Pset_Operation	IfcText; Single Value; hyperlink
	maintenance guide	Pset_Operation	IfcText; Single Value; hyperlink
	installation guide	Pset_Operation	IfcText; Single Value; hyperlink
circularity	list of components	Pset_MaterialCycle	IfcText; List Value
	reusable components	Pset_MaterialCycle	IfcText; List Value
	reference reusability	Pset_MaterialCycle	IfcText; Single Value; hyperlink
	reused components	Pset_MaterialCycle	IfcText; List Value
	joining techniques	Pset_MaterialCycle	IfcText; Single Value; (hyperlink)
	guideliness EoL treatment	Pset_Manufacturer	IfcText; Single Value;
manufacture	manufacturer	Pset_Manufacturer	IfcLText; Single Value
	sub-manufacturers	Pset_Manufacturer	IfcLText; List Value
	ownership	Pset_BusinessModel	IfcText; SingleValue
	businessmodel	Pset_BusinessModel	IfcText; SingleValue; hyperlink

Discussion and reflection

This chapter will provide a discussion and reflection on the results of this research. It also reflects on the approach and choices that are made during the process.

Meaning of this research

The outcomes of this research identify a gap in existing scientific knowledge about critical materials in the built environment. This research is scientifically relevant in presenting the importance and outlining new opportunities in handling critical materials.

Climate change has to be minimized and the built environment needs to adapt to reduce the carbon footprint. However, required high-tech systems that are broadly implemented need to be approached differently to optimize the use of critical materials. This research elaborates on an example of a high-tech system that commonly used. The use of sensors is claimed to improve energy efficiency and contribute to the smartness of a building. However, findings from this thesis show significant gaps in the implementation and the use of data collected by sensors. The data acquired by these sensors is often not usable for further applications due to social aspects and policies. Before a decision to install sensors, a clear objective of the obtained data should be set. Other applications containing critical materials with another purpose than collecting data, have different sets of requirements. An example is the placement of solar panels. Herein the yield should be analysed carefully per position. The desired results should be considered per building component and location.

As expected, knowledge about critical materials is insufficient in the built environment. The term 'critical materials' seems to be an unknown field in general. More awareness could lead to better use of the materials. Alternatives for buying a new product should be examined, following the circular economy principles. Also the product, or it's materials, should be given a new and useful function after demolition. If a product is not used anymore, make sure the product or its materials obtain a useful function again.

The findings of this research suggest a possible approach to trace critical materials and link the data to economic models. BIM is increasingly used in the built environment and since buildings contain about 40% of our resources, this method could potentially have a large impact on data management of stocks and flows of resources and thus critical materials. This research provides an opportunity to share information among different groups of stakeholders and increase knowledge about CRMs.

As mentioned before, the challenge in using the tested approach is the availability of the required data. Complete transparency and collaboration over the whole supply chain is required to implement this method. A different social technical mind-set is required to process the needed changes in the collaboration and communication between people. Likely, it will be a difficult and long process to realize this. Policies and regulations of the EU could speed up the process. Blockchain could provide an interesting opportunity to provide detailed information without violating intellectual property.

This research focuses on the critical material list of the EU. However, the described opportunities to optimize material efficiency and to process material data into BIM are applicable for all other materials.

Relevance of topic

The Sustainable graduation studio of the MSc Building Technology aims to emphasize topics related on sustainability and innovation. The topics critical materials, circular economy and Building Information Modelling are appropriate regarding both innovation and sustainability.

The combination of topics is innovative in the master track Building Technology (BT) and, likewise, within the faculty of Architecture.

Building Information Modelling was in the beginning the main focus of this research. Building Information Modelling is becoming common practice the built environment. In some countries, BIM is already mandatory for public buildings. This digitalization results in an integrated design approach wherein data is easily shared among stakeholders. The type and usage of data varies and new possibilities are being discovered. Within the faculty, BIM is not completely new. Students from other master tracks have been working with BIM, but so far mainly as a management approach.

Circularity is also a popular topic within many supply chains and is becoming increasingly important within the built environment. Especially through the goal of the Dutch government to have a complete circular economy by 2050.

In the built environment this is especially an important shift for the building technologist, being the link between architecture and its technology, it also encourages innovation. This makes circularity in the master Building Technology a prominent theme; it mainly focusses on construction and façade technology. However, it is generally applied on a larger scale than critical materials.

Critical materials seem to be an unknown field in the built environment and thus also within the faculty and the master Building Technology. At the same time, the systems for which CRMs are indispensable are broadly engaged to realize sustainable buildings. This makes the topic certainly relevant in the current building technology. Smart systems, innovative products and renewable energy are broadly implemented to realize sustainable buildings to achieve climate change targets. CRMs are integrated in products or building systems, which are not the design task for the architect or building technologist. However, they do decide about the use of these systems and knowing about the criticality of the used materials for these systems might lead to better considerations.

Considering a broader context, this study is highly relevant. Reports of the European Commission show the importance of critical materials, their circular use and the need for information technology to realize optimized use of the materials.

Reflection and approach

The chosen approach is connected to the studio by means of a broad of empirical research, that has been done often during the Master Building Technology, by using software tools and finding solutions to optimize different aspects of the built environment. For this purpose, often case studies have been done to test results.

Literature is broadly available on each topic separately, however, not on topics combined. There is overlap between critical materials and circularity and between circularity and BIM. Circularity in the built environment is a popular topic, but is applied on a larger scale. However, prove of results is missing since more time is required to analyse outcomes.
The literature on critical materials that is used in this thesis is often commissioned by the European Commission. Those reports mostly describe goals. Research on critical materials seems to be in a starting phase and more solutions for optimized use of materials need to be developed to reach the EU goals.
Literature on BIM is available; it mostly contains very general information about the BIM process and management purposes. Descriptions about the implementation and use of data connected to the model are scarcely available in literature. BIM and circularity are described in literature as a prosperous combination while detailed information about how BIM can be used for this purpose, is missing.

Empirical research for this thesis was based on understanding the possibilities of different programs and finding solutions for sharing data. CES Edupack has been used before in the master Building Technology. Some modelling tools, which are used for BIM, have been used during the Bachelor Bouwkunde, such as Revit and ArchiCAD. However, it was used for the modelling of buildings, instead for the specific information sharing capabilities. Most information about data implementation and IFC's was acquired by tutorials.

The building product for the **case study** was chosen carefully. A focus was layed on building components or products that are active and contribute to energy efficiency of buildings. Internet of Things is therefore an upcoming ideal, wherefore sensors are indispensable to collect data and connect all the smart systems. Thereby a lot of different sensor producers were able to find on the internet and within the Netherlands to conduct interviews with.
This case study shows the difficulty around the topic critical materials. A small object seems to consist of a large number of components. Limited amount of information is available on the exact content. This showed the need for transparency of the supply chain to make this data available.
The choice of another object could have led to different results. For example LEDs, which are already broadly collected at the end of use and the pay-for-lux services by Philips.

Interviewing the industry on this topic, could have brought a contribution to this research It could have given a better insight in the level of knowledge of producers who work with critical materials. Additional, answers could have been compared between similar interviews from a few years ago. Unfortunately this did not work out; most companies did not reply, some mentioned that they did not see the relevance or they were not working with these materials. In this part of the research, the choice for a case study could have had influence. LED producers that are possibly better informed on the content of their product might have responded.
The second batch of interviews was very useful, although there was not enough time to conduct interviews with more experts. The outcomes of the interviewed experts formed a validation of this research and gave some extra information and examples.

Limitations

Due to limited available time, not all possibilities have been elaborated.
BIM can use many different software programmes with different capabilities and limitations. This should be tested more extensively. In this research only IFC is elaborated as a possible solution within BIM, however BIM competences more comparable possibilities.
The invitations for interviews have been sent by electronic email to sensor producers with an office in the Netherlands. Phoning up companies or reaching out to more companies outside the Netherlands could have led to more responses and other outcomes. No follow up has been conducted about the nature of the non-respondents.
Due to a limited timeframe, only one building object has been analysed as a case study. The chosen case study forms a good representation of a relevant object. Nevertheless, the choice for another object could have led to other results concerning the available data, application and collaboration between linked companies. Also has the application of the sensor been analysed in a single building. Although this building is known as the most sustainable office building in the world, analysing more buildings could have led to more positive outcomes of using a sensor to optimize (energy) efficiency of buildings.

SWOT Analysis

The strengths, weaknesses, opportunities and threats are summarized and described in Figure 61.

Strengths	Weakness
Combining two themes into a new opportunity with the help from experts on both sides; Innovative;	CRMs is a difficult topic, limited knowledge of products containing CRMs; Combining different topics leads to too much information by going too much into depth;
Opportunities	**Threats**
EU reports support this research; need for information technologies on CRMs; Elaborate new possibilities by combining existing technologies; Introducing a new topic in the built environment;	Limited data available about the content of relevant building products; Industry does not want to collaborate to interviews;

Figure 61 – SWOT analysis

This study is the first attempt of testing BIM to facilitate knowledge of and solutions for critical materials. This research inspired different parties to continue this research. More research should be done in this field to elaborate the described opportunities and find more.

Recommendations for further work

This study was set out to explore new possibilities in sharing data about critical materials. An innovative topic and limited available time lead to a lot of new questions and opportunities for follow-up research. The following topics remained open for future research:

Conflict minerals

On January 1st 2019 a new law will implemented across the EU; 'the Conflict Minerals Regulation'. It aims to reduce the trade in four minerals that are used to finance war and other conflicts. Namely Tungsten, Gold, Tin and Tantalum. This regulation means changes for everyone involved in the trade of these minerals regarding import, smelt and refining and owning a diligence scheme. Starting in 2021, EU importers of these materials have to carry out checks on their supply by following a five-step framework. For this approach, BIM could be used to facilitate knowledge of and solutions for conflict materials as well. This provides an interesting opportunity to test the applicability of BIM in practice.

Data connection

BIM seems to be a qualified approach and tool to facilitate knowledge of and solutions for critical materials. The next step is to connect this data to other systems such as 'Urban Mine Platform' or other economic models. The data could be connected to big data or blockchain technology for more detailed information about the stocks and flows of critical materials.
A BIM Implementation Plan for critical materials should be developed to facilitate knowledge on processing the data and sharing it following a BIM approach.

Standardization

To connect the data of critical materials to further systems, standardized datasets must be developed. These should be made available in BIM or IFC and directly usable in other systems by exporting the data as a text format. Therefore, collaboration between BuildingSMART or similar BIM data developers and other organizations such as ProSUM is required.

Funding

There is a high chance that this research will form the foundation for a follow-up research, likely in the form of a PhD position at Delft University of Technology or in another research group. Funds need to be collected to support this research. Interesting partners should be identified, and arrangements have to be made to get access to required data, which can be identified as 'Intellectual Property'. Recommended is to involve large data driven companies that have access to more in depth knowledge of the content of relevant applications. Parties that are currently using the 'Urban Mine Platform' by means of comparison between methods should be included. A (large/known) manufacturer of EEE products could bring new insights in the extent manufacturing challenges. Finally, organizations mentioned in chapter 4.3 can be viable partners.

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