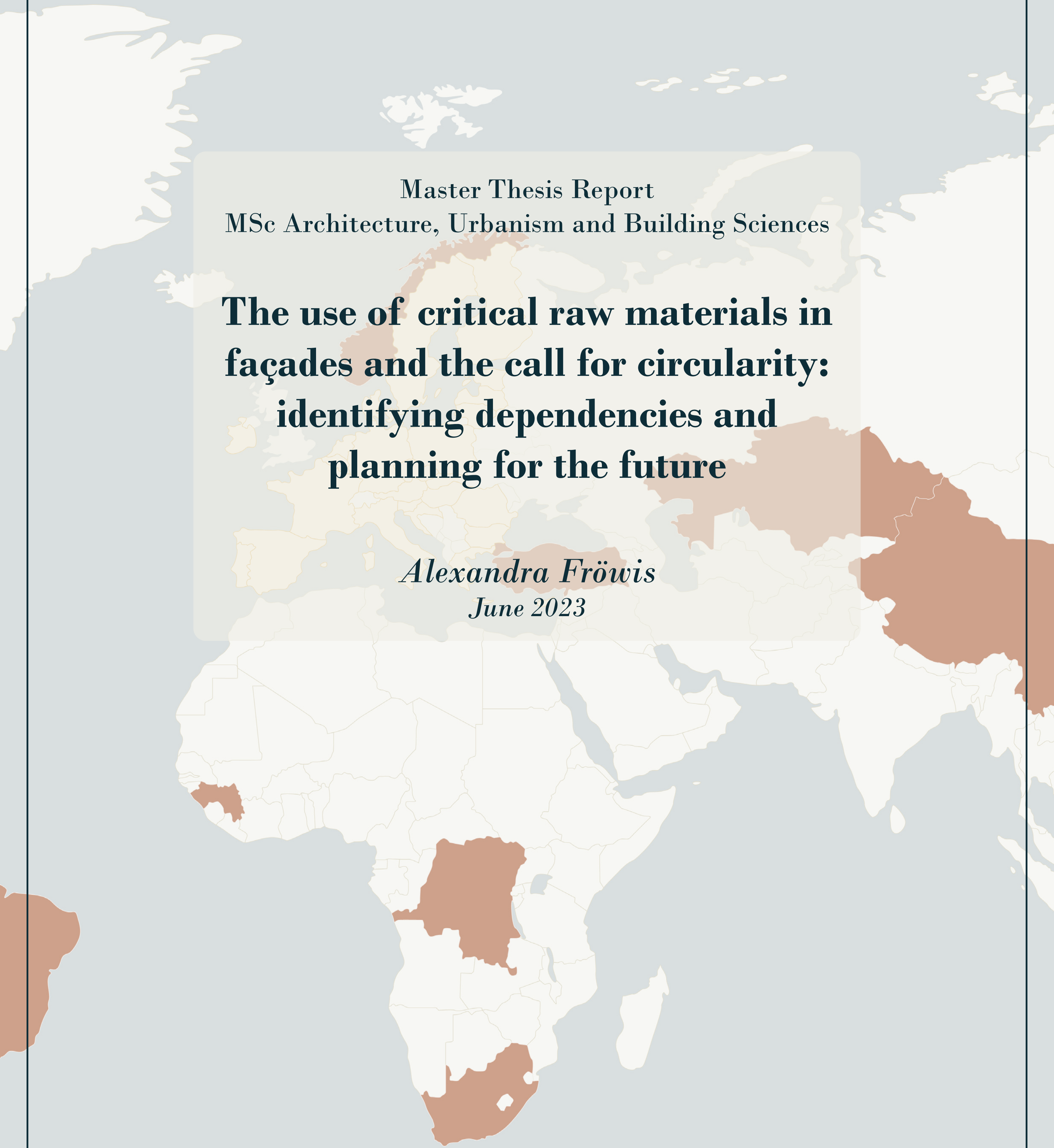

Master Thesis Report
MSc Architecture, Urbanism and Building Sciences

The use of critical raw materials in façades and the call for circularity: identifying dependencies and planning for the future

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Abstract

The climate crisis poses a significant threat to our planet, and the building sector plays a big role in that regard, as it is responsible for 30% of energy consumption and 27% of emissions globally [IEA, 2022]. The sector aims to reduce its impact on the environment through different strategies like transitioning to a circular economy or reducing energy consumption through the implementation of smart systems. However, these systems contain and rely on Critical Raw Materials (CRMs), which is a topic that is so far mostly discussed in regard to renewable energy technologies.

The research shows a gap in knowledge, information, and awareness when it comes to critical materials concerns regarding the built environment, which is demonstrated in the example of an aluminium curtain wall façade. The analysis indicates that façades can indeed contain a high level of critical materials both in regard to the amount as well as the variety of different critical materials. From the research, it is concluded that (1) the use of critical raw materials needs to be reduced wherever possible and (2) if a reduction is not possible, materials need to be kept in the loop as long as possible.

Circular strategies are therefore analysed as prospective mitigation strategies of critical materials concerns. The material policy research indicates that even though the combination of critical materials and circularity in regard to the built environment is not adequately addressed as of yet, effective policymaking could be a helpful tool in regard to the transition towards a more circular built environment and help prevent future bottlenecks in the industry. As a result, the formulated recommendations indicate how policies can address the mitigation of critical materials concerns through circular strategies.

Acknowledgements

With this thesis, my time at the TU Delft comes to an end already and I gladly take this opportunity to share a few words of gratitude.

First and foremost, I would like to thank the TU Delft, for not only meeting but exceeding my expectations regarding the last two years, which were filled with endless inspiration, joy, and a sense of meaning and belonging from the very first day on. Thank you especially to all the people from the Architectural Engineering Technology department and connected to the Building Technology track, for sparking hope and sharing passion to work towards a sustainable built environment in this time of crisis.

On a more personal level, my deepest appreciation goes out to my mentors, who both spent a lot of time with me discussing my topic, for sharing their expertise and enthusiasm with me.

Olga, my first mentor, was part of my academic journey in Delft since the very beginning and already played an important role in my first year to help me develop my focus on circularity in the built environment and eventually find a topic for this research that matched my interests and fascination. Thank you for asking difficult questions and for the level of detail in your feedback, I learned a lot from you through your way of teaching over the last two years.

Dave - who regularly left me both more inspired as well as more confused about the topic after our meetings - managed to spark my interest and sense of responsibility for a field previously unknown to me. Thank you for warning me about getting into this topic (you were right), and steering me in the right direction while providing me with the necessary background information.

To my friends here; thank you for opening up the world for me by bringing it closer together. For making these two years memorable; for struggling together and celebrating together. For sharing your stories and experiences with me, redefining geographical or cultural distances. I will treasure my time here with you and look forward to seeing how all our lives evolve from here on out.

Most importantly, my deepest gratitude goes out to my family and friends back home. Thank you for accepting my (dis-)appearing from/in your life from time to time, and for keeping me sane during the last eight months by keeping and putting things in perspective during stressful phases. To my parents for providing me with this opportunity, for supporting me and for believing in me throughout all of my decisions.

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Acronyms

BE Built Environment . . . 1
BIM Building Information Modelling . . . 82
BPP Building Product Passport . . . 81
CBE Hub Circular Built Environment Hub . . . 28
CBM Circular Business Model . . . 86
CE Circular Economy . . . 1
CRMA Critical Raw Materials Act . . . x
CRMs Critical Raw Materials . . . v
DfD Design for disassembly . . . ix
DPP Digital Product Passports . . . 34
EC European Commission . . . 5
EOL end-of-life . . . 2
EU European Union . . . ix
EU European Union . . . ix
EuP Energy-Using Products . . . 69
GHG Greenhouse Gas . . . 1
HHI Herfindahl-Hirschman Index . . . 13
IEA International Energy Agency . . . 63
IGU insulated glass unit . . . 6
LtG Limits to Growth . . . 17
NZIA Net-Zero Industry Act . . . x
PcB printed circuit board . . . 58
PVs photovoltaics . . . 71
RIR Recycling Input rate . . . 14
SDGs Sustainable Development Goals . . . 1
SRM Strategic Raw Material . . . 40
UN United Nations . . . 1

Introduction

Background

OUR PLANET AT RISK Our planet is in a crisis, and with that, all of us are facing the challenge of our lifetime. Melting glaciers, floods or forest fires due to extreme temperatures have become daily headlines in news reports. The world as we know it is changing rapidly for the worst and if we want to alleviate that progression we have to be quick and efficient. That is what the Sustainable Development Goals (SDGs) are about: The United Nations (UN) developed a road map on how to create a more sustainable, resilient and just world. This was done by defining 17 goals, covering different fields from ending poverty and hunger, over sustainable cities to climate action and institutions. But we are almost halfway through the 15-year plan[a] already and the latest SDGs report shows that the goals are struggling, especially in the areas directly influenced by Covid [UN, 2022]. But also Greenhouse Gas (GHG) emissions will keep increasing under current commitments to climate action. According to the SDGs report, global GHG have to decline by 43% by 2030 before going down to net zero by the year 2050, but with the current voluntary national commitments, we will instead see an increase of emissions by 14% by 2030. [UN, 2022]

The building sector is responsible for 30% of total global energy consumption and 27% of emissions.
[IEA, 2022]

THE IMPACT OF THE BUILT ENVIRONMENT A look at the overall annual global CO_2 emissions and the role the building sector plays in it shows the importance to also make changes in this sector: the sectors of buildings and building construction combined are responsible for 30% of total global final energy consumption and 27% of total energy emissions [IEA, 2022]. One aim of the Circular Economy (CE) is to help reduce these numbers by keeping materials in the loop; to reduce material waste by prolonging the lifetime of products or materials and by that also reduce the demand for new raw material.

SMART BUILDINGS Another approach to tackle the issue of energy consumption within the Built Environment (BE) is to build smart buildings, meaning that buildings are real-time monitored by complex systems and sensors in order to optimize the operational energy consumption while also improving the comfort of occupants [Sembroiz et al., 2019]. However, what most people (including architects) are not aware of is that these systems include - and are highly reliant on - materials that are classified as 'critical'.

[a] the SDGs were established in 2015 to be reached by the year 2030

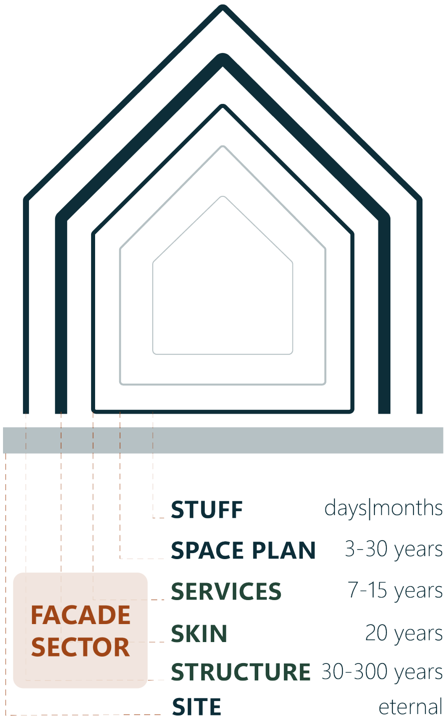


Figure 1: Shearing layers of change with a focus on the facade sector, adapted from Brand [1994]

CRITICAL RAW MATERIALS Because of the complexity of the topic, there are different definitions when it comes to CRMs but in short CRMs are described as materials which present supply insecurities while also being of high economic importance. CRMs are especially important when it comes to renewables and e-mobility, as those products mostly rely on a large number of critical raw materials. This also shows that - when we talk about becoming more sustainable or even energy neutral - we need to talk about critical raw materials. One more issue that makes this topic so challenging is that people are rarely aware of their existence, even though they are present in basically every field of our daily life.

LIFESPANS WITHIN BUILDINGS A building and its components can be divided into separate layers, as done by Steward Brand [1994] with his concept of the shearing layers of change. Brand describes how the different layers come with different rates of change - meaning that building products within the different layers have different lifespans and therefore will reach their end-of-life (EOL) at different times. Figure 1 shows how some components can change relatively quickly (like stuff which is replaced daily or monthly, or space plans and services which can adapt over few years) while other layers have very long lifespans (like structures that can stand for hundreds of years, or the site itself).

THE FACADE AND CRITICAL RAW MATERIALS The façade, together with the roof, forms the separating and protecting layer between the inside and outside of a building. It contains elements of different layers - namely from *services, skin,* and *structure* - which means that it brings parts together, that can differ greatly in their individual lifespans. Its overall function for the building is to separate the inside from the outside and it therefore plays an important role e.g. in terms of weather protection, climate or safety. There are many different types of façades, which are made up of many different parts, including structural components, windows, and cladding, but also very small elements like sensors and motors, which contain CRMs. However, the use of CRMs within the façade industry or even the BE is rarely addressed by research so far even though it has been stated that - especially in terms of the clean energy transition - we risk replacing our dependency on oil with a dependency on critical raw materials [EC, 2020].

MATERIAL POLICIES As this topic is rather complicated, it is questionable, whether industry can solve related problems and challenges by itself. The implementation of sector- and product-specific policies is therefore considered an important step.

OUTLOOK To adequately address this issue within the BE, we need to know where the critical elements are located and what functions they serve. Once some knowledge there has been established, it can be compared to the current state of affairs of policies and regulations for critical materials and regarding circularity. Following this background, this thesis aims to point out gaps in knowledge and within existing policies in an EU context and subsequently develop recommendations of how these can be addressed in the future to address critical material concerns.

Problem Statement

As a result of the previous background on the topic, the following key problem statements have been defined:

| The BUILDING SECTOR is responsible for a big share of global emissions and energy consumption.

| The CLEAN ENERGY TRANSITION is highly reliant on CRITICAL RAW MATERIALS as they are key components for renewable energy production technologies [EC, 2020] as well as SMART SYSTEMS (sensors, motors etc.) in buildings.

| FAÇADES also contain materials that are rated as CRITICAL but the exact amount and placement of these materials is HAS NOT BEEN PROPERLY ASSESSED so far.

| Therefore, METHODS to address possible reduction, reuse, recycling, etc. of CRITICAL RAW MATERIALS in FAÇADES are NOT PROPERLY INVESTIGATED.

| Current POLICIES do not address the IMPLEMENTATION AND HANDLING of CRITICAL MATERIALS in buildings and especially in the FAÇADE SECTOR.

Objectives

Based on the problem statement, the intent of the thesis is to analyse the critical raw material content in façade elements; quantify the materials used within the different components and assess whether circular strategies can be implemented as mitigation strategies.
The main objective then is to develop recommendations to help policymakers with decision-making in critical raw materials concerns in façade products to prevent future material bottlenecks in companies.

Research Questions

As a result of the problem statement and the objectives of this research, the main research question is as follows:

> How can *policies* address the implementation of *circular strategies* regarding *critical raw material* concern in the *façade industry*?

To address the topics mentioned in the main question, several sub-questions were formed to cover the link between critical raw materials and circularity, the façade sector, façade systems and policies:

> | What role do *critical materials* play in the built environment?
>
> | How are *critical materials* related to the circular built environment?
>
> | What policies regarding critical raw materials and circularity in the built environment already exist?

Methodology

The methods included in the research are literature review and a case study analysis.

Method 1: Literature review

The first step of the project is to figure out how much information can be found and therefore how much of the research can be done through a literature review. This includes a review of the main topics of the research, namely *critical raw materials, circularity* and *facades*, both on their own as well as combined. Another literature review is conducted regarding material policies, in order to assess in what detail the fields of the thesis are addressed by those or whether there is a lack.
For the literature review, the search engines Scopus and Google Scholar were used with the respective terms. In addition, MOOCs on *critical raw materials, circularity* and *façade* were followed.

Method 2: Case study analysis

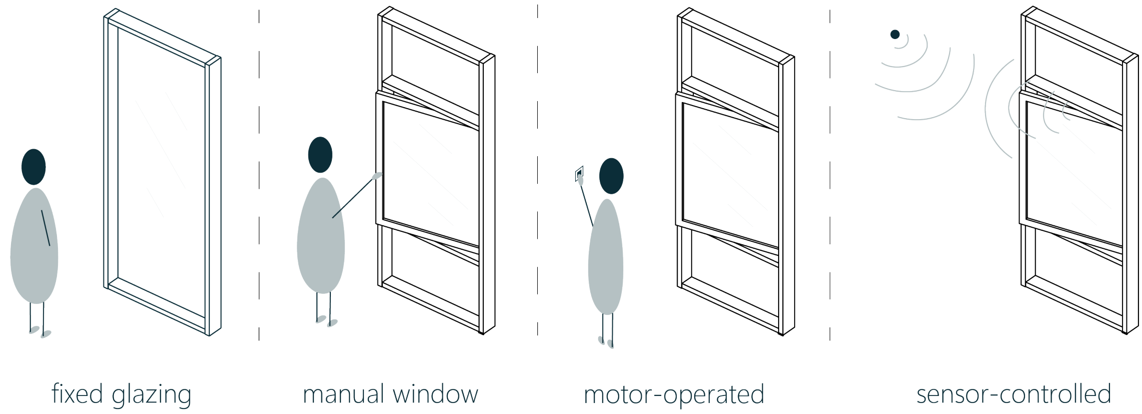


Figure 2: Different systems considered for analysis

ANALYSED SYSTEMS The analysis will compare different versions of a generic curtain wall system (see Figure 2). This means not one specific system is chosen, but rather a 'placeholder' system will be defined, which is meant to represent a typical system. To compare the critical material contents of different systems, the types of systems include; an element with fixed glazing compared to an element with an additional manually openable window as well as motorised and sensor-controlled systems (see Figure 2). As it is very difficult to gather information on CRMs content for motors and sensors, the analysis can only give assumptions of possibly included materials in that regard. In general, the mapping will be divided into three different fields of applications, namely (1) *alloys*, (2) *motors* and (3) *sensors*.

ANALYSIS STEPS The analysis consists of four steps, as Figure 3 shows. First, a specific system has to be defined in terms of components, materials and measurements. With enough information gathered, the different components can be grouped regarding their functionalities (alloys, motors, sensors) and then broken down into their material composition. This list of included materials or elements is then compared with the European Commission (EC) CRMs list of 2023 to define the criticality of the individual components and the overall system. As a final step, the findings are visualised as clearly as possible.

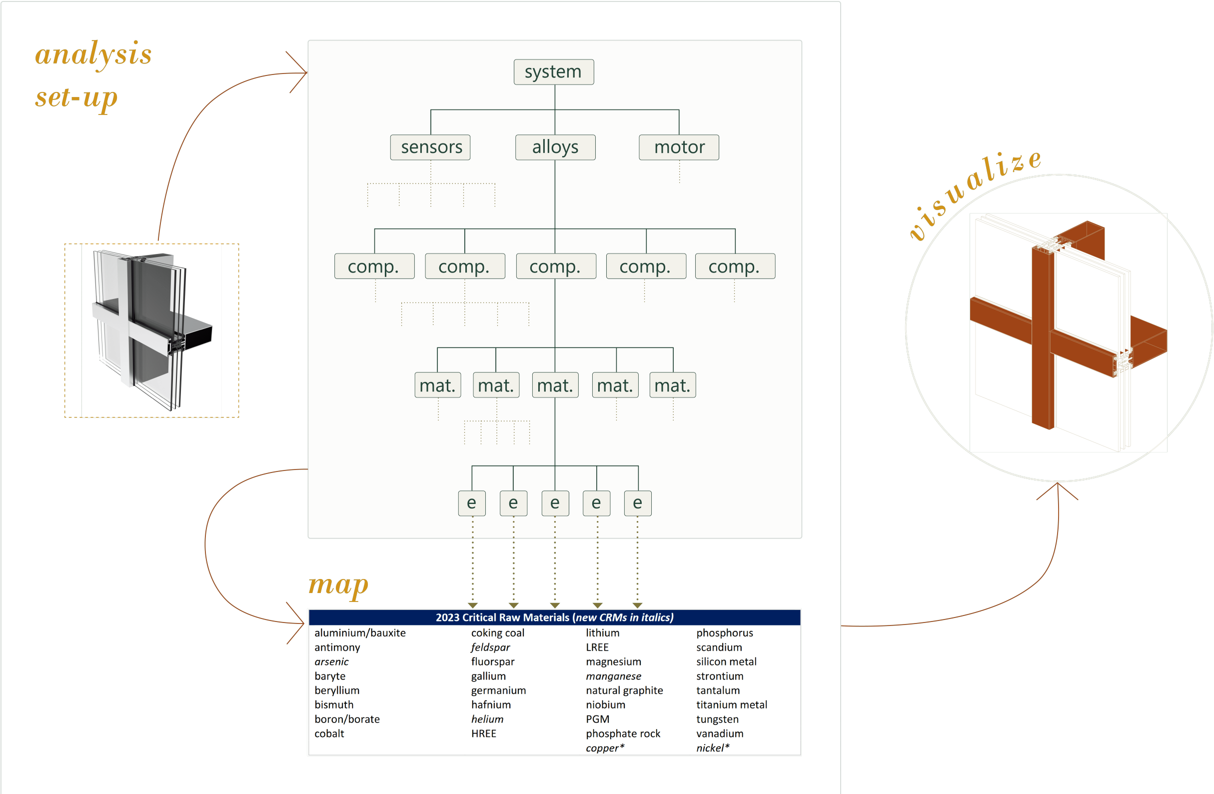


Figure 3: Analysis set-up (own image)

Properties of the analysed element

The measurements of the analysed element were defined as width=1200mm and height=3000mm (as central lines of the mullions and transoms), as Figures 3 and 4 in the appendix show. Figure 3 shows a curtain wall element with fixed glazing while Figure 4 has an additional openable window in the middle of the unit.

Limitations

The analysis only considered the key components of a glass mullion transom system. External connections (e.g. the connection from the mullion to the building floor), additional elements (e.g. shading systems), or varying facade panels (e.g. opaque elements, PV-panels) were therefore excluded. Some volume calculations were based on assumptions, like the number and weight of screws, the aluminium warm edge spacer tube in the insulated glass unit (IGU) (modelled in 3D as rough estimation) or the overall volume of the window hardware (modelled as one continuous edge around the window sash). The calculation tables are attached in the appendix.

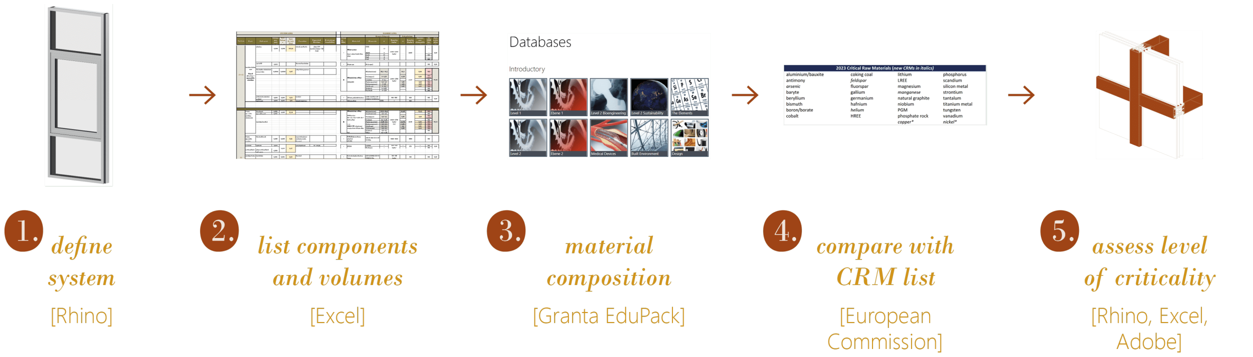


Figure 4: Tools used for analysis

Tools and data for the case study analysis

Different tools were used for the analysis, as Figure 4 shows. These were Rhinoceros 3D for modelling of the element, Excel for calculations, Granta Edupack for information on material compositions, as well as the EC CRMs list 2023 to compare with in order to assess the level of criticality of a component and the complete system.

RHINOCEROS 3D The defined system is a combination of different systems from different companies, as this was thought to give a more holistic result and also allowed to fill in missing information from one system with the information provided by others.

2D drawings from the Schüco FWS 50.SI curtain wall system (available on their website) were used to build up a 3D model in Rhinoceros 3D. When there was a need for more clarification, especially in regard to connections, additional systems were used for comparison by looking up information on the websites of Gutmann, Lindner, or Reynaers. This approach meant to ensure the applied connection was not just used in the Schüco system but could also be seen as typical in other systems.

The different components of a typical curtain wall system, as shown in Figure 5 in the appendix, are mullions and transoms, pressure plates, cover caps, (transom to mullion) connection pieces, gaskets, insulation, an IGU and fixings (screws). For the element with the openable window, it was decided to simplify the hardware components into one continuous edge around the window sash. This was due to the difficulties to find specific measurements for the separate components in combination with the again many different types of hardware systems used by different companies and manufacturers. The respective volumes of the different components could then be taken directly from Rhino and inserted into the Excel spreadsheet with the calculations in regard to material compositions.

EXCEL An Excel spreadsheet was developed as the general calculation tool for the material composition. It was used to combine the volume information from the 3D model with the material information from Edupack. To do this, the system was divided into components and sub-components before a material was assigned. With the volume values (Rhinoceros 3D) and the material density (Granta EduPack) the weight of the system was calculated. The weight of the different components was then divided into the respective percentages of the material composition, in order to calculate the weight of each contained material or element individually. This material weight per component was then added up to give a result of the different critical materials within the complete system.

GRANTA EDUPACK The Granta Edupack software was used to get the specific material compositions of the different components.

Figure 5 shows the framework of the research.

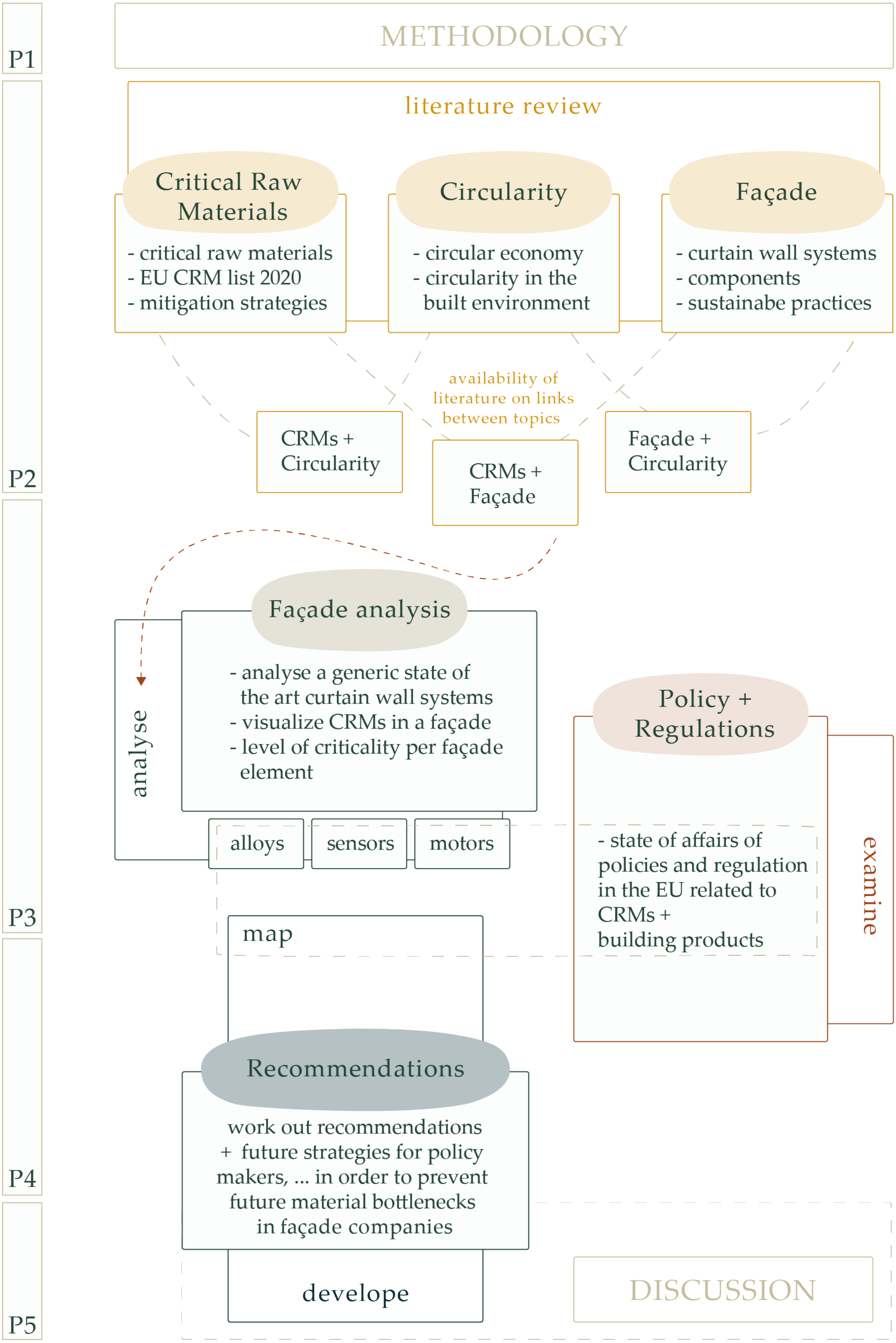


Figure 5: Methodology

Structure of the report

The previous introductory part of the report gave an overview of the aim and objectives of the research, research questions and methodology. From here on the structure is as follows:

CRITICAL RAW MATERIALS The first two chapters cover the main topics of the research. Chapter 1 gives an introduction to CRMs in general; an overview of the materials that are on the latest list of EU CRMs is given, and related challenges are discussed. After introducing their applications and connection to the BE, a first link to the CE is made.

THE PREMISE OF CIRCULARITY Chapter 2 then elaborates on circularity. What is a circular economy and what are the goals of a circular built environment? Different strategies, concepts and limitations are discussed in regard to the BE. The second part of the chapter then looks into the façade sector, and especially curtain wall systems, as they are the main focus of this research.

ANALYSIS RESULTS Chapter 3 shows the results of the analysis of a curtain wall system with respect to its parts and how they perform in terms of criticality. This is done as described in the methodology.

MATERIAL POLICIES Chapter (4) introduces the concept of policymaking regarding different strategies and policy instruments. It then examines existing policies in the EU related to materials and gives a conclusion on the identified gaps in policies.

RECOMMENDATIONS Finally, in Chapter 5, the findings of the previous chapters are concluded, in order to define recommendations of possible strategies on how CRMs concern should be addressed. The thesis ends with a discussion of the results.

Figure 6 shows the time planning of the project.

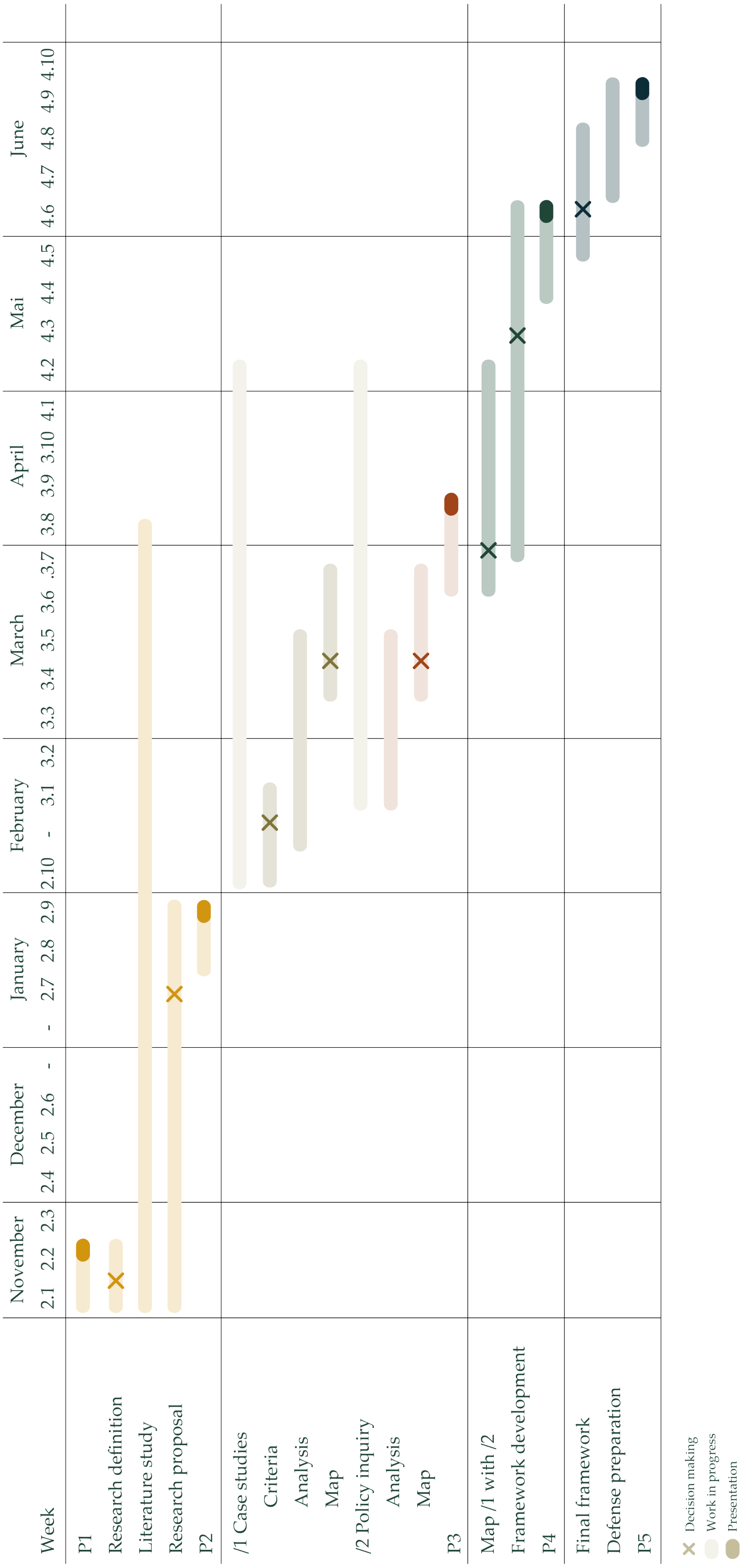


Figure 6: Project planning

Relevance of Study

The available literature on critical materials today mostly discusses the concern in fields related to low carbon, e-mobility or security and defense. There is a gap in research and knowledge of critical materials in the built environment. This thesis will analyse an aluminium curtain wall façade system and its relation to critical raw materials, and evaluate current EU policies in order to show up gaps. As a result, the thesis aims to work out recommendations to mitigate critical materials concerns in the built environment through the application of circular strategies. *Scientifically* it aims to provide research for this defined gap, *professionally* the goal is to prevent future material concerns in façade companies, and *socially* the relation of critical materials to the climate crisis and energy transition is discussed.

1 Critical (raw) materials

The field of CRMs has been getting more and more attention over recent years, but the general level of awareness for the topic is still rather low. This is a problem as, through Europe's transition to climate neutrality, there is a risk that the current reliance on fossil fuels might be replaced with a reliance on raw materials sourced from abroad to a large part. Regarding most metals, for example, the EU is 75-100% reliant on imports. [EC, 2020a] Figure 1.1 shows the EU's biggest suppliers in regard to different CRMs.
This chapter gives an overview of how the criticality of a material is assessed, which materials are currently on the EU list of CRMs and what role they play in our economy as well as in the BE.

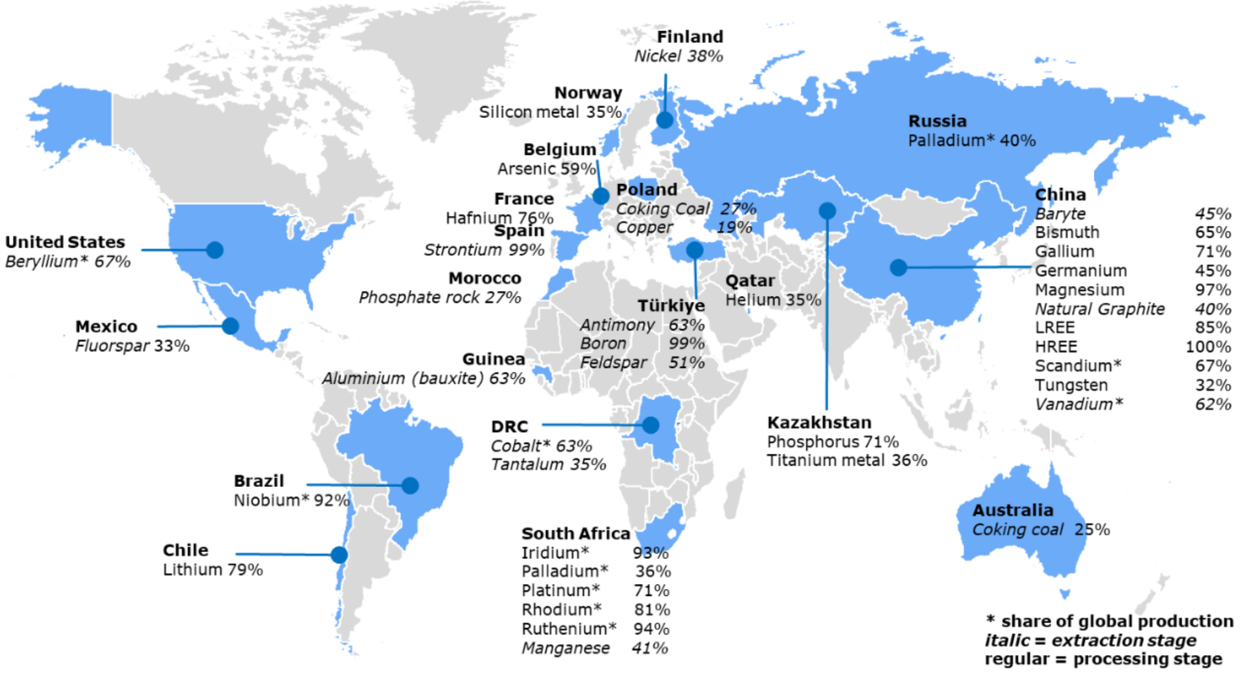


Figure 1.1: Countries accounting for the largest share of EU sourcing of CRMs [European Commission, 2023d]

1.1 Introduction to critical (raw) materials

To assess the criticality of a material, different approaches can be applied. These can be based on price volatility and supply restrictions [Peck, 2016], as well as ecological, social, or political factors [Ruuska and Häkkinen, 2014]. For the EC [2020a], to define a material as critical, two main factors come together:

(1) the material is of high economic importance and

(2) presents a high level of supply risk.

For (1) economic importance the assessment analyses raw materials regarding their end-uses on industrial applications [EC, 2020a], this already demonstrates that materials criticality is highly dependent on the specific economic context. (2) Supply risk on the other hand considers a broad range of topics; where raw materials are sourced and how country-concentrated the global production is, respective governance of the supplier countries, environmental aspects like recycling rates, substitution possibilities, trade restrictions in third countries as well as the EU import reliance. [EC, 2020a]

Figure 1.2: The EC factors for the criticality assessment.

The following factors were described by Ashby [2021] as part of the supply chain risk:

ABUNDANCE RISK The problem here is not the 'running out' of an element, as the earth's crust shows an abundance of the different elements. The problem is that some elements only occur in very low concentrations, which means that much more energy is required "to expose, mine, and crush the rock in which [the element] lies." [Ashby, 2021, p.301]

PRICE VOLATILITY RISK The metal market cannot respond to changes in demand quickly (so-called *price inelasticity*), as the expansion of mines and construction of new processing plants usually takes about three years.

MONOPOLY OF SUPPLY RISK AND GEOPOLITICAL RISK The Herfindahl-Hirschman Index (HHI) describes supply chain concentration of different elements on a scale from 0 to 1. The higher the value, the less balanced the market is. The closer the value is to 0, the more individual countries share supply, meaning there is less dependency on few specific nations. Concentration is, therefore a big issue for CRMs.

LEGISLATION AND REGULATORY RISK Nowadays, legislation on a national level also has global implications, as manufacturers from one country also have to work within other countries legislation if they wish to sell their products there. When a material - which up until that point is seen as an essential part of different products - is found to harm the environment, human health, and society, and therefore has to be eliminated or replaced, this poses a considerable risk for existing products (and especially long-lived products like aircraft).

EXPORT RESTRICTION RISK Reasons for export restrictions can be "to generate revenue for the government, to control the export of illegally mined products, to limit environmental damage, or to give a competitive advantage to domestic industries", although export restrictions are not the best strategies to achieve these objectives, as studies show. [Ashby, 2021, p.305] Some countries see the opportunity for job creation - by banning the export of unprocessed minerals - and processing jobs are also of higher value, especially when compared to the smaller employment rates of the mining sector.

CONFLICT RISK AND CORPORATE SOCIAL RESPONSIBILITY RISK Many countries in which conflict compromises human rights are rich in minerals, making mineral purchases from there ethically questionable. This can lead to higher prices, as it takes around three years to restore balance (through substitution or higher production in other countries) after production loss.

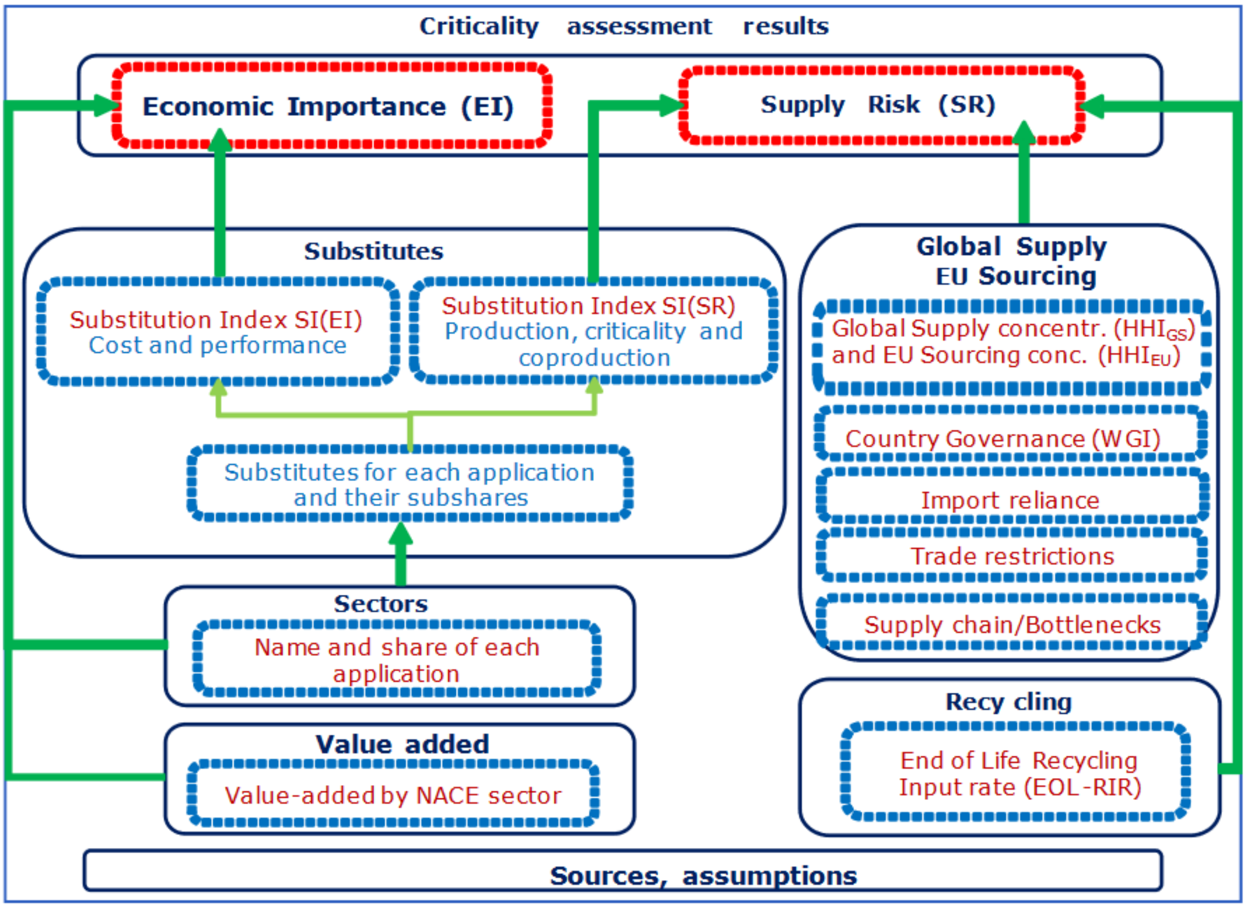


Figure 1.3: Assessment factors for economic importance and supply risk [European Commission, 2023d]

Figure 1.3 visualises the different factors included in the assessment for Economic Importance and Supply Risk. [European Commission, 2023d] The previous list by Ashby [2021] already described different factors regarding the supply chain in more detail. The European Commission [2023d] also mentions e.g. EOL-Recycling Input rate (RIR)s. Economic Importance then includes e.g. substitution indexes.

1.1.1 EU list of critical raw materials

The first list of CRMs for the EU was published in 2011 and has been renewed in intervals of three years from then on, with the latest published in March 2023, see Figure 1.4. As the definition of what makes a material or element critical gets more elaborate over the years, so does the list. However, these lists can only be seen as a rough guide on whether or not a material is considered critical at the moment, as the specific point in time plays an important role in every criticality assessment [Peck, 2016]. Figure 1.5 shows the changes in the CRMs list from 2020 to 2023, put together by the EC [2020b]. It depicts the differences between different materials; some only show relatively small 'movements', while others (e.g. LREE, Strontium or Niobium) present significant changes. Figure 1.6 shows the materials from the CRMs list highlighted on the periodic table.

2023 Critical Raw Materials (*new CRMs in italics*)			
aluminium/bauxite	coking coal	lithium	phosphorus
antimony	*feldspar*	LREE	scandium
arsenic	fluorspar	magnesium	silicon metal
baryte	gallium	*manganese*	strontium
beryllium	germanium	natural graphite	tantalum
bismuth	hafnium	niobium	titanium metal
boron/borate	*helium*	PGM	tungsten
cobalt	HREE	phosphate rock	vanadium
		*copper**	*nickel**

Figure 1.4: 2023 CRMs for the EU [European Commission, 2023d]

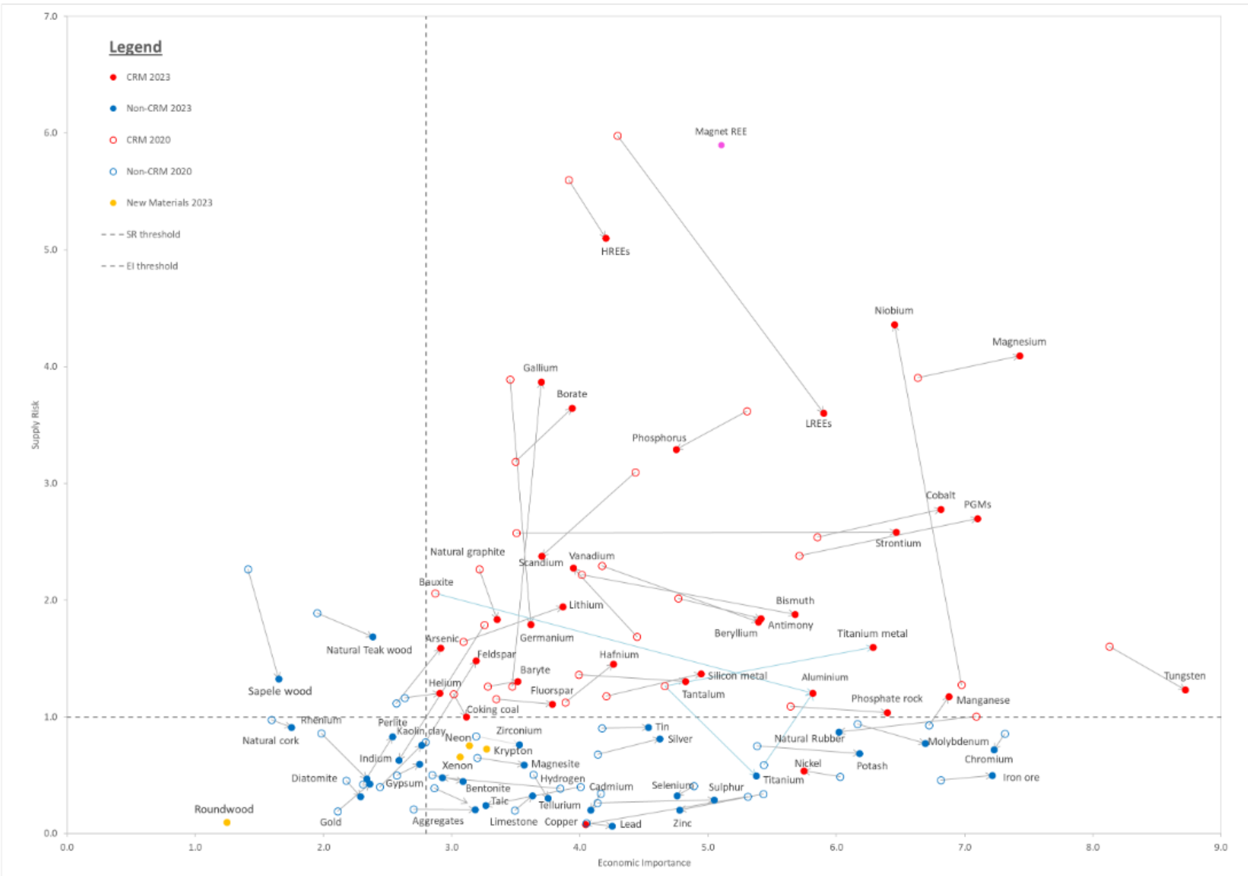


Figure 1.5: EU CRMs changes from 2020 to 2023 [European Commission, 2023d]

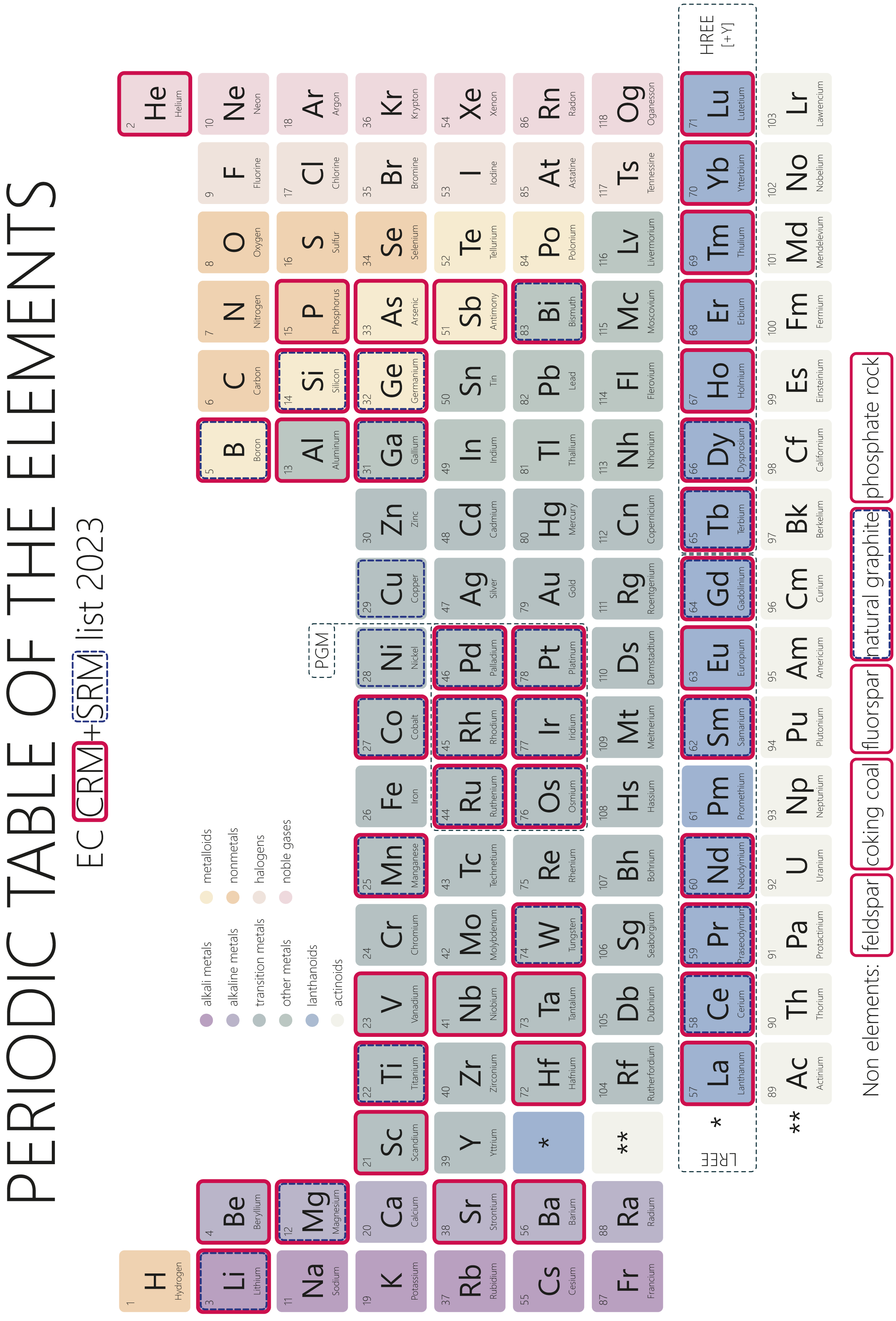


Figure 1.6: Critical materials shown on the periodic table

1.1.2 Resource consumption and shortages

With the increase in wealth and population in the 20th century, there was also an increase (by a factor of 8) in material extraction and consumption, leading to worsening environmental effects. There is still a big inequality between different countries regarding resource distributions; e.g., in 2017, the average material footprint of a North American person was about 10 times as big as the footprint of an African person. However, over the last decades, it can be seen that the material footprints in developed economies are rather constant or even decreasing, while in developing economies, the footprints have been increasing quickly. [UNEP, 2011]

21% of global energy use are consumed, and 21% of carbon emissions are released through the production of materials.
[Offerman, 2018]

21% of global energy use is consumed, and 21% of carbon emissions are released through the production of materials [Offerman, 2018]. As indicated in the introduction of this chapter, by shifting to clean energy production techniques, the demand for metals will increase dramatically - for some metals, the use could increase by a factor of a thousand [Offerman, 2018] - which already implies a possible risk of supply. The topic of material shortages is not new; it just appears in a different context - and a wider variety of individual technologies and materials - compared to earlier cases. Product design has already been linked to material use before, but nevertheless, designers are often unaware of their influence on the material choice and that some elements might be considered critical. [Peck, 2016]

The definition of what we understand as CRMs today has been developed in the 21st century - mainly by the works of "industrial ecologists, economists, material scientists, mining engineers, international relations experts, etc. and has seen far less contribution and involvement by product designers", as Peck [2016, p.77] points out.

The growing concern regarding the Limits to Growth [...] set the foundation of today's understanding of critical materials.
[Peck, 2016]

Earlier situations of material shortages were triggered by wars and geo-political tensions. The growing concerns regarding the Limits to Growth (LtG) and the energy/oil crisis in the 1970s set the foundation of today's understanding of critical materials. Over the following decades, the range of materials and development of new technologies grew significantly. By 2006 it had also become clear that the required increases in materials - which are needed for the *tech will fix it*[a] approach to tackle climate change - brings even more urgency to the critical materials concern. [Peck, 2019]

[a] The idea of *tech will fix it* stands opposed to the 'Limits to Growth', as the concept argues that 'LtG' does not take the ever-evolving nature of technology into account. [Peck, 2019]

1.1.3 Sourcing of critical raw materials

Various fields discuss the inequality that the energy transition might bring about, as two groups can be identified; one group is the one that benefits from the transition to clean energy, while the other group suffers the consequences of the "related resource extraction and associated environmental pollution and degradation, societal, social and cultural impacts, armed conflict, and land-grabbing, and/or loss of livelihoods". [Kügerl et al., 2023, p.2]

[...] a problem with any element that occurs only in very low concentrations: the energy it takes to expose, mine, and crush the rock in which it lies. One kilogram of the richest iron ores contains almost 0.5 kg of iron, but to get 1 kg of platinum requires the mining of about 500 tonnes of ore. [Ashby, 2021, p.301]

ETHICAL CONSIDERATIONS Kügerl et al. [2023] also address topics like neo-, resource-, and green colonialism - which link colonial practices to mineral resource extraction - and green extractivism, which has its focus on "social, ecological and climate impact of low-carbon infrastructure (i.e., deforestation, habitat loss and fragmentation, competition with agricultural land, etc.) and securing minerals and metals for low-carbon technologies (land enclosure and privatisation of common resources)". [Kügerl et al., 2023, p.2] It is outside the scope of this thesis to go deeper into these topics, but this already demonstrates that there is a need to ensure that approaches for the energy transition are ethical and just, as it is not unusual for CRMs to be located in countries or regions which are politically and economically unstable. Responsible sourcing can, therefore, not be guaranteed in these places, e.g. remote areas in developing countries. Social challenges include forced/child labour, health and safety concerns, and corruption. This should be dealt with by sustainable procurement rules imposed on the supplier by consumers. [TU Delft (Producer), 2018]

EU DEPENDENCE Figures 1.7 and 1.8 show the main global as well as EU supply countries for CRMs, especially visualising China's dominating role as it is responsible for 44% of EU CRMs supply. Germany, Finland, Spain, and France together are responsible for 15% of EU supply, with the other 85% coming from outside the EU. Only 4% (France 2% and Spain 2%) of CRMs of global supply come from within the EU. The EU's dependency on material supply from other parts of the world results from its limited capacity for "extraction, processing, recycling, refining and separation". Even some minerals currently mined in Europe (e.g. lithium) have to be processed outside of Europe. [EC, 2020a, p.7]

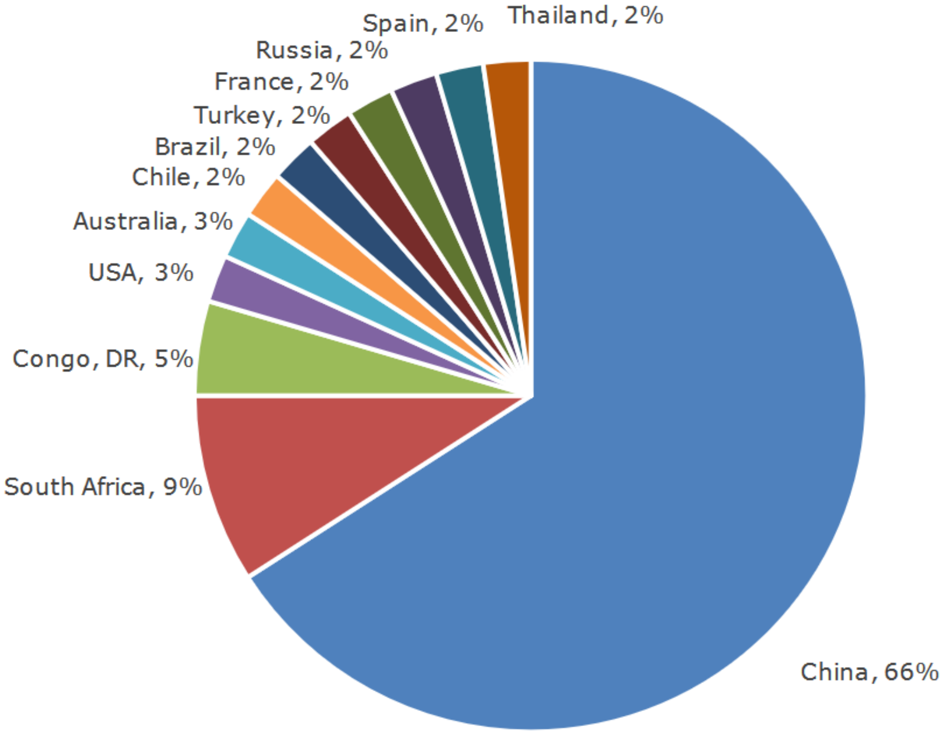


Figure 1.7: Main global supply countries of CRMs (based on number of CRMs supplied, average 2012-2016) [EC, 2020b]

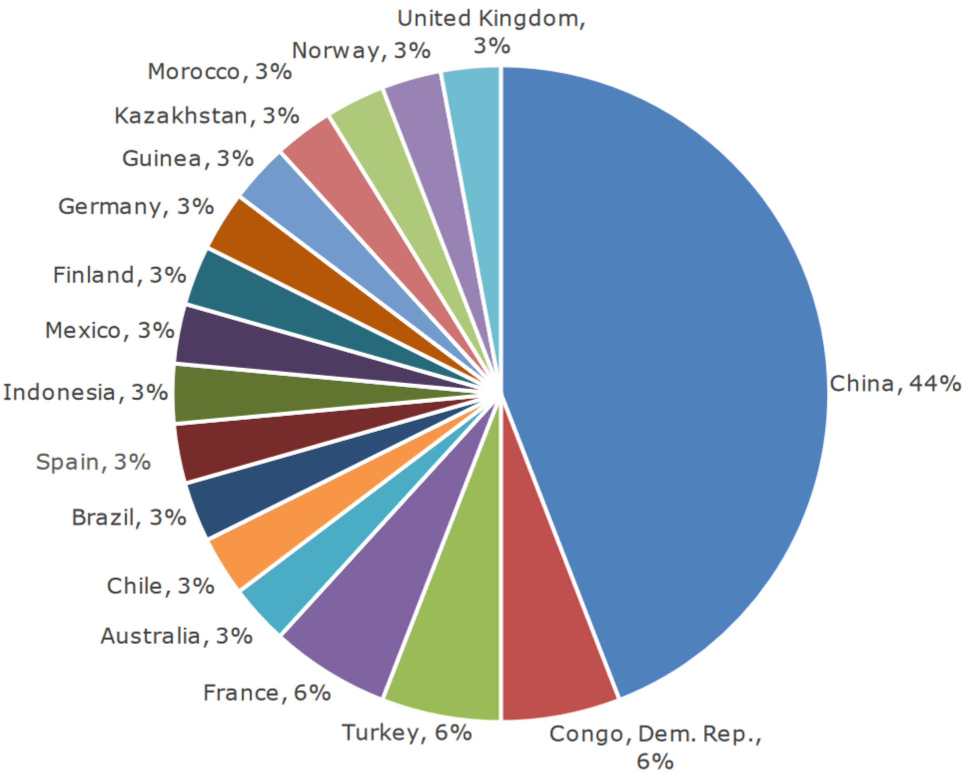


Figure 1.8: Main EU suppliers of CRMs (based on number of CRMs supplied, average 2012-2016) [EC, 2020b]

1.1.4 Application + importance of critical (raw) materials

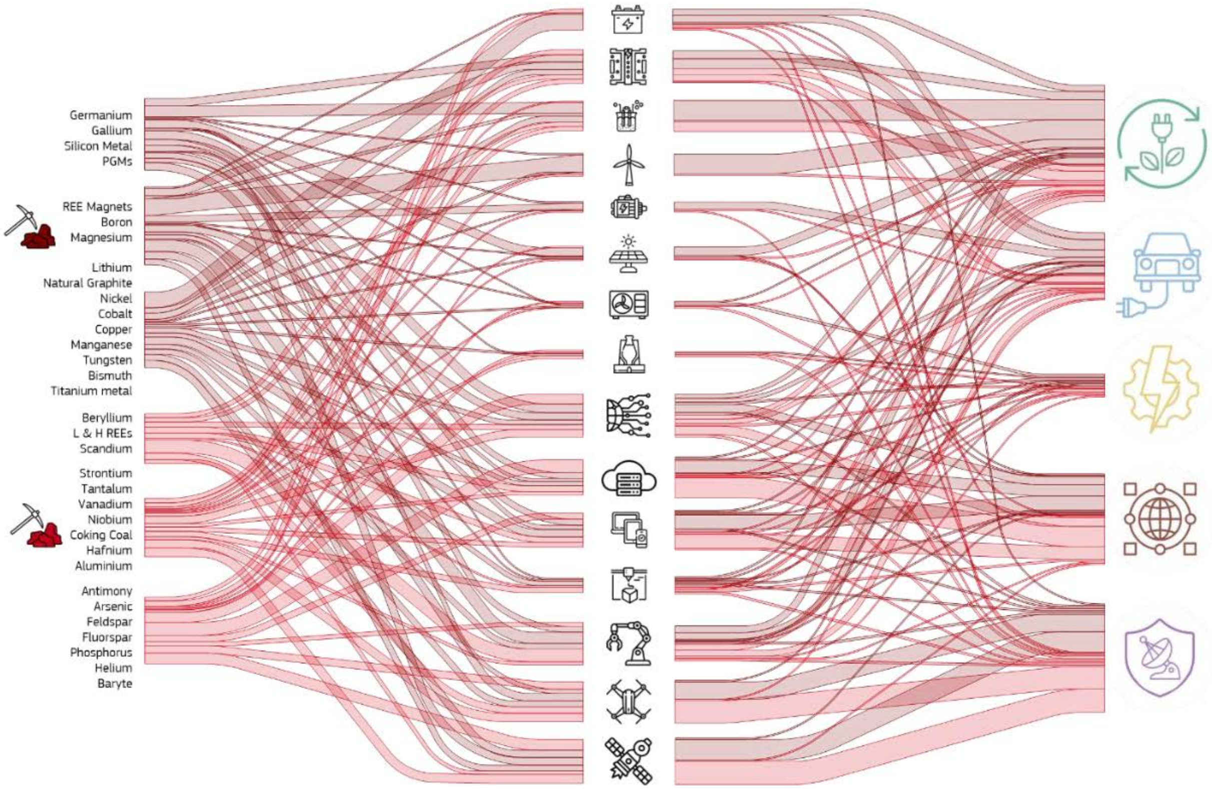


Figure 1.9: CRMs for Strategic Technologies and Sectors in the EU 2023 [European Commission, 2023e]

"Energy transitions are already the major driving force for total demand growth for some minerals."
[IEA, 2022, p.50]

SECTORS AND TECHNOLOGIES Current sectors affected by CRMs are those of renewables, electric mobility, industry, information & communications technology, and aerospace & defence, as shown in the right column in Figure 1.9. The middle column lists different technologies covered in these sectors: Li-ion batteries, wind turbines, fuel cells, electrolysers, wind turbines, traction motors, solar photovoltaics, heat pumps, hydrogen direct reduced iron and electric arc furnaces, data transmission networks, data storage and servers, smartphones, tablets and laptops, additive manufacturing, robotics, drones, and space launchers and satellites. [European Commission, 2023e]

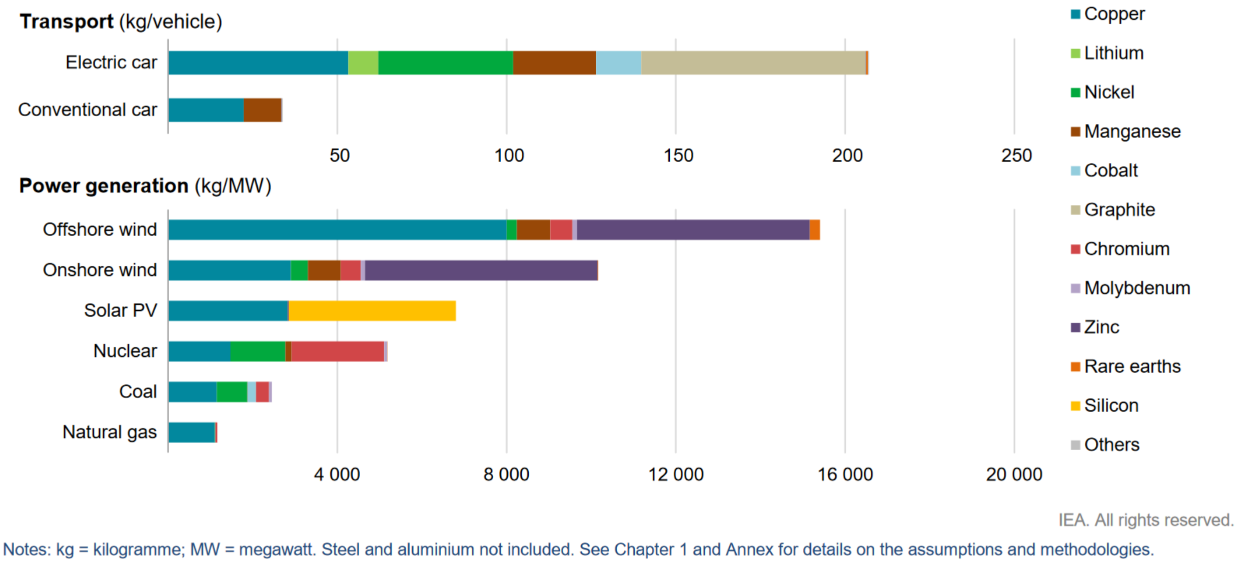


Figure 1.10: Energy technologies and their mineral demand [IEA, 2022]

INCREASE IN DEMAND The transition from fossil fuels to clean energy technologies brings about an enormous increase in mineral requirements. Figure 1.10 visualizes the material demand of clean energy technologies compared to conventional ones, e.g. a 6:1 rate for electric cars vs. conventional ones and a 9:1 rate for onshore wind plants compared to gas-fired power plants. [IEA, 2022]

1.1.5 Critical materials in the built environment

The BE greatly impacts the environment regarding emissions and energy consumption. This impact needs to be significantly reduced, and there are different strategies to do so. One way to address this is by moving away from the linear 'take-make-waste' economy towards a circular one, in order to keep components and materials in the loop which means reducing the impacts on the environment caused by materials production and processing, including land and water use or emissions - the following chapter will go deeper into this topic.

Another way is to make buildings 'smart', which means monitoring them with systems that optimise their operational energy consumption. This can e.g. include smart thermostats, smart lighting, smart appliances, smart windows, smart plugs and so on [HDL Automation, 2023].

However, these systems work through sensors and motors, which all contain critical materials. The use of CRMs in façades will be discussed in the following chapter, in subsection 2.3.3 with a particular focus on three fields for which CRMs are very important; (aluminium) alloys, motors, and sensors. The following section will now give an overview of different mitigation strategies regarding critical materials.

1.2 Critical materials mitigation strategies

Especially regarding CRMs, it is crucial to anticipate supply-chain constraints, explore substitutes, adapt to legislation, or guide the transition towards a more circular materials economy, which also brings about new challenges for material engineers [Ashby, 2021]. But even though strategies to cope with critical material concerns are mostly technical in nature, the implementation of them - like new business models, legislation and public acceptance - are not [Offerman, 2018].

Offerman [2018] provides the following list of (technical) mitigation strategies for CRMs:

1. Circular product design
2. Substitution of critical materials by
   a) non-critical materials,
   b) alternative technologies that do not rely on critical materials
   c) replacing a product that contains critical materials by a service that does not rely on critical materials.
3. Improve the resource efficiency of materials
4. Maximize the properties (functionality) per unit of material to minimize material and/or energy use for a particular function.
5. Sustainable mining
6. Materials design for recycling
7. Minimize the embodied energy of the material
8. Valorization of by-products/waste of materials
9. Improve the recycling and the recyclability of materials

This section will now look into some of them in more detail. This includes different types of substitution, the potential of urban mining and recycling, and a first introduction to circularity and design related to CRMs issues.

1.2.1 Substitution

The previous list mentioned substitution as a mitigation strategy, which can happen on different levels. In general, substitution can influence a product's performance, cost, and reliability. Extensive testing is, therefore, necessary to ensure technical and legal reliability. Limitations can also be seen regarding certification or compliance requirements within industries, which can make substitution a rare undertaking, as it comes with a long process. [Goddin, 2020] Goddin [2020] then mentions four different types of substitution:

> **[...] it is not the element that we are seeking to substitute but the performance of the material that is enabled by that element.** [Goddin, 2020, p.200]

SUBSTANCE FOR SUBSTANCE SUBSTITUTION
The goal here is not to substitute a certain element but a specific performance instead, and "the net effect of all of the elements in the composition and what these, acting together, will allow the material to do." [Goddin, 2020, p.200]
Example: Replace rare-earth elements with other - more abundant - rare-earth-elements.

SERVICE FOR PRODUCT SUBSTITUTION
This substitution might make a product provide service to multiple users, resulting in savings for the individual users. Users also do not have to maintain (or store, depending on the type of product) the product themselves. The quality might also be better, as products meant to be hired out often have better durability.
Example: We buy electricity, not a power station.

PROCESS FOR PROCESS SUBSTITUTION
The replacement of a process, meaning to focus on the solution itself, is often achieved by moving back to an already existing, older solution, resulting in fewer needs for qualification etc., compared to the development of a completely new one.
Example: Rare-earth-based permanent magnets vs gearboxes in wind turbines.

NEW TECHNOLOGY FOR SUBSTANCE SUBSTITUTION
The development of lightweight transistors allowed for the use of switched reluctance motors instead of rare-earth-based permanent magnets in Teslas.
Example: Substitution of silicon-based solutions with organic solar cells.

1.2.2 Urban mining and recycling

Recycling is mentioned as a mitigation strategy, as it can decrease supply dependence and provide another source of supply besides primary mining. However, recycling certain metals can be impractical, as not all metals can be treated or separated with conventional thermal or chemical separation processes. This makes it difficult to channel certain EOL products to the right facility. [Tercero Espinoza et al., 2020] [IEA, 2022] Metal recycling can also be rather complex because alloys can consist of many different metals with different characteristics [Reuter et al., 2013].

FROM WASTE TO RESOURCE Offerman [2018] describes four steps to turn a waste stream into a resource:

1. Collection of waste
2. Separate mixed solid waste into different streams to enhance the concentration of the different target materials
3. Extract and refine metals from scrap and residues
4. Process the refined metals to high-value alloys

IMPORTANCE OF RECYCLING Recycling is of high importance regarding the possible further utilisation of metals, and it relies not only on waste collection systems but also on individual consumers' sorting practices, e.g., decentralised facilities like private solar PV systems. [Pehlken and Bleicher, 2020] To ensure that EOL products are kept from entering into non-recoverable systems or land-fill, and therefore prevent the loss of technologically valuable elements, it is crucial to be alert for "urban mines" Reuter et al. [2013].

> **[...] the "geology" of the "urban mine" is complex and unpredictable and makes economic predictions difficult. [Reuter et al., 2013, p.45]**

THE URBAN MINE The urban mine includes any materials and products which are currently used, stored, discarded or disposed of, not only located in cities but also covering human-made products in rural areas [TU Delft (Producer), 2021], like tailings or scrap from processing, manufacturing, and fabrication, as well as end-of-life products [IEA, 2022].
Currently, the EOL recovery rates for many elements are well below 1%, e.g. for gallium, germanium, or rare earth elements. Urban mining is therefore promising when done efficiently, as there are for example also large unexploited stocks of rare and critical metals in vehicles. [TU Delft (Producer), 2021]

BOTTLENECKS Regarding the recycling of critical materials, many bottlenecks can be defined, such as the limited economic feasibility or missing related infrastructure and technologies. [Bleicher and Pehlken, 2020] End-of-life recycling rates cannot be linked to recycled input rates, as the lifetime of a specific product and the meanwhile demand growth also play a role here. As an example, improved recycling of aluminium in the past few years only enabled us to keep recycled input rates at the same level [IEA, 2022].

1.2.3 Critical materials, circularity and design

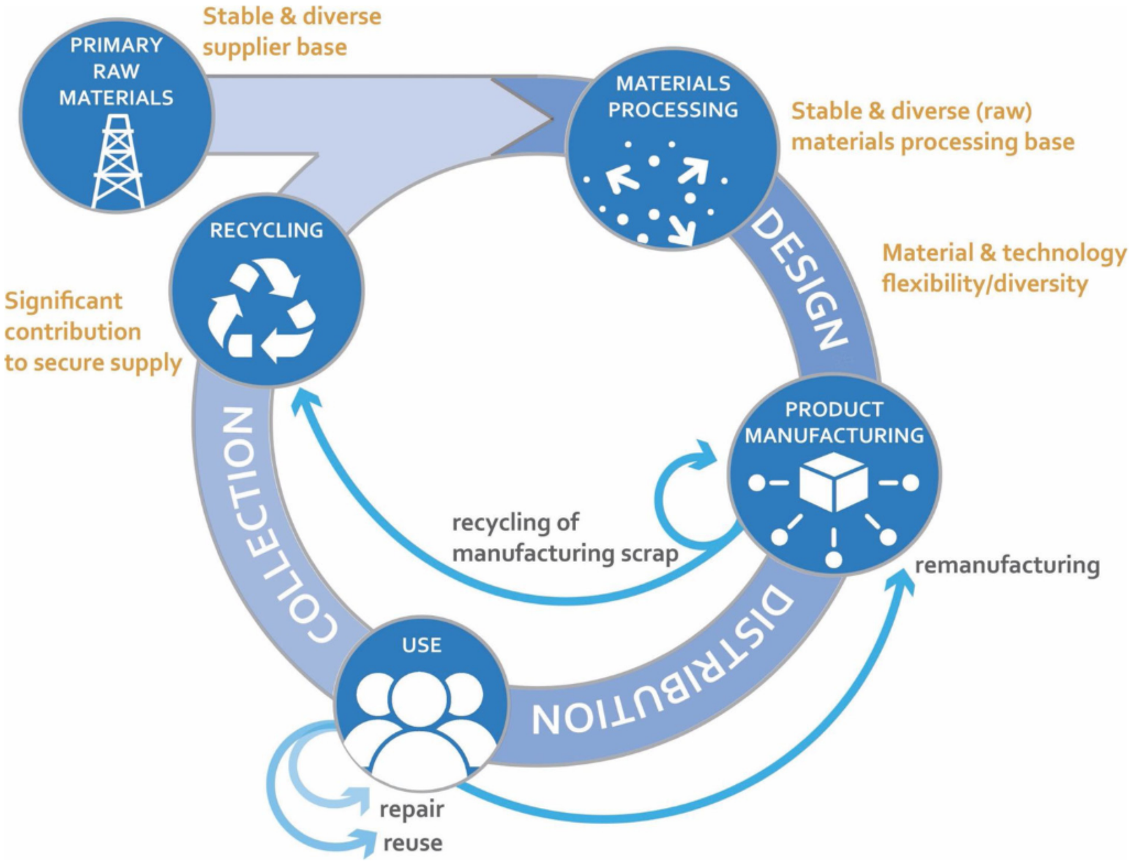


Figure 1.11: Loops within a circular economy [Tercero Espinoza et al., 2020]

THE ROLE OF DESIGN Peck [2016] points out the important role the design plays in terms of CRMs use, as it defines how long the life of a product might be, how hard it is to dis- and re-assemble, to reuse, refurbish, remanufacture or recycle. However, (product) design can be described as a social process which takes place in a field of "interests, value systems, and practices of different social actors (e.g., engineers, designers, and economists)" [Pehlken and Bleicher, 2020, p.227]. In that sense, design can hinder or facilitate strategies to extend a product's life.

CIRCULARITY AS A STRATEGY The most crucial step that has to be done in terms of a mitigation strategy for critical materials is to move away from the linear *take-make-use-dispose* economy and instead to establish a circular economy [Offerman, 2018]. This way, materials are not lost forever after their first application. Circularity will be the topic of the following chapter.

Figure 1.11 visualises the different loops within a product's lifetime, starting with primary raw materials, and covering material processing, product manufacturing, use and recycling. [Tercero Espinoza et al., 2020]

1.3 Chapter conclusion

ASSESSMENT OF MATERIAL CRITICALITY The assessment of material criticality involves both supply risk and economic importance, these then include different factors, e.g. substitution index, global supply concentration, country governance import reliance, or EOL-RIR. The assessment is, due to possible changes within these factors, a dynamic process, and the number of materials assessed as critical continues to increase over recent years. The production and consumption of these materials have significant implications, such as resource consumption, inequality in resource use among countries, energy consumption, and carbon emissions.

MATERIAL RESTRICTIONS Material shortages have been a concern before - historically triggered by wars and geopolitical tensions – and the foundation of today's definition of material criticality can be linked back to the Limits to Growth concept. The "tech will fix it" approach to addressing climate change increases critical material concerns.

SOCIAL INJUSTICE THROUGH MATERIAL EXTRACTION Two groups can be identified regarding the transition to clean energy: those who benefit from it and those who suffer the consequences of resource extraction, including environmental pollution, societal impacts, conflicts, land-grabbing, forced or child labour, and health and safety concerns, as the mining of CRMs often takes place in politically or economically unstable countries. This is also addressed by concepts like 'green colonialism' or 'green extractivism'.

EU IMPORT DEPENDENCY OF CRMS The European Union faces a significant dependency on CRMs imports, with 85% sourced from outside the EU. This dependency is especially relevant in the context of the energy transition, where CRMs play a vital role as the needed (and quick) scale-up of related sectors (e.g. renewables and electric mobility) results in a rapidly increasing demand of CRMs.

MITIGATION STRATEGIES Mitigation strategies for these issues include e.g. substitution, urban mining, recycling, and circularity. However, these strategies also face challenges. The different types of substitution can impact the performance, cost, and reliability of a product. Recycling often lacks economic feasibility or faces technical limitations, and circularity is mostly not accounted yet for, especially when it comes to tiny parts of materials used within components.

IMPORTANCE TO ADDRESS ENVIRONMENTAL, SOCIAL AND ECONOMIC INJUSTICE Addressing the criticality of materials and related issues is essential for ensuring a sustainable and just transition to clean energy. It requires a comprehensive approach that considers environmental, social, and economic factors while developing strategies for responsible sourcing, efficient use, and end-of-life management of critical materials.

OUTLOOK These statements summarise the issues with CRMs and also indicate that (1) the use of CRMs should be reduced wherever possible in order not to risk material dependencies and (2) it is important to keep the CRMs that are already in use in products in the loop. The following chapter will examine the circular economy and respective strategies, which aim to minimize the negative impacts associated with (critical) material extraction, before focusing on the façade sector in regard to its material use.

2 The premise of circularity and how it challenges the use of critical raw materials in the façade industry

This chapter will introduce the concept of circularity in general and within the BE. The transition towards a CE is not a simple one, as it "requires changes in the mindset and practices of designers and engineers" [Pehlken and Bleicher, 2020]. At least four domains are crucial for circularity: materials, design, manufacturing and management. (Figure 2.1) They all should be considered when wanting to become more circular, which can make circularity quite complex to assess. The chapter will then describe the link between circularity and the façade sector while also giving an overview of CRMs related to the field.

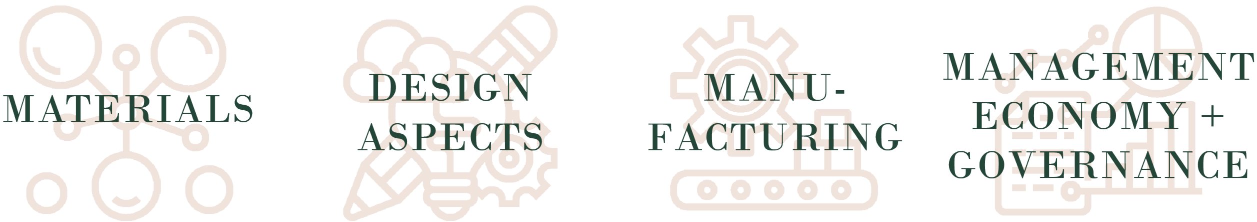


Figure 2.1: 4 domains of circularity

2.1 Introduction Circular Economy

1. design out waste and pollution
2. keep products and materials in use
3. regenerate natural systems
[Ellen MacArthur Foundation, 2017]

Acting sustainable means taking care of inter-generational needs while also being aware of planetary boundaries [D'Amato, 2021]. In that sense, the CE aims at reducing the impacts on the environment caused by materials production and processing, including land and water use or emissions [Allwood et al., 2011]. This is important from different views, on one hand in regard to the ongoing climate crisis and on the other hand as our planet's resources are limited, meaning that we need to keep them in the loop instead of following the traditional - linear - take-make-dispose plan. According to the Ellen MacArthur Foundation [2017], a CE is based on three principles: (1) design out waste and pollution, (2) keep products and materials in use, and (3) regenerate natural systems.

The CE plays an important role when it comes to the protection of biodiversity and ecosystems but also regarding social challenges covering the "just distribution of resources, opportunities and prosperity". [D'Amato, 2021, p.231] D'Amato points out that in order to maintain human prosperity, health and justice, we need healthy ecosystems and biodiversity, as well as e.g. climate regulation and water cycles. This means - to enable a quality life for all - loss of biodiversity and degradation of ecosystems need to be reversed. [D'Amato, 2021] This already indicates a systematic connection of different elements.

CIRCULAR BUILT ENVIRONMENT HUB The *Scales to Aspects* (Figure 2.2) model of the Circular Built Environment Hub (CBE Hub) [CBE Hub, 2020] also aims at visualising the underlying systems of circularity. The inner circle depicts the different *scales*, starting from the smallest part and gradually expanding; materials, components, buildings, neighbourhoods, cities and regions. All of these scales demonstrate different points of concern for the CE, from base ingredients to resource flows and urban metabolisms. [CBE Hub, 2020]. The outer circle then focuses on the *aspects* that are deemed important to consider in order to transition to a CE, namely technology, design, resource flow, stakeholders, economy and management.

Figure 2.2: 'Scales to Aspects' model from the CBE Hub [2020]

> **If efficiency is defined as 'doing things the right way', effectiveness means 'doing the right things'.** [Braungart et al., 2007, p.1342]

2.1.1 Concepts and initiatives addressing a Circular Economy

OVERVIEW The exact origin of the idea of a circular economy cannot be defined but the concept started gaining attention in the 1970s. This resulted in different schools of thought, for example; *Regenerative Design, Performance Economy, Industrial Ecology* or *Biomimicry*. [Ellen MacArthur Foundation, 2013] Today there are by now quite a few initiatives and organisations that are concerned with the concepts of circularity. With the *Cradle to Cradle* concept Braungart et al. [2007] defined a strategy for 'eco-effective product and system design'. They defined the difference between eco-efficiency and eco-effectiveness as follows: "If efficiency is defined as 'doing things the right way', effectiveness means 'doing the right things'" [Braungart et al., 2007, p.1342] They also point out that most recycling strategies actually result in down-cycling, as the quality of the materials is reduced and they therefore can only be used in lower value applications as an result. The materials lifespan might be prolonged but they don't keep their status as resources, as some of them still end up being landfilled or incinerated. [Braungart et al., 2007]

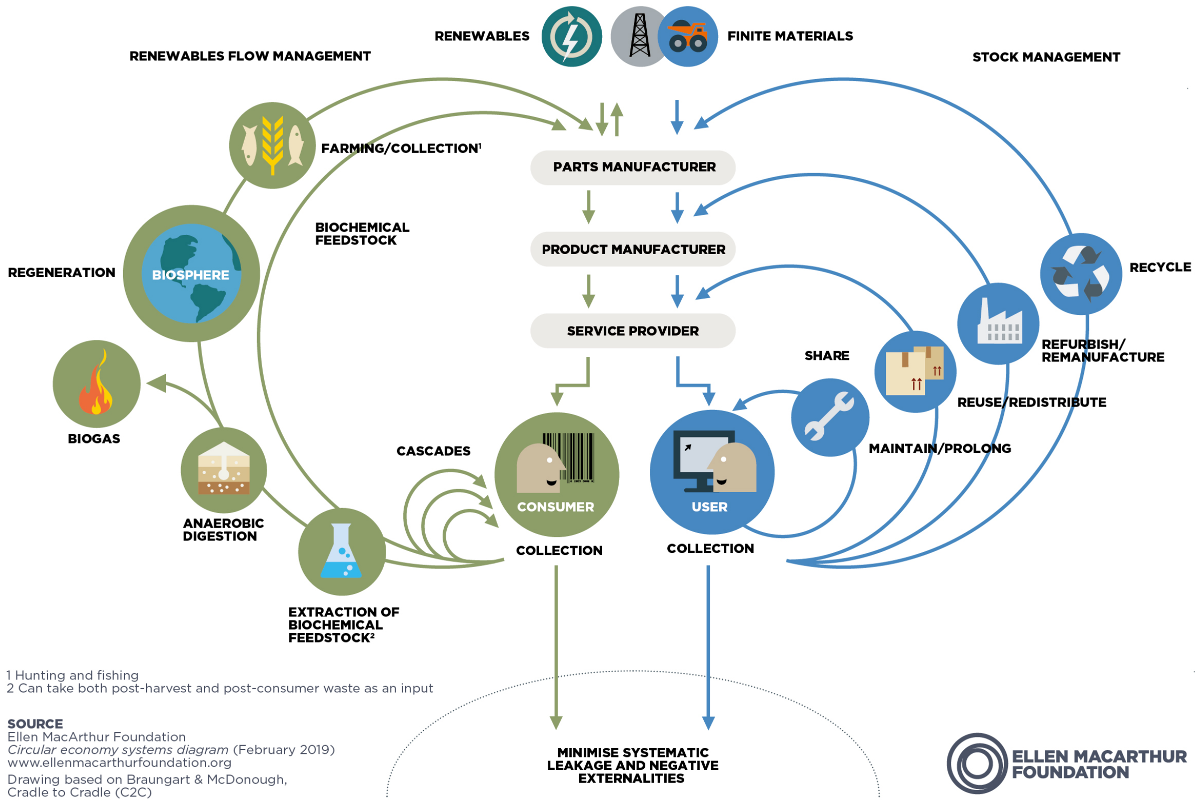


Figure 2.3: Butterfly diagram by the Ellen MacArthur Foundation [2019]

NATURAL VS. TECHNICAL CYCLE The butterfly diagram in figure 2.3 by the *Ellen MacArthur Foundation* [2019] shows the respective flows of a natural cycle (left; renewables) compared to a technical cycle (right; finite materials).
As this research has its focus on critical materials, related strategies lie rather within the right side, as the CRMs list mostly consists of metals.

In general tighter cycles result in bigger material savings, as well as less labour, energy use or capital investment. In the long run, a circular approach could lead to a decreased need for virgin material extraction as well as a decrease in the growth of total material stock and landfill. [Ellen MacArthur Foundation, 2013]

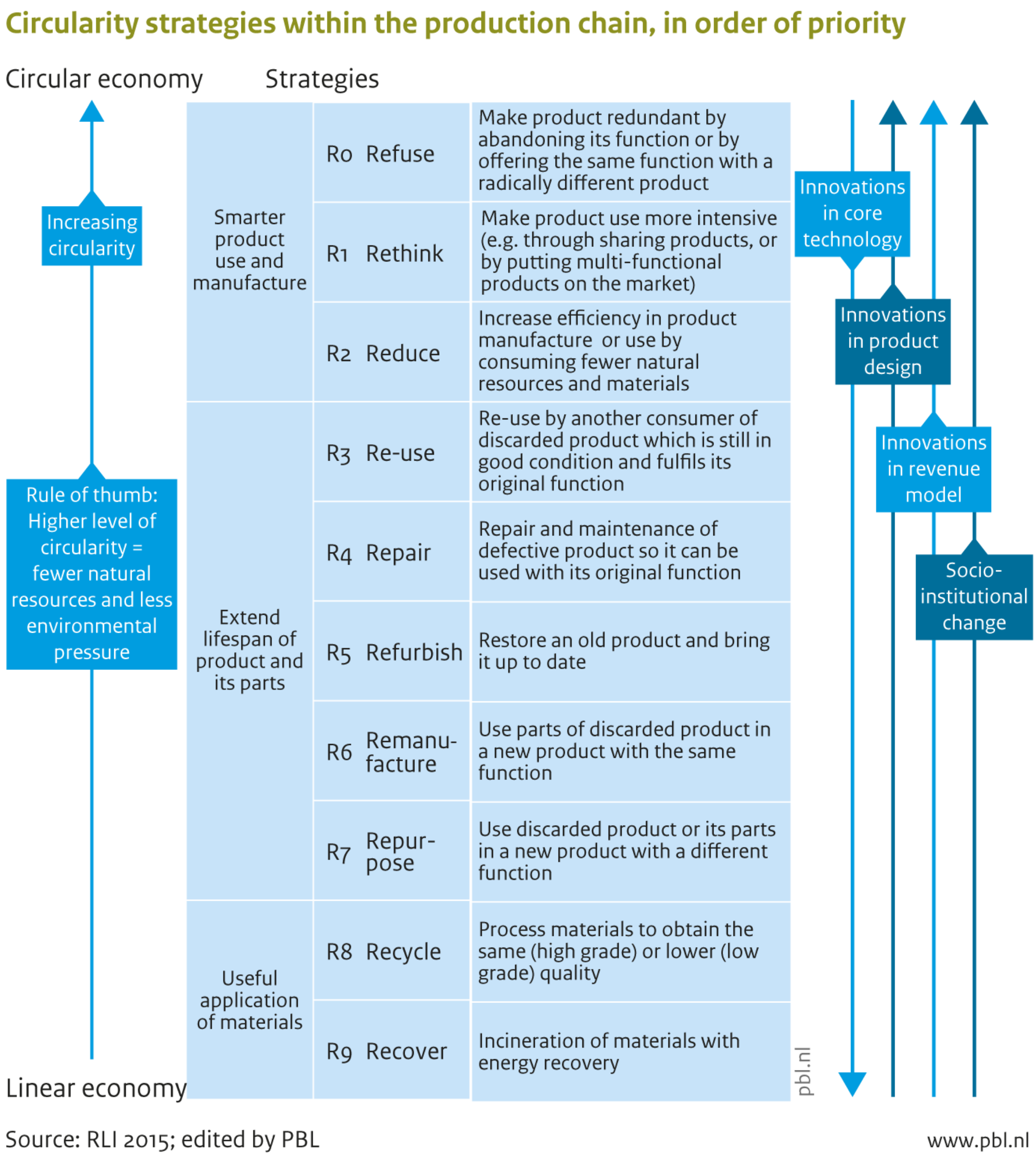


Figure 2.4: The nine r-strategies to keep materials in the loop [PBL, 2018]

PRIORITISING CIRCULAR STRATEGIES Strategies to keep materials in the loop are summarised by the so-called *R-strategies* (Figure 2.4), starting with the most efficient one on top - which is to *refuse* a product by making it redundant - with decreasing circularity towards the bottom [PBL, 2018], ending with energy *recovery* through incineration. The strategies are split into three fields; smarter product use and manufacture, extended lifespan of the product and its parts and lastly the useful application of materials. This then also depicts that *recycling* which is commonly seen as desirably is second to last in the ranking, meaning that there are many other options that are actually more effective in a circular sense.

CIRCULAR STRATEGIES AND CRMS Babbitt et al. [2021] also describe the potential of circular strategies related to critical material concerns, see Figure 2.5.

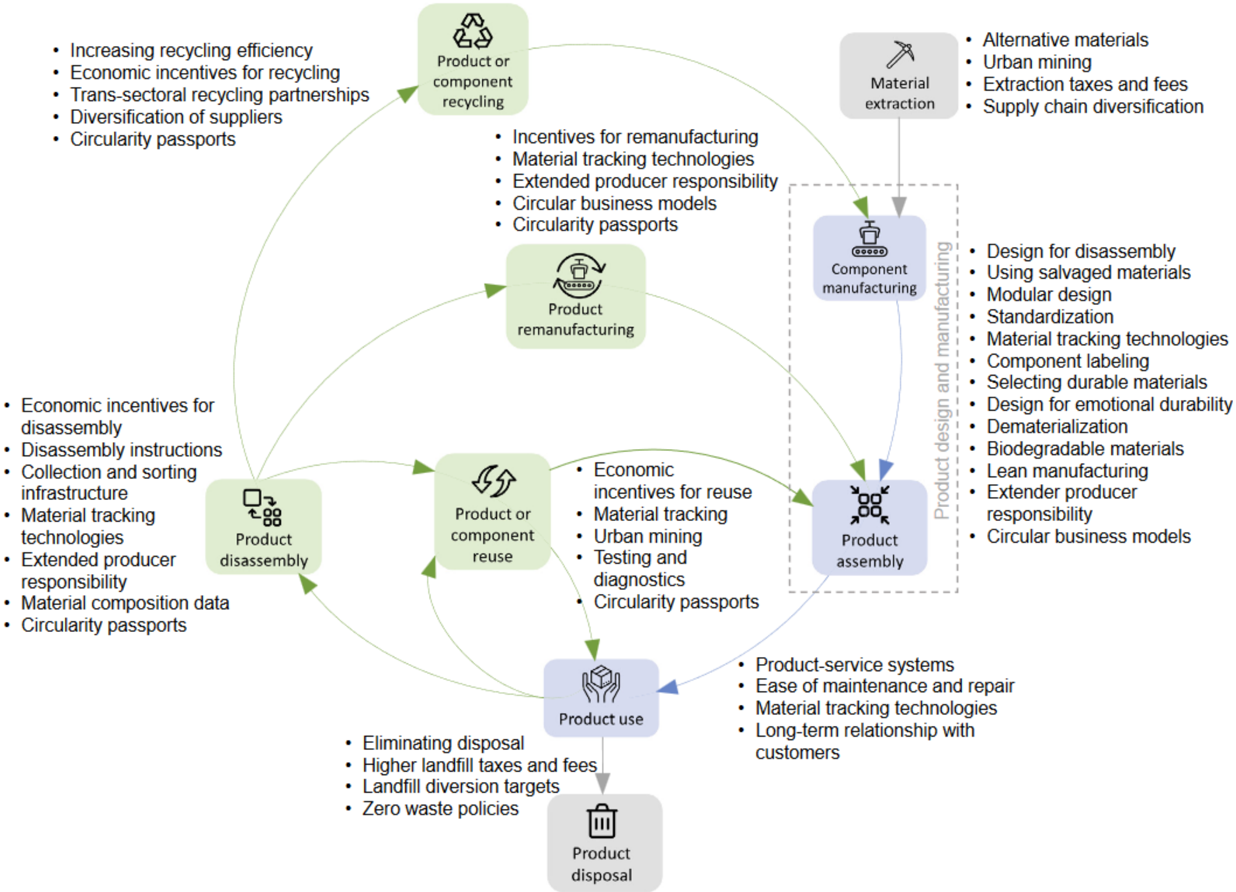


Figure 2.5: Circular economy enablers related to CRMs [Babbitt et al., 2021]

The green boxes illustrate ways to extend a product's life through recycling, remanufacturing, reuse or disassembly. This can include increased recycling efficiency, technologies to track materials, extended producer responsibility, or economic incentives.

The blue boxes represent practises which are common for both circular and linear systems; component manufacturing, product assembly - which is combined as product design and manufacturing - and product use. This covers e.g. design for emotional durability or the use of biodegradable materials, as well as product-service systems and the ease of maintenance and repair. The also mentioned DfD will also be further explored in the following section.

Material extraction and product disposal, in grey, are meant to be eliminated within a circular economy, and are therefore addressed with alternative material use, urban mining, or higher landfill taxes and fees. [Babbitt et al., 2021]

2.1.2 Restrictions concerning the *'perfect'* circular economy

There is no 100% circular economy, as, "a literal interpretation of circularity, one in which materials circulate endlessly, is totally unrealistic." [Ashby, 2021, p.334] The three main bottlenecks towards the perfect circular economy, according to Ashby [2021], are related to stock dynamics, loss of quantity, and loss of quality:

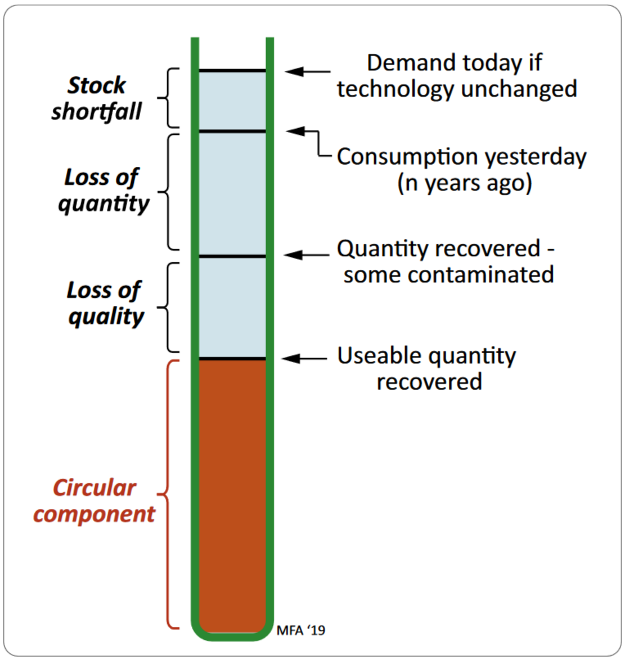


Figure 2.6: Three obstacles towards the perfect circular materials economy [Ashby, 2021]

> **[...] a literal interpretation of circularity, one in which materials circulate endlessly, is totally unrealistic.** [Ashby, 2021, p.334]

STOCK DYNAMICS The concept of circularity is to recover materials from EOL products and keep them in the loop by reusing them. As long as a material is part of a product, it is out of reach for use in other applications. It is very likely, that during the product's lifetime, the overall demand for the material will increase. Therefore, even if the material is completely recoverable, there will still be the need for additional raw materials.

LOSS OF QUANTITY It is simply unrealistic and impossible to recover each and every material. The collection of EOL products can never reach all products, as there is a trade-off between recovery cost and gain.

LOSS OF QUALITY For some metals, most polymers, and almost all composites, their level of pureness is very important in relation to their possible further use. Separating them can result in high energy use and costs. Like in the case of loss of quantity, economic viability plays an important role here.

2.2 Circularity in the Built Environment

The BE is a highly complex and technical field. Returning to the shearing layers of Brand [Brand, 1994], the layers show a first differentiation of services and functions that are part of a building, and each layer has a different lifespan. There are a lot of steps involved from start to finish of the construction of a building, including groundwork, structure, facade, HVAC, electrical, roofing etc. Each of these sectors should be addressed to build a genuinely circular building. However, the term 'truly circular' might be misleading, as circularity does not work as an on/off button. To assess whether a product can be considered circular, it has to be analysed through various domains, e.g. the previously mentioned ones (Figure 2.1): *material, design, manufacturing,* and *management* [Klein and Ioannou, 2021].

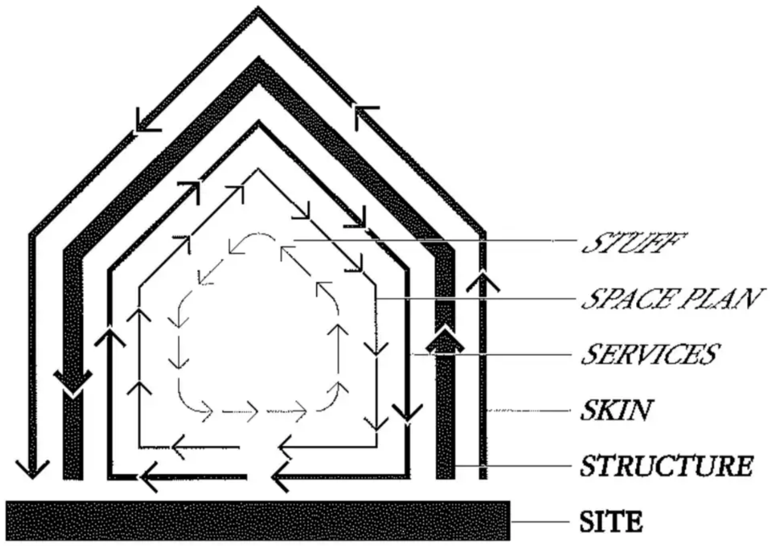


Figure 2.7: Shearing layers according to Steward Brand [1994]

DESIGN FOR DISASSEMBLY Circularity starts at the beginning, meaning the early stages of the planning and design process, as concepts can be more easily implemented if they are accounted for from the start. This is especially important for the so-called DfD. Buildings parts today are often cast together, welded or glued which makes it difficult to separate the different elements from each other at the end of the building's life. DfD aims at making connections reversible allowing for structure to be disassembled into its original parts which then can be reused again. [Merrild, 2016] This is not only true for buildings but for all types of products that are made up of multiple parts. It is also not a new concept but in the past, it was mostly based on necessity - for example when building temporary structures that should be able to be moved after a certain time - and not made by conscious choice [Merrild, 2016].

According to a report by GXN [2016], the five principles that have to be considered when aiming for DfD are (Figure 2.8):

- **MATERIALS** Quality, Healthy, Pure: material properties should ensure that they can be reused
- **SERVICE LIFE** Layers, Flexibility, Interim: the function of a building might change over time
- **STANDARD** Modularity, Prefabrication, Components: the building should be simple enough to fit into a larger context
- **CONNECTIONS** Accessible, Mechanical, Dissolvable: connections need to be reversible and durable for repeated use
- **DECONSTRUCTION** Strategy, Stability, Environment: deconstruction should be accounted for from the beginning

Figure 2.8: 5 principles to consider for DfD according to GXN [Merrild, 2016]

MATERIAL PASSPORTS After making sure that the building can be demounted again, the next step is to re-use - or (if damaged) repair, refurbish etc. - the individual parts. This is where material passports could come into the picture. Material passports, or Digital Product Passports (DPP) are meant to provide all the relevant information about a product, including "information on the origin, composition, repair and dismantling options of a product, as well as on its handling at the end of its service life", which could help with the transition towards a circular and low-carbon economy by filling the gap of information [Adisorn et al., 2021, p.2].

Material passports are one topic to address circularity, other approaches also include new business models, like take-back schemes, leasing contracts like products as a service, or logistic platforms. [Merrild, 2016] [Arup and BAM, 2018] This concept is also being researched for façades, as it is assumed that this could lead to reduced consumption of primary raw materials, as performance delivery would be the main focus and this could then stimulate increased reuse and remanufacturing.

2.2.1 Choices to make within a design or product design

In order to make a product more sustainable, it is important to know and quantify the impacts of the different stages. Only then it can be assessed which intervention would bring the biggest improvement in terms of minimization of the impact on the environment. [Ashby et al., 2018]

According to Ashby et al. [2018] the stages that should be considered towards 'eco-design' cover:

MATERIALS PRODUCTION PHASE This is often a very energy-intensive phase, as it includes extraction and processing of the raw material.

PRODUCT MANUFACTURE PHASE Further processing is mostly less energy intensive than the making of it in the first place. Local circumstances have to be considered here, as manufacturing can produce significant emissions and toxic waste.

PRODUCT USE PHASE Mechanical, thermal, and electrical efficiencies should be maximized in order to minimize the use-energy.

PRODUCT DISPOSAL PHASE The focus here lies on non-toxic as well as recyclable materials.

TRANSPORT The mass, distance, and energy mode of transport should be considered here.

Each of these different phases includes different stakeholders, but the role of the designer or architect can maybe be seen as the connecting figure between these. In the end, the design is what influences

As shortly discussed in the introduction, the further research of this thesis focuses on façades. For one, they can combine different layers (service, skin, and structure) and also contain parts with relatively long lifespans, like metals and alloys, as well as parts with relatively short lifespans, including sensors and motors. This shows the relevance of circularity in this sector; by following a take-make-waste strategy, many (critical) materials here would be lost for good after only a couple of years.

2.3 The Façade Industry

It is rather self-explanatory that the façade is a crucial part of a building. In general, it functions as a barrier that separates - and protects - the inside from the outside. The history of façades goes back thousands of years, starting with the most basic building materials like straw and mud before getting more and more complex up until today. Traditionally, a façade would always reflect its context in terms of materiality and construction method as different regions come with varying resource availability and environmental influences that need to be accounted for in the building envelope. But as the world grew more and more connected, knowledge and innovation were also shared globally. Buildings could be built taller while also looking more similar all over the world due to the developments in building services.

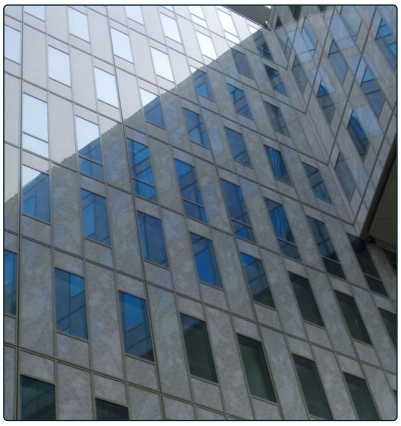
2.3.1 Overview

Just a few decades back, windows were still made with single glazing and therefore did not require complex aluminium profiles as is common today. With technology and engineering knowledge advancing during the Industrial Revolution, new materials became available, allowing construction to be bigger, stronger, higher, and lighter. Modernist architecture called for buildings without unnecessary decorations, focusing on functionality and transparency [Clarke, 2019]. This eventually led to the development of the type of big transparent glass façades we are so used to seeing today.

Facades are directly related to the design, use and structure of a building, including building services.
[Knaack et al., 2014]

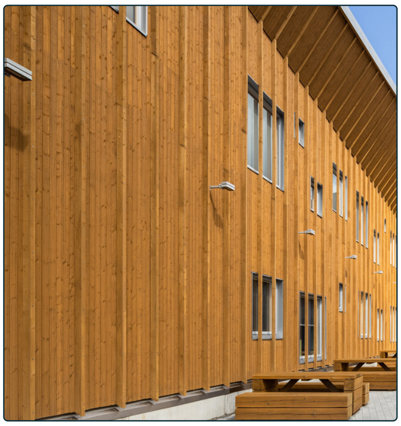
Today's façades need to cover a broad variety of tasks starting from view and lighting over ventilation and user comfort to building services as well as load-bearing. They are therefore directly related to the design, use and structure of a building, including building services. Façades are no isolated component and should consider functions like creative expression just as much as active or passive environmental control. [Knaack et al., 2014]

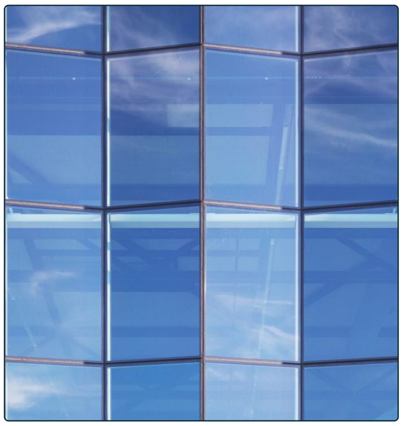
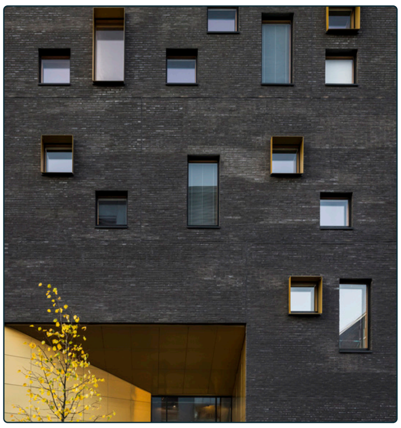
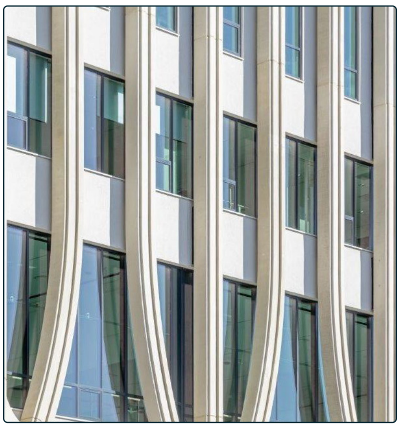
There are different types of façades; walls with skeletal structures (half-timbered construction, platform and balloon framing), loadbearing structures and façades (post-and-beam façades, post façades, beam façades, curtain walls, system façades) or double façades (second-skin façades, box-window façades, corridor façades, alternating façades, integrated façades) [Knaack et al., 2014]. This thesis will now focus on curtain wall systems.









1a: Spoolderwerk, Zwolle
1b: TU/e Atlas, Eindhoven
1c: Orion Lyceum, Breda
2a: Renovatie BB gebouw, Amsterdam
2b: Vinoly Mahler 4, Amsterdam
2c: Kobe Port Museum, Japan
3a: Keravanjoki, Kerava River Valley
3b: Éco-Campus, Vitry-sur-Seine
3c: hAL 5 RAI, Amsterdam
4a: The Soiva Building, Helsinki
4b: Amare, Den Haag

2.3.2 Curtain walls

Curtain wall systems come with the advantage that the façade is structurally separated from the building's main load-bearing structure. This means the aesthetic and functional demands of the envelope can be structured independently from the rest of the building. This freedom also allows for the prefabrication of separate elements as well as whole wall elements which then again can lead to quicker on-site assembly or installation and therefore requires less labour while also ensuring production quality. [Knaack et al., 2014] Another reason for prefabrication is the complexity of today's façades, dealing with numerous building physical issues, which only allows for tolerances within the millimetre range [Klein, 2013].

Figures 2.9 and 2.10 list the typical components of a contemporary curtain wall. According to Klein [2013] these are *profiles*, *mullions*, *insulators*, *insulated glass units*, *pressure plates*, *cover caps*, *coating or anodising*, *screws* and *inner/outer glazing rebate gaskets*. The diagrams link the various functions that the façade is supposed to fulfil to the different components.

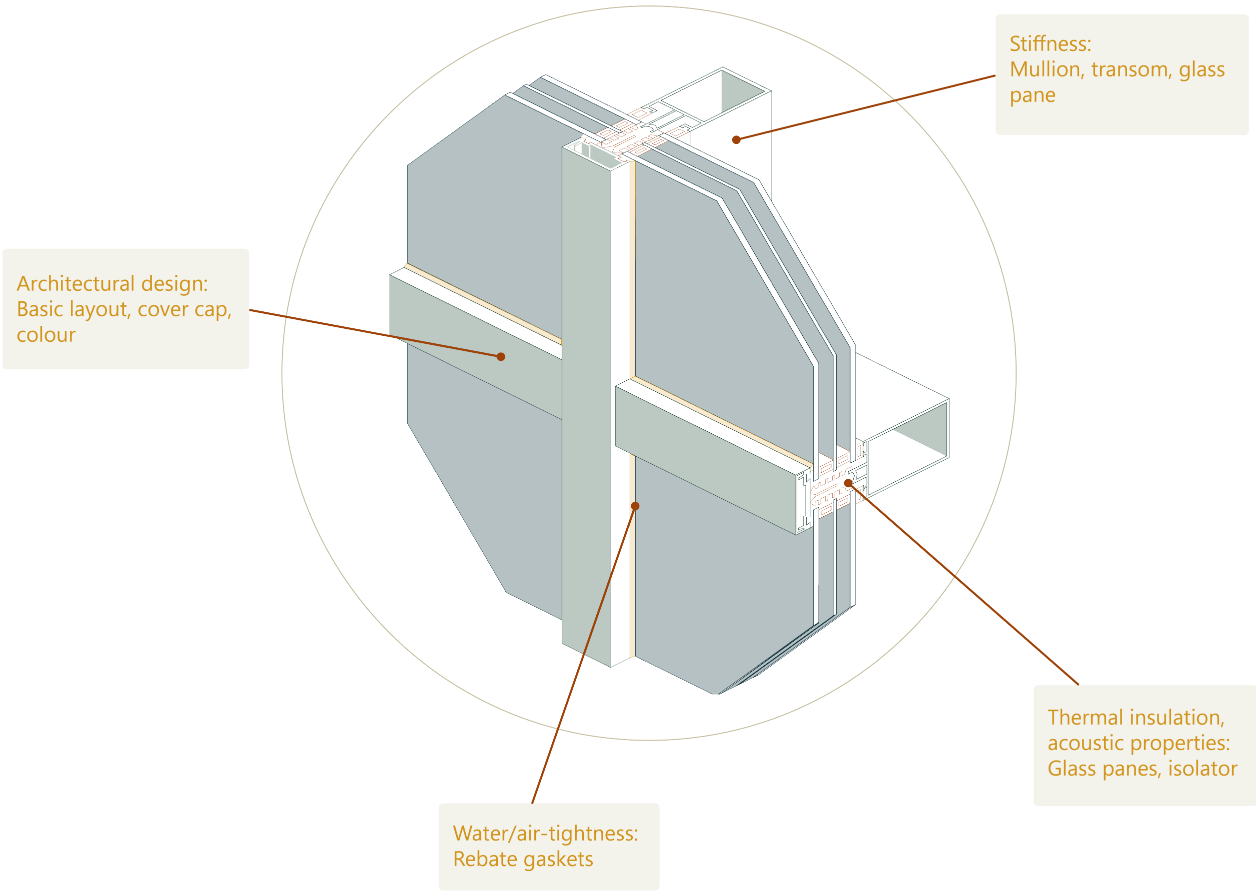


Figure 2.9: Functions of different components of a curtain wall system, adapted from Klein 2013.

A curtain wall system can be seen as a toolbox; parts and components can be composed into the desired grid structure with specific infills and special parts like cover caps or mullions with a specific shape. As long as the interfaces of the different components remain the same, parts can be adjusted individually. This allows for a certain level of architectural variety while still ranking high in standardisation and therefore meeting required standards and regulations. [Klein, 2013]

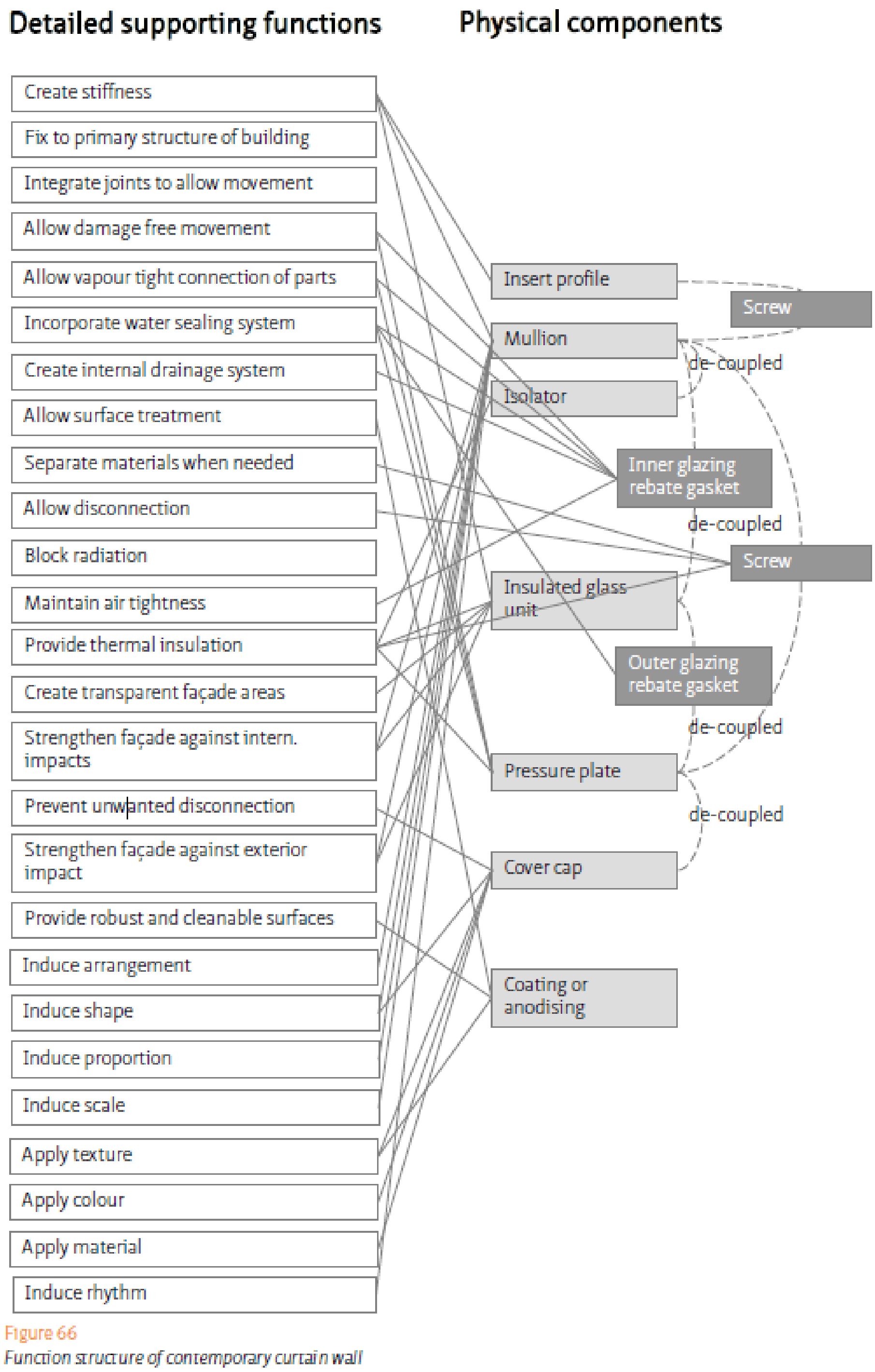


Figure 2.10: Function structure of contemporary curtain wall [Klein, 2013]

2.3.3 Elements of a façade from a critical materials view

Figure 2.11: Elements of a curtain wall facade

When it comes to utility buildings, most façades nowadays are built as curtain wall systems. Figure 2.10 depicts the typical functions that should be addressed by a contemporary curtain wall related to the physical components within the system.

The number of components usually ranges somewhere between 120 and 400 pieces. [Klein, 2013] Components can change from system to system, but on a material level, Klein [2013] lists the following: Steel, EPDM, polythermid, stainless steel and aluminium. At first sight, only aluminium is listed on the EU 2023 CRM list. However, in regard to aluminium as well as steel, we are talking about alloys, which then also contain several other elements. Looking at the usual alloy compositions for this type of application (which will be analysed in more detail in Chapter3), a basic stick and beam system then contains at least seven materials which are defined as critical. These are: Aluminium, Magnesium, Manganese, Phosphorus, Silicon metal, Titanium metal, *Copper* (Strategic Raw Material (SRM)), and *Nickel* (SRM).

The number of components usually ranges somewhere between 120 and 400 pieces.

However, no literature was found that directly discusses the use of CRMs in façades. This shows a gap in research which also seems to apply for other building sectors. Figure 2.11 shows a first assumption of elements in curtain wall systems which are connected to critical materials. In the middle we see the 'main system' of a typical post-and-beam façade. Depending on the design of the specific building, there are also doors and windows integrated in the façade. These might be automated, which means that there are some sensors which measure or react to something, like light, temperature, movement, humidity and so on. Once the sensors assess that a window or door needs to be opened or closed, magnets in motors perform that movement. Other possible elements included within a curtain wall system are e.g. cladding panels, lights, PV, or (automated) shading elements. All the moving, automated elements here, which are often described as parts of 'smart systems' which are meant to optimize a buildings operational energy consumption, can be assumed to contain critical materials.

sensors can measure or react to e.g. light, temperature, movement, humidity,...

The next chapter will analyse curtain wall façade systems more in detail, in order to visualise where critical materials are located in a façade and to assess the level of criticality per façade component.

ALUMINIUM ALLOYS The increased application of aluminium in buildings was made possible in the first half of the 20th century when the development of different alloys - which made the material strong and ductile - enabled its use for construction purposes. The extrusion process was also more economical. Aluminium alloys were especially suited for window sections, as they could be extruded easily into precise and fine shapes before being tempered to result in higher strength, making them an ideal material for curtain walls. [Klein, 2013][Clarke, 2019]

the development of specific alloys (= enhanced functionalities) made the wide application of aluminium for construction purposes possible

Within the buildings and construction sector, aluminium products are used for a variety of applications including windows, doors, cladding or curtain walls, with possible substitution materials being e.g. composite materials, steel or wood. However, an increasing variety of different aluminium alloys has led to enhanced functionalities of the alloys and improved their specific properties including resistance and strength, weldability and corrosion [Gaustad et al., 2018]. While this is desirable, it also makes recycling more challenging, if not impossible, as there can hardly be a recycling system developed that can handle thousands of different alloy compositions without mixing grades which then leads to changes in the respective compositions. [Graedel et al., 2022]

Figure 2.12 shows some characteristics of the two groups of aluminium alloys; cast and wrought. They two processes result in different strengths and limitations for the final product, which then also leads to different applications.

Al	System	Strengths	Limitations	Uses	Effect of composition
Cast	**xxx.x** nr 1 = principal element added nr 2-3 = specific alloy within the series n4 = product form (.0=casting, .1/.2=ingots) letter prefix (e.g. A360.0) = modification ot specific grade or impurity limit	properties vary amongst classes; - good fluidity - good feeding ability - good corrosion resistance - good strength	lower ductility and strength than wrought alloys	machinery, engine blocks, gas meters, gear blocks, gear cases, fuel pumpls, instrument cases, intake manifolde, clutch housings, oil pans, outboard motor propellers, pistons, cylinder liners	Si = improve fluidity (alloys alloy to flow into intricate mold shapes Al-Mg alloys = best combination of strength and toughness, but difficult to cast Al-Mn alloys = exceptional for non-load bearing application, low cost, poor mechanical properties
Wrought	**four-digit number** nr 1 = major alloying element(s) nr 2 = indicates close relationship (e.g. 5352 closely related to 5052 and 5252 in composition nr 3-4 = minimum purity (in 1xxx series), serial numbers (other series) letter suffixes = indicate how alloy has been processed F = 'as fabricated' O = 'annealed wrought products' H = 'cold worked' T = 'heat treatment'	generally better strength, ductility, and fracture toughness than cast alloys	reduced corrosion resistance through increased alloying additions	aerospace, aircraft applications, domestic electrical appliances, weapons industry, transport applications, forged missile and aircraft fittings, pistons	increasing alloying additions reduces corrosion resistance

Source: Edupack

Figure 2.12: Characteristics of cast and wrought aluminium alloy classes, source: Granta Edupack

Al	Series	Alloy elements	Characteristics
Cast	1xx.x	Pure Al	best corrosion resistance
	2xx.x	Cu-alloyed	lowest corrosion resistance but highest strength
	3xx.x	Si, Cu, Mg-alloyed	most widely used
	4xx.x	Si-alloyed	second best corrosion resistance
	5xx.x	Mg-alloyed	best combination of strength and toughness, most difficult to cast, variable weldability
	7xx.x	Zn-alloyed	excellent surface appearance and machinability, most susceptible to stress corrosion cracking
Wrought	1000	Pure Al	inferior machinability to other wrought alloys, lowest strength
	2000	Cu-alloyed	
	3000	Mn-alloyed	inferior machineablility to other wrought alloys
	5000	Mg-alloyed	
	6000	Mg and Si-alloyed	particularly excellent extrudablility
	7000	Zn-alloyed	most susceptible to stress corrosion cracking
	8000	Li-alloyed and other	lightest

Source: Edupack

Figure 2.13: Overview of aluminium alloy classes, source: Granta Edupack

The different aluminium alloys are grouped into different classes, depending on their main alloying elements and general material composition, as Figure 2.13 shows. This then results in very specific characteristics and therefore optimisations for the intended applications.

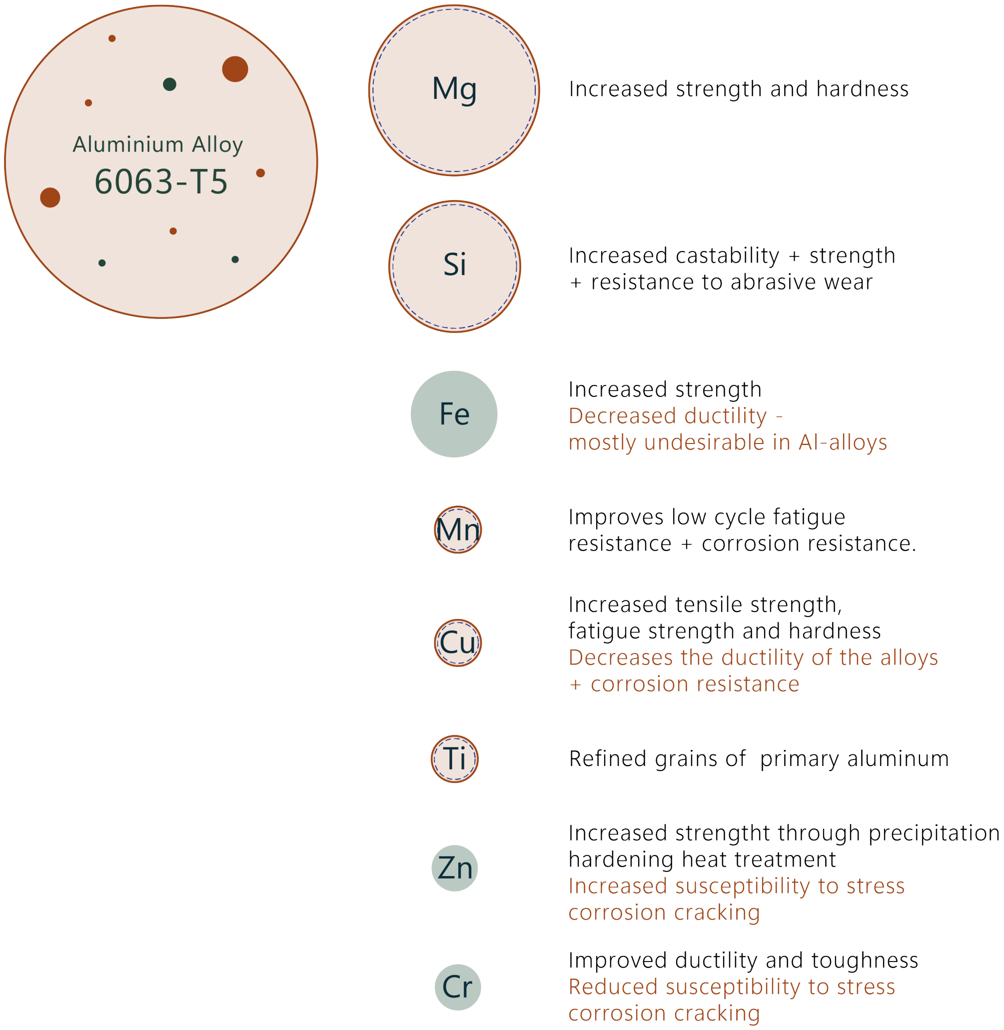


Figure 2.14: Alloying elements of the "architectural aluminium" (Source: Granta EduPack)

Aluminium alloy 6063 (see Figure 2.14) is generally described as the architectural alloy. It consists of eight different materials, with five of them (red) being defined as critical. Material science is a very complex field and a deeper explanation of how exactly the different materials are important for the final performance of the alloy is therefore outside the scope of this research. The specific % of the materials within the alloy is part of the analysis in chapter 3.

The smaller dots in the circle on the left visualise the proportions of the alloying elements compared to the main material. This can then be linked back to the challenges regarding the recycling of alloys, as very small traces of materials still influence the overall performance of the material. This can e.g. be improved ductility and toughness through chromium, increased castability through silicon, and so on.

SENSORS are programmed to measure values or react to changes within a variety of fields, e.g. safety or comfort related. This can include:

- HVAC and indoor air quality: temperature, humidity, carbon oxides, air velocity
- Occupancy sensors: motion sensors attached to lighting systems
- Safety and security sensors: motion sensors for alarm systems, fire detecting sensors, gas detecting sensors, smoke detectors
- Outdoor sensors: outdoor motion sensors for security, compact weather stations
  [Alhorr et al., 2016], [Dong et al., 2019]

The issue with sensors, especially in regard to CRMs, is that they are - and often have to be, as they are meant to fit into the smallest of applications - very very small. This is especially problematic when it comes to the recycling of the respective materials.

MOTORS Necessary or desired changes in systems are then performed through motors; e.g. opening a window or a door, or turning HVAC systems on/off. Within these motors, there are small permanent magnets as crucial components. These magnets can have a significant amount of CRMs content.

The range of different types of motors and magnets that can be used is enormous. A total overview of all possibilities is not just because of the range outside the scope of this thesis, but also because it was difficult to find information, specifically regarding motors in applications used within the façade industry.

In general it can be said that the recyclability of elements of curtain wall systems usually comes off well, as it is a modular product that can be separated into its materials, elements and components. This also applies for possible upgrades of the construction. However, in case of refurbishments of façades, which usually happens after 30-40 years, typically the complete façades gets renewed as the previous structures are not up to standards - e.g. in terms of structural load or insulation properties - anymore. [Klein, 2013]

2.4 Chapter conclusion

This chapter discussed the goals of a circular economy, especially in regard to a circular built environment. In that sense, design should be used to reduce waste and pollution, keep products or materials in use, as well as regenerate natural systems. A CE addresses the protection of biodiversity, as well as social challenges, such as ensuring a just distribution of resources, opportunities, and prosperity for all.

AWARENESS AND STRATEGIES TOWARDS A CIRCULAR ECONOMY The rise of awareness towards the necessity for the transition to a more circular economy can be seen by the development of different organizations or initiatives over recent years, for example, the CBE Hub or the Ellen MacArthur Foundation. Different strategies, as wells as different levels of effectiveness within circular strategies are discussed with the butterfly diagram and the R-strategies (Fig. 2.4). In the BE, different concepts are promoted, like DfD, material passports, and design considerations. A perfect CE is, however, impossible, due to factors like stock dynamics, loss of quantity, and loss of quality.

THE ROLE OF FACADES The façade industry holds a critical position as it directly influences the design, use, and structure of buildings, including building services. The industrial revolution enabled us to build bigger, stronger, higher, and lighter structures. With modernist architecture, the focus has shifted towards functionality, transparency, and user comfort (consideration of views, lighting, ventilation, and environmental control).

ADVANTAGES AND COMPONENTS OF CURTAIN WALL SYSTEMS Curtain wall systems, with their advantages of structural separation from the main structure, the possibility of quick assembly and disassembly, and precision through prefabrication, have become inherent to today's architecture. They can be regarded as toolboxs, including profiles, mullions, insulators, IGU, pressure plates, cover caps, coatings, screws, and glazing rebate gaskets.

MATERIALITY AND CRMS OF CURTAIN WALL SYSTEMS Typical materials mentioned in literature for curtain wall systems are steel, EPDM, polythermids, stainless steel, and aluminium. Based on a first assumption, CRMs are likely found in these systems within alloys, motors, and sensors. However, in general it can be stated that the CE largely does not show awareness for CRMs concerns so far. One complicating factor within façades is the combination of components or materials which have different lifespans, as was shown with the shearing layers of Brand (Fig. 2.7). It is also likely that the criticality of the included materials will change within the time of use.

THE CIRCULAR ECONOMY AND FACADES Applying the principles of Circular Economy to the façade industry had potential to address the challenges of resource consumption, waste generation, and environmental impacts, and therefore to contribute to a more sustainable and resilient built environment. Building Product Passports can be used to assemble information and facilitate prospective future use scenarios.

The following chapter will now present the results of the analysis of the façade element, as mentioned in the methodology.

3 Analysis: Critical Materials in Façades

This chapter will now show the analysis results, as outlined in the Methodology. The results are grouped in System 1 (fixed glazing) + System 2 (fixed glazing and openable window) and System 3 (motor-operated window) + System 4 (sensor-controlled motor-operated window), to give a clear overview. For the first group (alloys) the results show quantification of the different critical materials contained within the systems, while for the second group (motors and sensors) only general assumptions on the critical materials included can be given.

3.1 Results: analysis and comparison of the different systems

3.1.1 S1 + S2: Fixed glazing and openable window

For the first two systems, the critical materials were defined as parts of alloys. The assumptions which specific alloys to analyse are based on a comparison of various websites of companies, manufacturers, or wholesale companies. The three different types of alloys which were then assumed to be used in a typical curtain wall system are Aluminium 6063, Aluminium 3004, and Stainless Steel AISI 304, as shown in Table 3.1.

Material information from Granta Edupack				*values used for calculation*		Overall criticality
Alloy	Material	%	Density	%	Density	
Aluminium alloys 6000 series: Al + 1.2% Mg + 0.25% Zn + Si, Fe, Mn 6063-T5 aluminum-magnesium-silicon alloy as typical alloy for architectural applications	Al (aluminium)	97,5 - 99,4	2660 - 2710 kg/m³	98,45	2685 kg/m³	99,68%
	Cr (chromium)	0,0 - 0,1		0,05		
	Cu (copper)	0,0 - 0,1		0,05		
	Fe (iron)	0,0 - 0,35		0,175		
	Mg (magnesium)	0,45 - 0,9		0,675		
	Mn (manganese)	0,0 - 0,1		0,05		
	Si (silicon)	0,2 - 0,6		0,4		
	Ti (titanium)	0,0 - 0,1		0,05		
	Zn (zinc)	0,0 - 0,1		0,05		
	Other	0,0 - 0,15		0,075		
Aluminium alloy 3004, H19 (thermobar aluminium spacer tube in IGU)	Al (aluminium)	95,6 - 98,2	2690 - 2750 kg/m³	96,9	2720 kg/m³	99,48%
	Cu (copper)	0 - 0,25		0,125		
	Fe (iron)	0 - 0,7		0,35		
	Mg (magnesium)	0,8 - 1,3		1,05		
	Mn (manganese)	1 - 1,5		1,25		
	Si (silicon)	0 - 0,3		0,15		
	Zn (zinc)	0 - 0,25		0,125		
	Residuals	0 - 0,15		0,075		
Stainless steel AISI 304 (1/8) (hardware; screws, corner connection window frame, hinges)	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m³	0,04	7955 kg/m³	10,57%
	Cr (chromium)	18 - 20		19		
	Fe (iron)	65,8 - 74		69,9		
	Mn (manganese)	0 - 2		1		
	Ni (nickel)	8 - 11		9,5		
	P (phosphorus)	0 - 0,045		0,0225		
	S (sulfur)	0 - 0,03		0,015		
	Si (silicon)	0 - 1		0,05		

crm 2023 list

Figure 3.1: Alloy compositions used in the analysis, values from Granta Edupack

CRMs IN ANALYSED ALLOYS The table (3.1) shows the material composition of the respective alloys in terms of overall alloy weight and the percentages of the different materials within, and indicates which of these contained materials are listed as critical. This gives eight materials: Aluminium, copper (SRM), magnesium, manganese, nickel (SRM), phosphorus, silicon, and titanium. If the average percentages of the different CRMs included in the alloys are added up, an average criticality assessment of the different materials can be made. This gives a percentage of 99.68% for Aluminium 6063, 99.48% for Aluminium 3004, and 10.57% for Stainless Steel AISI 304.

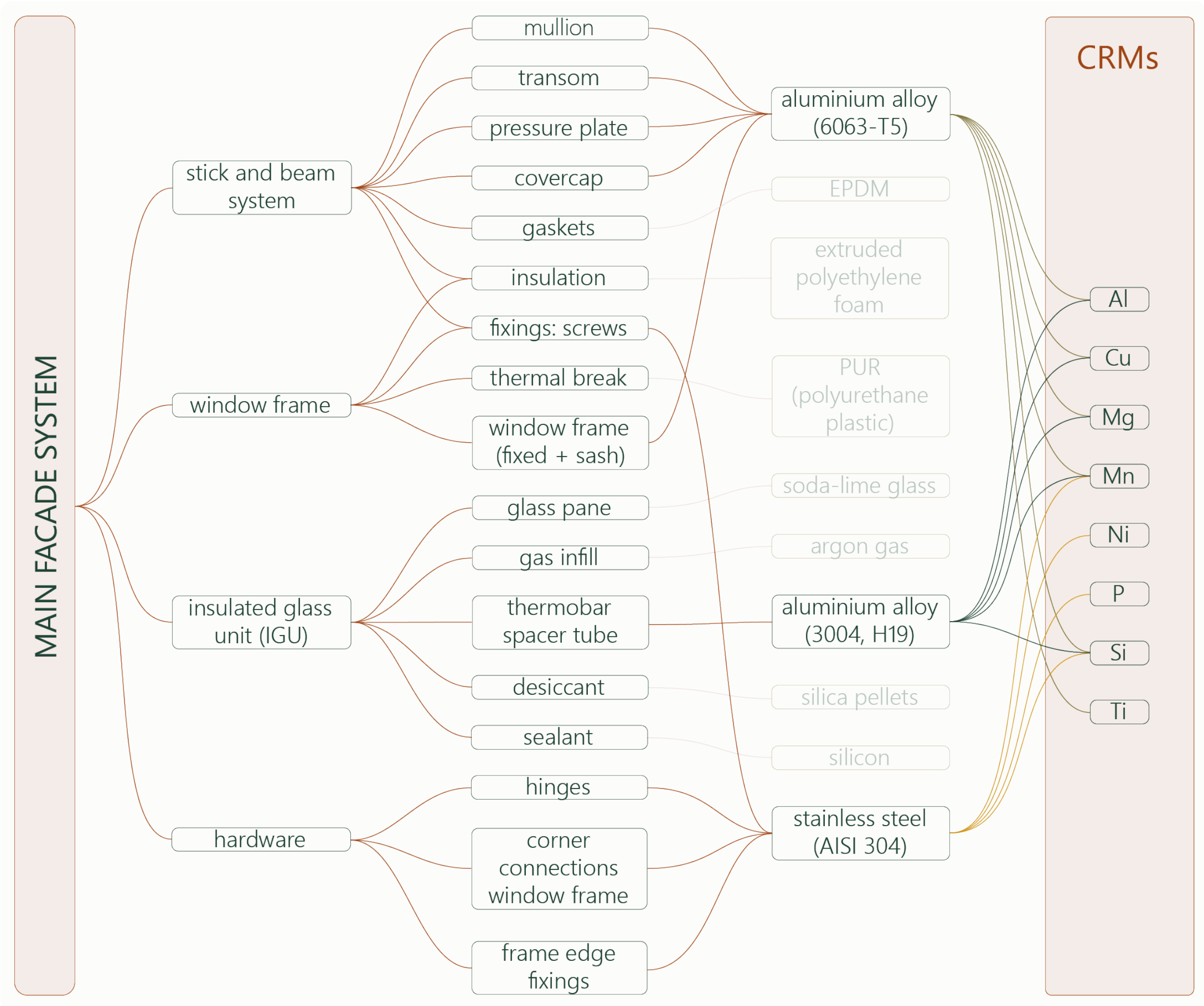


Figure 3.2: Alloys in the aluminium curtain wall façade analysis

ALLOYS AND COMPONENTS Figure 3.2 shows the different components and sub-components of the system and the CRMs part of their material composition. First, the façade system was split into its main components, namely stick and beam system, window frame, IGU, and hardware components. These were then further divided into sub-components before their material composition was linked to the critical materials.

The different alloys were then used for the following parts:

- Aluminium alloy 6063: mullions, transoms, pressure plates, cover caps, window frame (window handle was excluded from the calculation)
- Aluminium alloy 3004: thermobar spacer tube in the IGU
- Stainless Steel AISI 304: fixings (screws), hinges, corner connections in the window frame

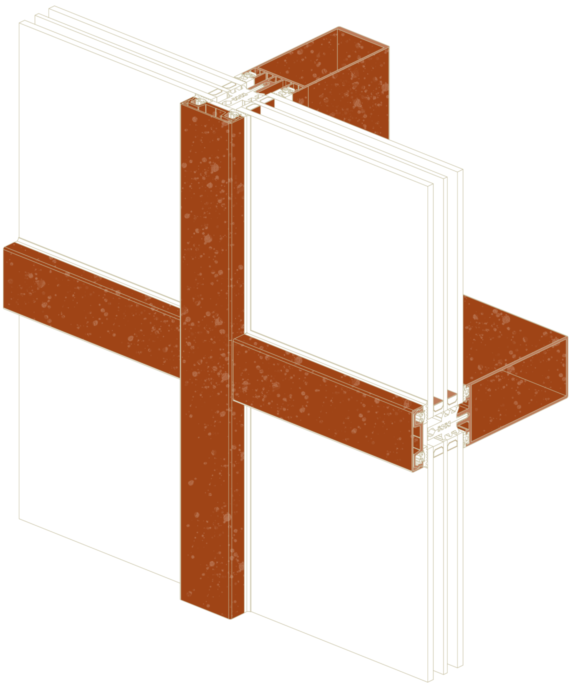


Figure 3.3: Fully glazed system (own image)

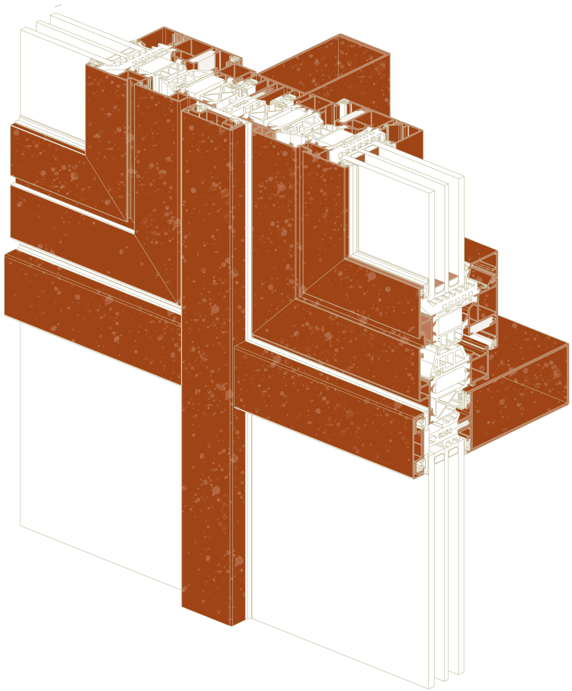


Figure 3.4: Element with openable window (own image)

PARTS WITH HIGH PERCENTAGE OF CRITICALITY Figures 3.3 and 3.4 show a first visualisation of the assessment of criticality per component in a 3D-section of S1 and S2. This does not show much, as the components visible in the image had either a very high percentage of critical materials or none at all.

MATERIAL COMPOSITION OF ALLOYS Figure 3.5 then visualises the material composition within the alloys.

The first column (blue) shows the proportion of the main material to the alloying elements. For the first two alloys, the main material - aluminium - is also listed as critical, which automatically gives the overall material a high level of criticality. The iron in the stainless steel alloys is not, which reduces the possible criticality level. The blue pie charts also show a difference in the ratio of main materials to alloying elements; as for the aluminium alloys, only 1.55% and 3.1% are added as alloying elements, while the stainless steel consists of 30.1% alloying elements.

The middle column (red) then visualises the ratio of CRMs compared to non-CRMs within the alloying elements. This again shows a difference between the aluminium alloys and the stainless steel alloy, as the aluminium alloys have higher percentages of critical alloying elements.

The left column (yellow) shows the split between the different CRMs within the alloying elements. For the stainless steel alloy, the main (critical) alloying element is nickel, which is on the CRMs list as a SRM. The main critical alloying elements within the different analysed alloys are magnesium, manganese, silicon, and copper (also SRM).

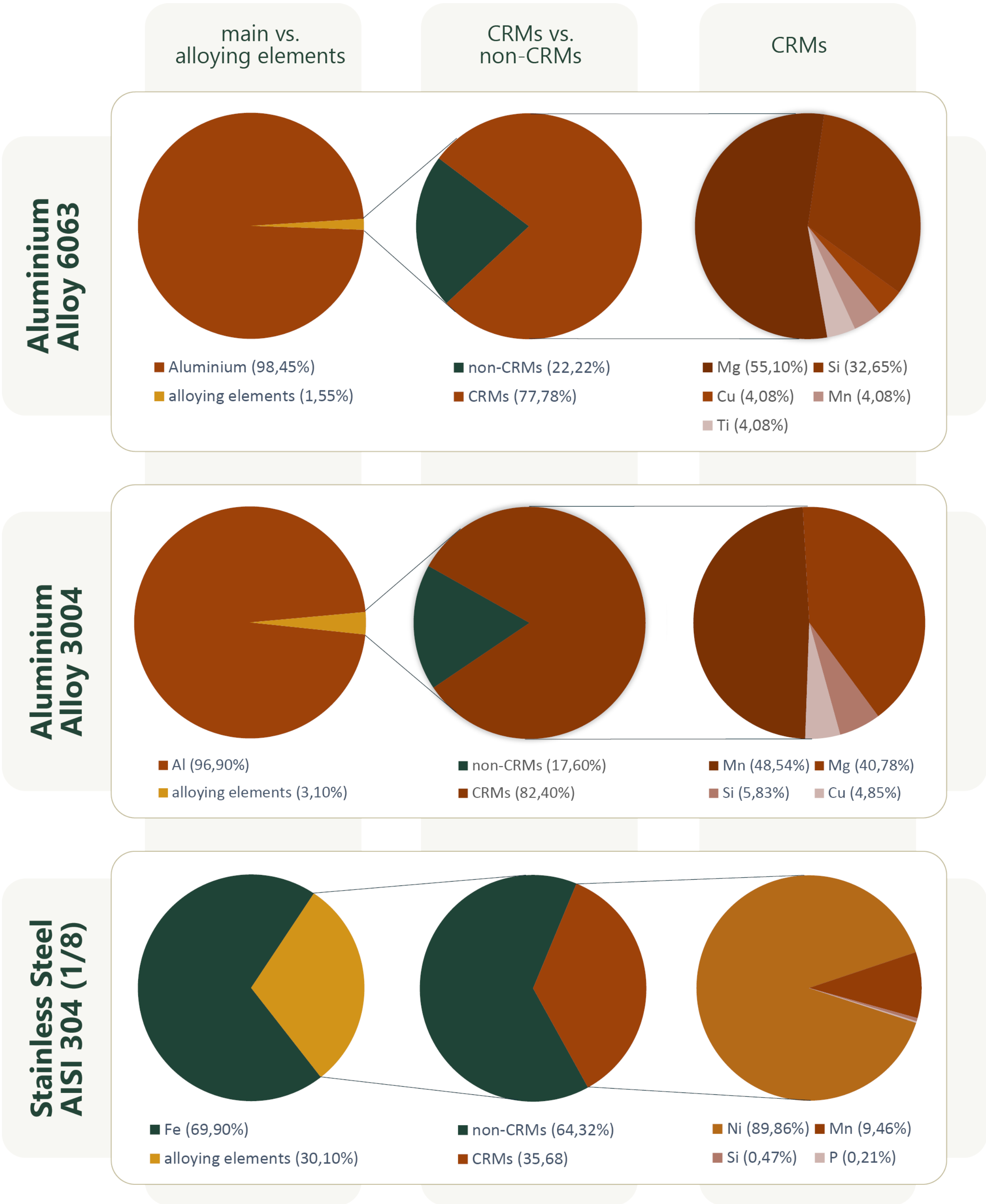
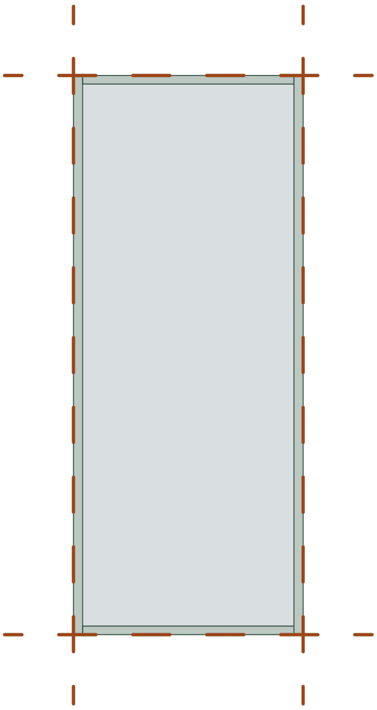


Figure 3.5: Material composition within the different alloys

S1.a: fixed glazing



fully fixed glazing

element size:	3.81	m^2
glazing area:	3.4	m^2
volume total:	0.07	m^3
weight total:	163.85	kg
weight glass:	129.25	kg
weight CRMs:	28.48	kg

CRMs:	**kg**	**total %**
Al (aluminium):	27.92	17.04
Mg (magnesium):	0.19	0.12
Mn (manganese):	0.04	0.02
P (phosphorus):	0.0005	0.0003
Si (silicon metal):	0.11	0.07
Ti (titanium metal):	0.01	0.006
Cu (copper):	0.01	0.006
Ni (nickel):	0.21	0.13
CRMs total:	**28.48**	**17,4%**

Figure 3.6: % of CRMs in the analysed S1

The first system analysed was the one with fixed glazing. Figure 3.6 shows a resulting criticality assessment of 17,4% of the total element weight. 28.48kg of the total 163.85kg are made up of critical materials, with 27.92kg of these being aluminium. The main material by weight is glass with 129.25kg. Figure 3.7 shows the material composition of the overall element.

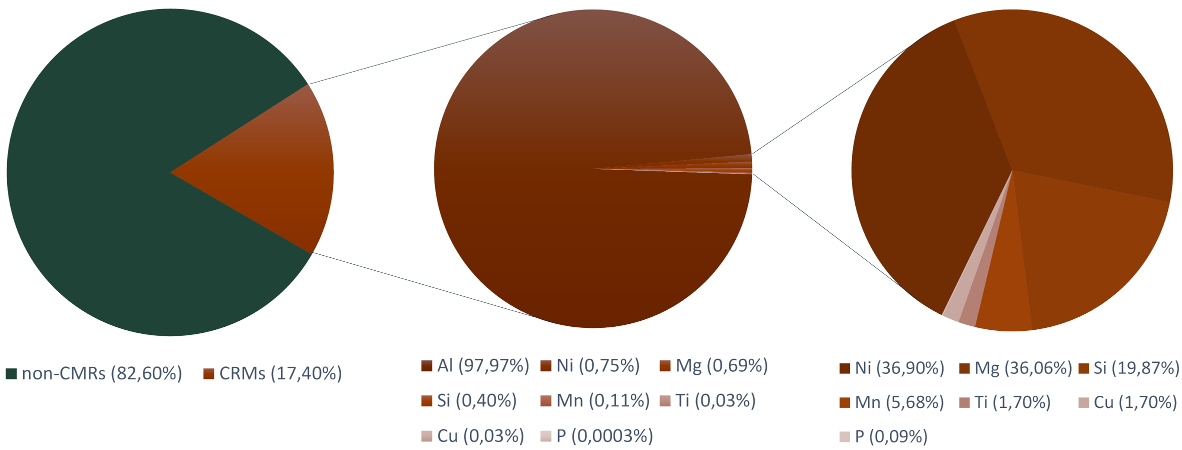
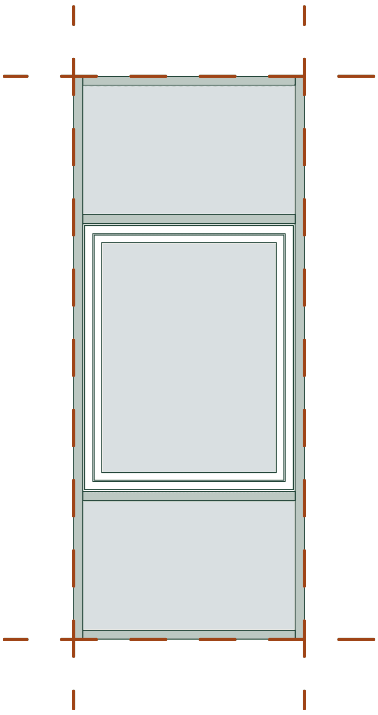


Figure 3.7: %: non-CRMs vs. CRMs | Al vs. alloying elements | alloying CRMs

S2.a: element with openable window



+ openable window

element size:	3.81	m^2
glazing area:	2.8	m^2
volume total:	0.09	m^2
weight total:	181.06	kg
weight glass:	109.05	kg
weight CRMs:	50.60	kg

CRMs:	**kg**	**%**
Al (aluminium):	48.84	26.97
Mg (magnesium):	0.34	0.19
Mn (manganese):	0.14	0.08
P (phosphorus):	0.0024	0.0013
Si (silicon metal):	0.20	0.11
Ti (titanium metal):	0.02	0.01
Cu (copper):	0.03	0.017
Ni (nickel):	1.02	0.56
CRMs total:	**50.60**	**27.95%**

Figure 3.8: % of CRMs in the analysed S2

The system with the additional openable window resulted in a criticality assessment of 28.32% related to the total weight, as Figure 3.8 shows. The higher percentage compared to the S1 is due to the addition of aluminium components of the window element two extra transoms, as well as the minimised glass area and thus volume. The material composition (see Figure 3.9) then shows a slightly higher percentage of critical materials in the overall element,

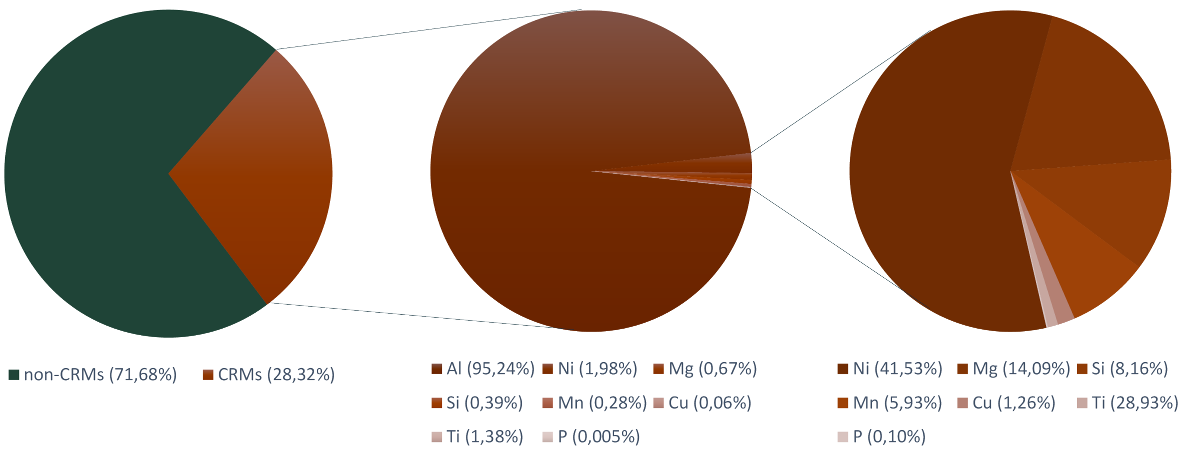


Figure 3.9: %: non-CRMs vs. CRMs | Al vs. alloying elements | alloying CRMs

3.1.2 Façade scale-up

S1.b: element with openable window | inner edge

To allow for a quantification of the element, which can then lead to an estimation of kg/m² for different size facades, only half of the outer mullions and transoms were included in the following calculation. Figure 3.10 shows a smaller element size while the glazing area stays the same, and Figure 3.11 shows the diminished ratio of CRMs compared to the first calculation. This significantly reduces the amount CRMs, as only components with CRMs contents are reduced, and leads to a CRMs content of 9.8%. Dividing the resulting 14.7kg of CRMs by the element size (3.6m²) give a value of 4.08kg(CRMs)/m².

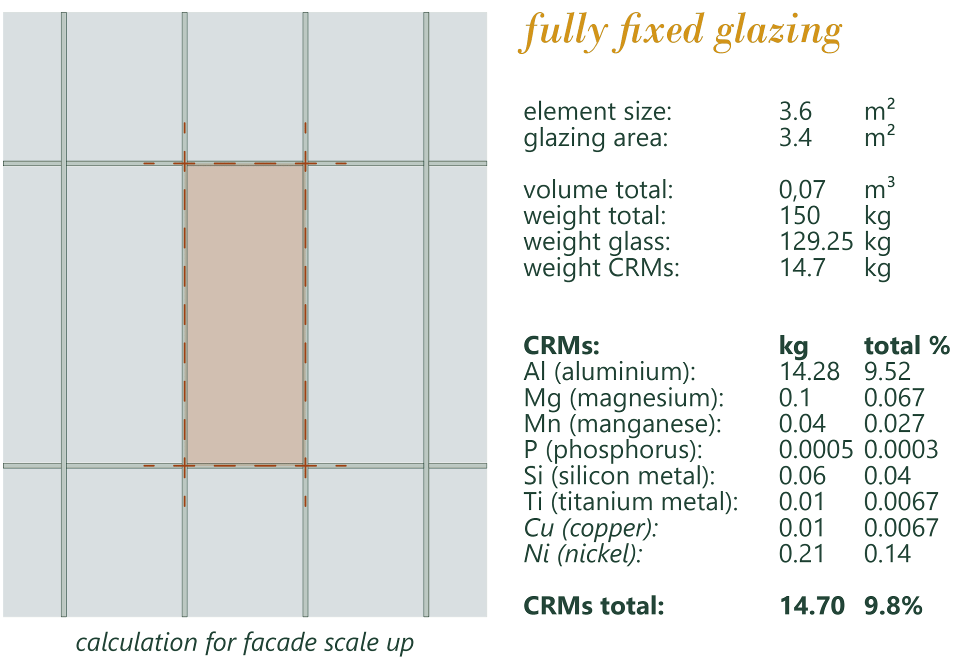


Figure 3.10: % of CRMs in the analysed S1 with adjusted edges to quantify

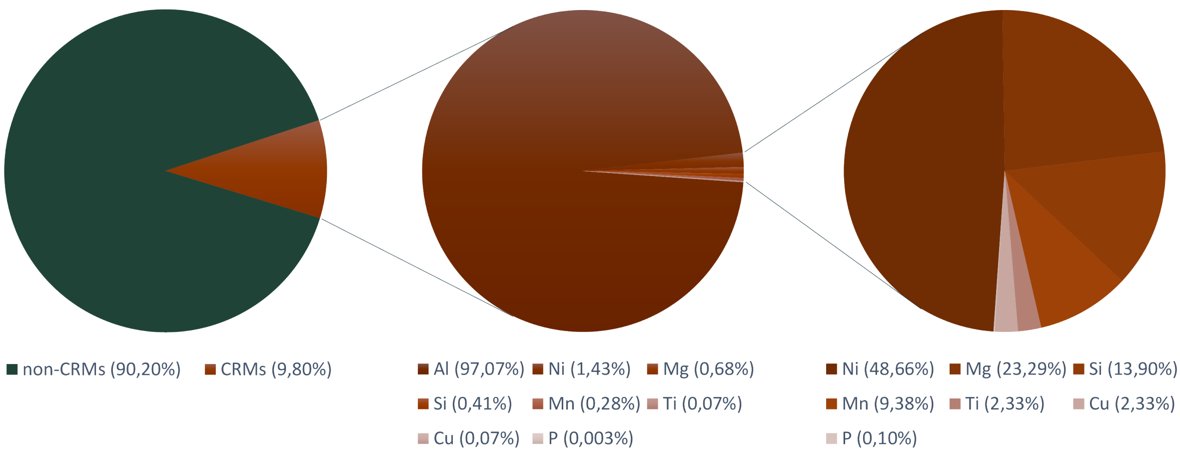
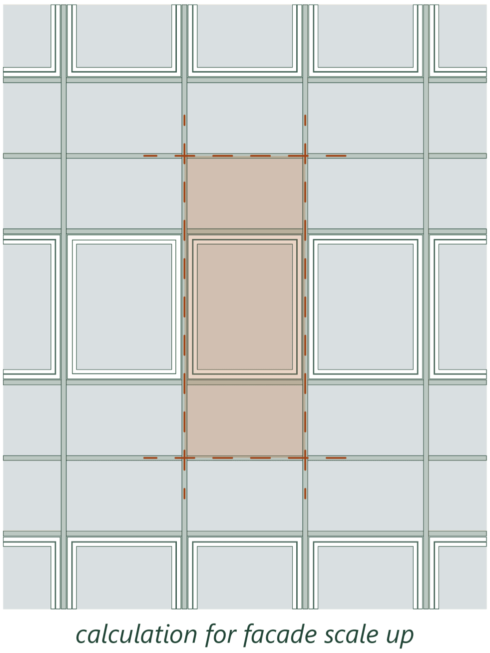


Figure 3.11: %: non-CRMs vs. CRMs | Al vs. alloying elements | CRMs (*although Ni is only SRM, not CRM*)

S2.b: element with openable window | inner edge

The same adjustment (moving the edge for the calculation) was made from S2.a to S2.b. The result is a criticality assessment of 22%, which leads to roughly 10.2kg/m² (36.79kg/3.6m²).



+ openable window

element size:	3.6	m^2
glazing area:	2.8	m^2
volume total:	0,08	m^3
weight total:	167.21	kg
weight glass:	109.05	kg
weight CRMs:	36.79	kg

CRMs:	**kg**	**total %**
Al (aluminium):	35.2	21.05
Mg (magnesium):	0.25	0.15
Mn (manganese):	0.14	0.08
P (phosphorus):	0.0024	0.0014
Si (silicon metal):	0.15	0.09
Ti (titanium metal):	0.02	0.01
Cu (copper):	0.02	0.01
Ni (nickel):	1.02	0.61
CRMs total:	**36.79**	**22%**

Figure 3.12: % of CRMs in the analysed S2 with adjusted edges to quantify

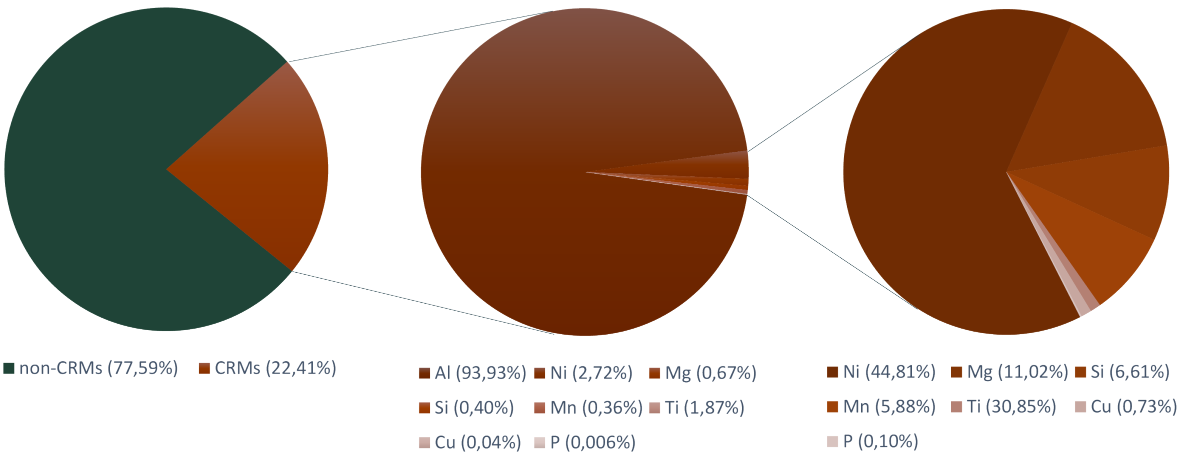
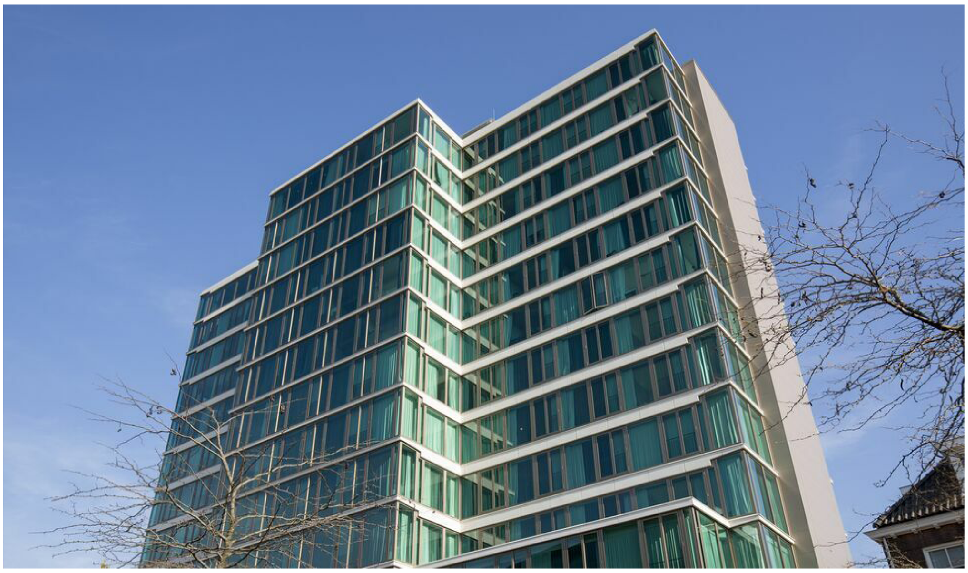


Figure 3.13: %: non-CRMs vs. CRMs | Al vs. alloying elements | CRMs (*although Ni is only SRM, not CRM*)

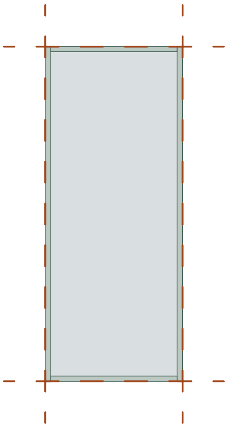
Figure 3.14 shows an example scale-up of system 1a. If the *Groene Toren* in Eindhoven was built with this system, it would contain 38.136,9kg of critical materials on a facade area of 5.100m². The same scale-up was done for *De Rotterdam* in Rotterdam with system 1b in Figure 3.15, which would then result in 183.881,25kg of critical materials on 45.000m².

example scale-up

GROENE TOREN,
EINDHOVEN



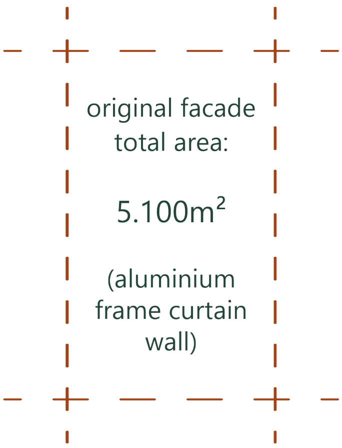
if built with: *S1.a*



	kg/el*	kg/m²
Al	27,92	7,33
Mg	0,19	0,05
Mn	0,04	0,01
P	0,0005	0,00
Si	0,11	0,03
Ti	0,01	0,00
Cu	0,01	0,00
Ni	0,21	0,06
	28,49	7,48

el*=element (3.81m²)

scale up



Al	37373,2 kg
Mg	254,33 kg
Mn	53,54 kg
P	0,67 kg
Si	147,24 kg
Ti	13,39 kg
Cu	13,39 kg
Ni	281,10 kg

total CRMs: **38.136,9 kg**

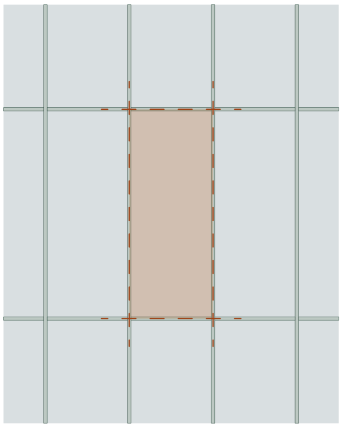
photo, m²: https://www.reynaers.com/inspiration/aluminium-project-references/sliding-folding-doors-groene-toren-eindhoven-eindhoven

Figure 3.14: ASSUMPTION: S1a scale-up for *Groene Toren, Eindhoven*

example scale-up

DE ROTTERDAM,
ROTTERDAM

if built with: S1.b



	kg/el*	kg/m²
Al	14,28	3,97
Mg	0,1	0,03
Mn	0,04	0,01
P	0,0005	0,00
Si	0,06	0,02
Ti	0,01	0,00
Cu	0,01	0,00
Ni	0,21	0,06
	14,71	4,09

el*=element (3.6m²)

scale up

original facade total area:

45.000m²

(mix of different facade types)

Al	178500	kg
Mg	1250	kg
Mn	500	kg
P	6,25	kg
Si	750	kg
Ti	125	kg
Cu	125	kg
Ni	2625	kg

total CRMs: **183.881,25 kg**

m²: https://www.permasteelisagroup.com/project-detail?project=1895, photo: https://www.cityrotterdam.com/attractions/architectuur-rotterdam/de-rotterdam-gebouw/

Figure 3.15: ASSUMPTION: S1b scale-up for *De Rotterdam, Rotterdam*

3.1.3 S3 & S4: Motors and sensors

Within the available information, it was impossible to quantify the amount or volume of CRMs added by implementing motors or sensors to the facade system. The results can, therefore, only give an overview of the different materials that are part of typical motor and sensor applications.

Material	Elements	%	Density kg/m³
Neodymium iron boron (NdFeB) magnets (used for e.g. brushless DC motors, sensors, switches,...) e.g.: neodymium magnet N42	B (boron)	1	7400-7500 kg/m³
	Co (cobalt)	0,25-2,5	
	Dy (dysprosium)	0-0,25	
	Fe (iron)	65,5-69	
	Nd (neodymium)	30,5	
	Tb (terbium)	0,25	

Figure 3.16: NdFeB magnet: material composition (numbers from Granta Edupack)

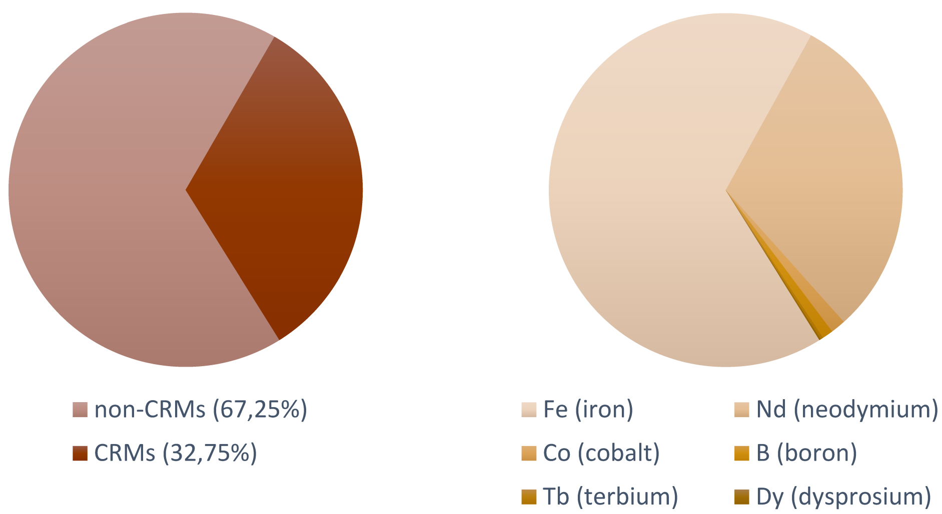


Figure 3.17: %: non-CRMs vs. CRMs | material composition

MAGNET IN MOTOR Figure 3.16 gives an example of the material composition of a neodymium-iron-boron magnet. Only the main element iron, with 65.5-69%, is not on the list of critical materials. This leaves a criticality rate of up to 34.5% for the other material composition elements. Figure 3.17 then visualises first the range of critical vs. non-critical materials and also the division within the different materials, with neodymium with the second biggest share (30.5%).

Figure 3.18: CO2 & Temperature & Humidity Sensor (Kiwi electronics)

SENSORS There are many different types of sensors, and therefore there is also a wide range of different materials that can be part of the sensor composition. Figure 3.18 shows the size of a CO2, temperature, and humidity sensor by Kiwi electronics.

Figure 3.19 gives an overview of different semiconducting gas sensing materials, which can be part of, e.g. CO2 measuring sensors. [Nikolic et al., 2020] The materials can be divided into carbon nanotubes, metal oxides, conducting polymers, or 2D materials. Cross-checking the various metal oxides mentioned by Nikolic et al. [2020] (SnO_2, ZnO, (Nb-doped) TiO_2, WO_3, CuO, NiO, Cr_2O_3, Co_3O_4, Sr-doped Fe_2O_3, or Sm-doped $CoFe_2O_4$), gives a list of CRMs that might be part of a sensor:

- Cu (copper)
- Co (cobalt)
- Nb (niobium)
- Sm (samarium)
- Sr (strontium)
- Ti (titanium)
- W (tungsten)

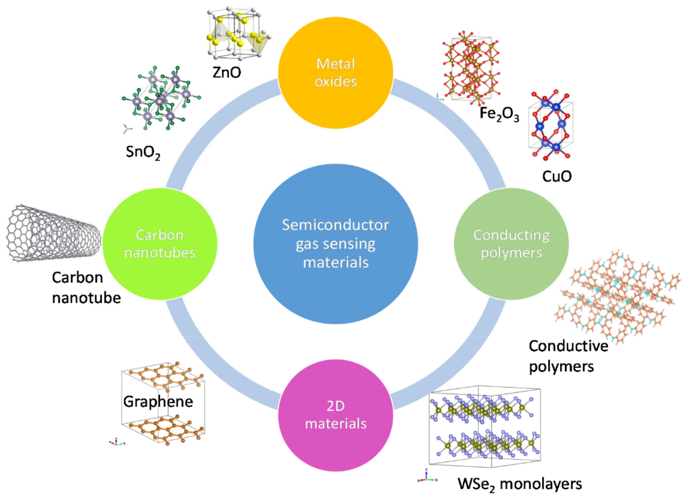


Figure 3.19: Semi conducting gas sensing materials [Nikolic et al., 2020]

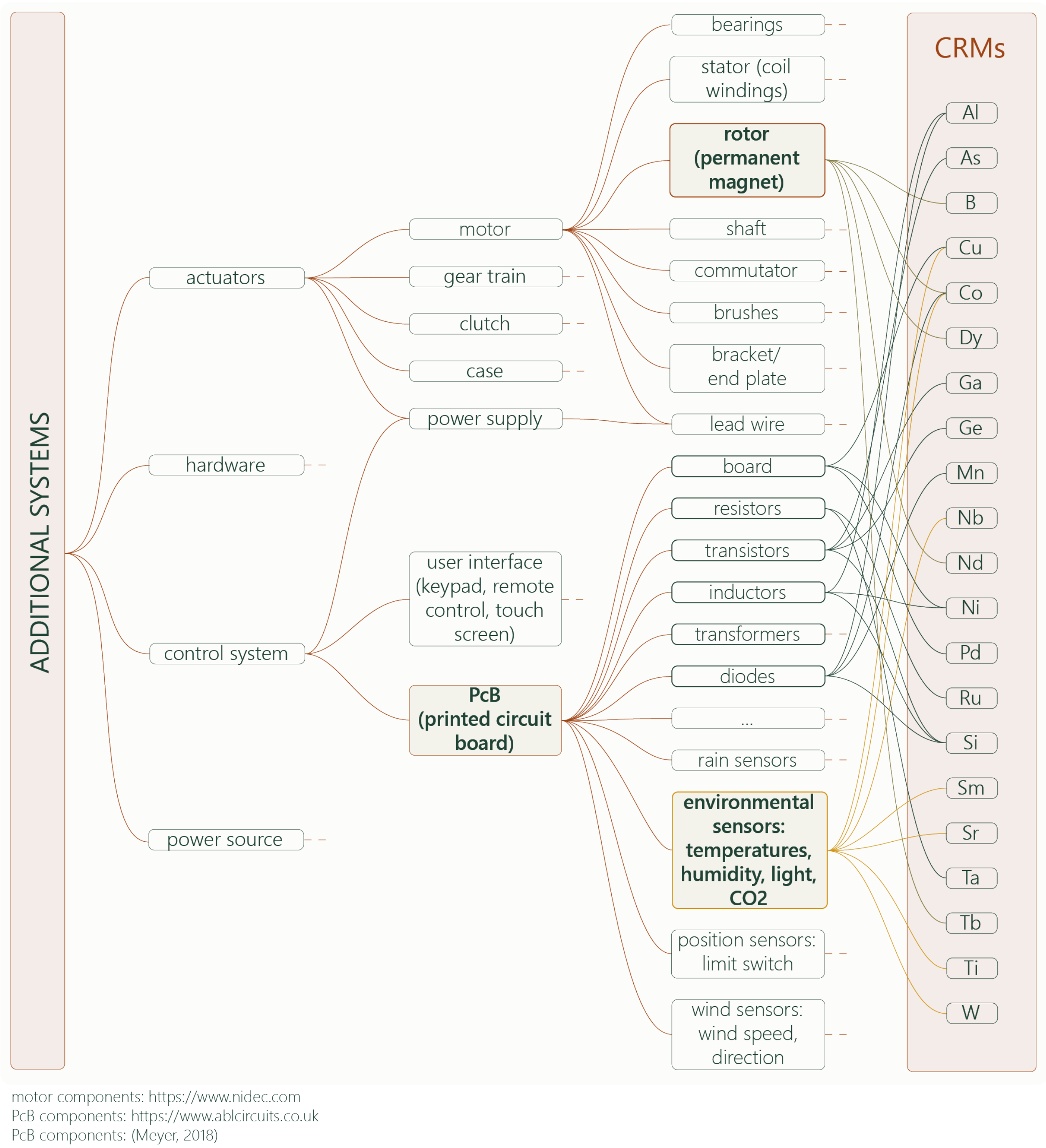


Figure 3.20: Motors and sensor parts in the curtain wall analysis

As seen before in Figure 3.2 related to components and material composition of the general mullion transom system, Figure 3.20 now shows an overview of components and sub-components within motors and sensors. First, a split can be made into at least four parts; actuation, control system, power source, and hardware elements. Each of these can then be further divided into multiple sub-components. However, with limited information, the focus is on permanent magnets as parts of motors, printed circuit board (PcB)s, and sensors. Alone from these four systems, 21 different critical materials can be listed.

3.1.4 Comparison of the different systems

In Figure 3.21, we see how the number of different critical materials increases by adding first motors and then sensors to a generic aluminium curtain wall system. According to the analysis, a system without motors and sensors contains around eight materials which are defined as critical; aluminium/bauxite, magnesium, manganese, phosphorus, silicon metal, titanium metal, copper (SRM), and nickel (SRM). By adding motors to the system - e.g. in folding arm actuators, chain actuators, or linear actuators - the permanent magnet alone (depending on its exact composition) can already add five new critical materials, namely boron, cobalt, dysprosium (HREE), neodymium (LREE), and terbium (HREE). And finally, an additional environmental sensor, e.g. a CO2 sensor, in combination with a PcB adds ten more critical materials: arsenic, gallium, germanium, niobium, ruthenium (PGM), samarium (LREE), strontium, tantalum, tungsten, and palladium (PGM).

In total, around 23 CRMs are included in smart, motor- and sensor-controlled façade systems.

CRMs in the façade

	alloys	motors	sensors
aluminium/bauxite	●		●
antimony			
arsenic			●
baryte			
beryllium			
bismuth			
boron/borate		●	●
cobalt		●	●
coking coal			
feldspar			
fluorspar			
gallium			●
germanium			●
hafnium			
helium			
HREE		●	
lithium			
LREE		●	●
magnesium	●		●
manganese	●		
natural graphite			
niobium			●
PGM			●
phosphate rock			
phosphorus	●		
scandium			
silicon metal	●		●
strontium			●
tantalum			●
titanium metal	●		●
tungsten			●
vanadium			
copper (SRM)	●	●	
nickel (SRM)	●		●

For motors only the material composition of permanent magnets were considered so far.

Figure 3.21: Critical materials in alloys, motors and sensors

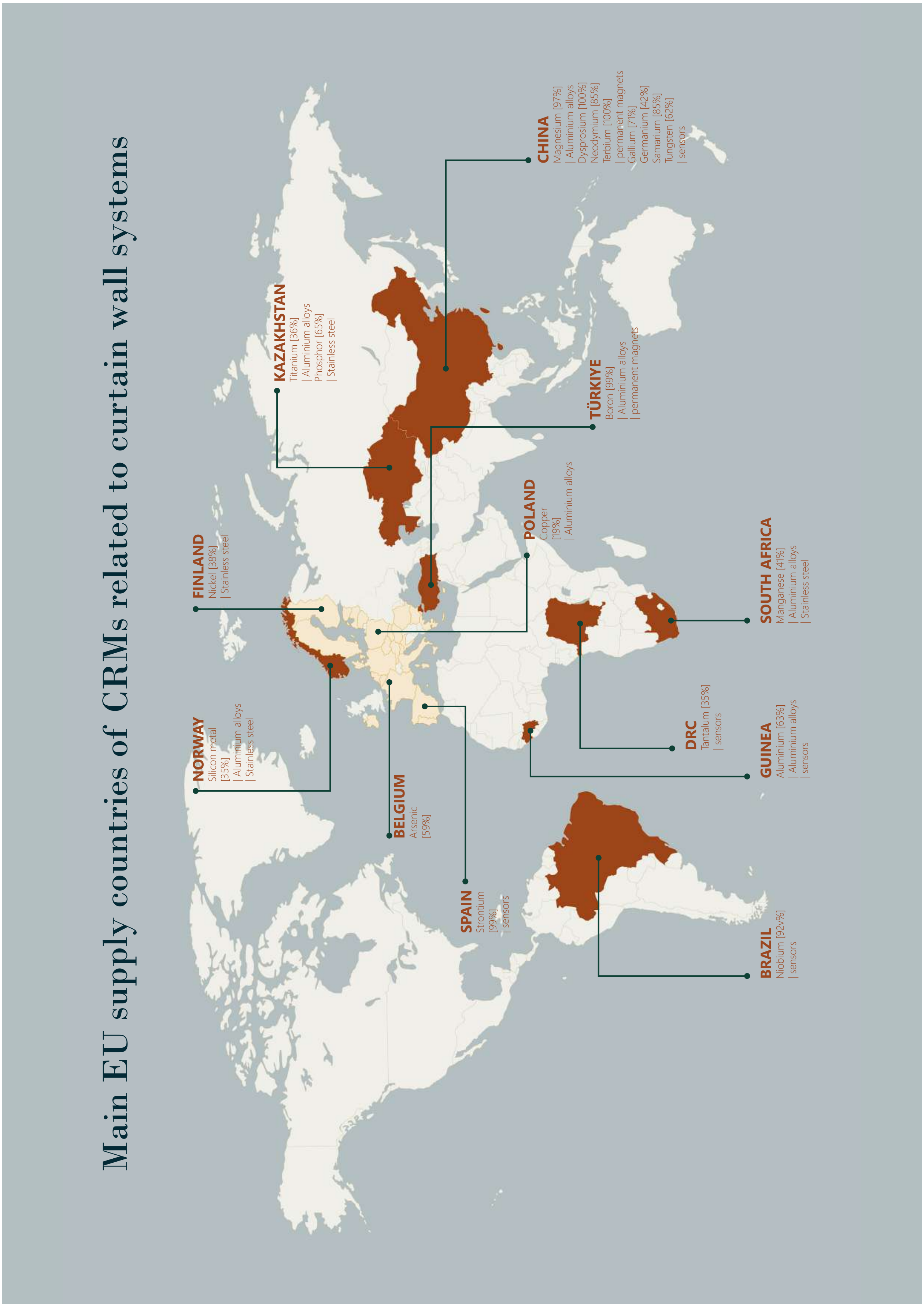


Figure 3.22: Main EU supply countries of CRMs related to aluminium curtain wall systems

GEOGRAPHICAL DISTRIBUTION The world map in Figure 3.22 shows the geographical distribution of the main EU supply countries of the different materials mentioned before as contained in aluminium curtain wall façades. The percentages stand for the EU import of the respective materials from the different countries and were taken from the *Study on Critical Raw Materials for the EU* from European Commission [2023d].

Of the countries listed, three are within the EU (Finland, Belgium, Spain), two more in the rest of Europe (Norway, Poland), and seven more countries supply materials from outside of Europe (China, Kazakhstan, Türkiye, South Africa, DRC, Guinea, Brazil). While most countries are suppliers of one or two critical materials to different percentages, China stands out both regarding the number of critical materials it supplies and the high percentage of EU imports.

China is an EU supplier of eight different materials, with mostly very high EU import percentages: magnesium (97%), dysprosium (100%), neodymium (85%), terbium (100%), gallium (71%), germanium (42%), samarium (85%), and tungsten (62%). Other very high import rates per country are boron (99%) from Türkiye, niobium (92%) from Brazil, or phosphor (65%) from Kazakhstan.

3.2 Chapter conclusion

The results in this chapter showed the amount or CRMs in the defined aluminium curtain wall panel. For the chosen aluminium alloys, the criticality was assessed to be at 99.68% and 99.48%, while the stainless steel alloy was assessed to be around 10.57%. It was found to be impossible to adequately quantify critical materials used within sensors and motors, therefore only an overview of possibly included materials could be given. The analysis showed, that in the main element, CRMs were included in big components made from a few different material compositions.

For versions S1.a, S2.a, S2.b, and S2.b of the aluminium curtain wall elements, the criticality assessment resulted in 17.4%, 27.95%, 9.8%, and 22% respectively.

A façade area of 5.100m² built with S1.a would then result in 38.137kg of critical material content (Fig.3.14), and an area of 45.000m² built with S1.b would result in a total of 183.881,25kg of critical materials (Fig.3.15).

In the case of sensors and motors, the lack of information on their (small) components and sub-components made it impossible to perform a quantity assessment. However, the final assessment (see Figure 3.1) shows how the number of different critical materials increases from alloys applications (five different CRMs) to applications with motors (13 different CRMs), to applications with sensors (23 different CRMs).

System	number of CRMs
S1: Alloys	5
S2: Alloys	5
S3: Alloys, magnets in motors	13
S4: Alloys, magnets in motors, sensors	23

Table 3.1: Number of CRMs in the different systems

The following chapter will look at material policies related to the built environment, and whether an awareness of CRMs concerns is represented there.

4 Material policies and the Built Environment

> **Sustainable development is development that meets the needs of today without compromising the ability of future generations to meet their own needs.** [UN, 1987, p.37]

It is quite self-evident that a construction, like a building, must follow certain rules, like structural requirements. In other regards, it can be a lot more difficult to justify or demonstrate the need for policy intervention. This especially applies to the broad public which does not necessarily study certain complex or interwoven topics, like resource consumption within buildings and their wider effects, on a regular basis.
As a consequence, if the public does not support the implementation of new policies or regulations, it can be quite tough for policymakers as well as politicians to take action. According to [Patel, 2020, p.20], "both sense and sensibility play a role in policymaking, as emotions enable politicians to sense citizens' concerns, fears, hopes or suffering. Emotions can help mobilise action, but they can also override reason."

COMPLEXITY Policymaking always takes place within a specific context and therefore must be seen as a dynamic process. In a sense, policy-making is a reflection of specific social and economic developments and in addition to that also demonstrates the role of government within a society. Influencing factors can be related to social, economic, or political fields. [Weimer and Vining, 2017] Patel [2020] adds environmental constraints to the shaping process of policymaking.

> **[...] emotions enable politicians to sense citizens' concerns, fears, hopes or suffering. Emotions can help mobilise action, but they can also override reason.** [Patel, 2020, p.20]

ROLE OF POLICYMAKING With a growing number of challenges that we are facing as a society, policy becomes more and more complex. Everything that brings considerable change to our society or economy will sooner or later need to be addressed through policy, in order to ensure a fair and level playing field for all, but also to prevent unsustainable practices. In recent years, one of the overarching topics is the climate crisis and its associated challenges, and as such it has led (and will continue to lead to) the development of more policy frameworks.

CONSTRAINTS What can cause risk to the achievement of different goals is uncertainty, which is, for example, a problem with undefined stringency around climate policies. The International Energy Agency (IEA) therefore also highlights the importance of policy-makers in regard to the Paris Agreement; in order for it to be successful, policymakers not only need to clarify the ambitions but also have to transform the targets into concrete actions, in order to ensure for example reduced investment risks as well as capital flows to new projects. [IEA, 2022]

1962 Rachel Carson, *Silent Spring*	Meticulous examination of the consequences of the use of the pesticide DDT and of the impact of technology on the environment
1972 Club of Rome, "Limits to Growth"	The report that triggered the first of a sequence of debates in the 20th century on the ultimate limits imposed by resource depletion
1972 The Earth Summit in Stockholm	The first conference convened by the United Nations to discuss the impact of technology on the environment

Figure 4.1: Landmark publications [1] [Ashby, 2021, p.89]

MATERIAL POLICIES In his book *Materials and the Environment*, Ashby [2021] lists the most far-reaching publications related to material restrictions and sustainability, see Figures 4.1 and 4.2. For example, in 1972, the Club of Rome first initiated the discussion in regard to resource limitations. The Brundtland Report then defined sustainability as: "Sustainable development is development that meets the needs of today without compromising the ability of future generations to meet their own needs." [UN, 1987, p.37]

Building upon the publications in Figure 4.1, Figure 4.2 lists further policies. These protocols and conventions were formulated to restrict the use of chemicals or pollutants, or reduce gas emissions, up until the 2015 Paris Agreement, which defined the need to keep global average temperature rise below 2°C compared to preindustrial levels. [Ashby, 2021]

This chapter will now look at policy making - in the context of the EU - as a tool towards fair and sustainable development and to what extent the BE and especially building products are addressed by different policies.

1987 The UN World Commission on Environment and Development, "Our common future"	Known as the Brundtland Report, it defined the principle of sustainability as "Development that meets the needs of today without compromising the ability of future generations to meet their own needs"
1987 Montreal Protocol	The International Protocol to phase out the use of chemicals that deplete ozone in the stratosphere
1992 Rio Declaration	An International statement of the principles of sustainability, building on those of the 1972 Stockholm Earth Summit
1998 Kyoto Protocol	An international treaty to reduce the emissions of gases that, through the greenhouse effect, cause climate change
2001 Stockholm Convention	The first of a series of meetings to agree on an agenda for the control and phase-out of persistent Organic Pollutants
2007 IPCC 4th Assessment Report, "Climate change 2007—the physical basis"	This Report of the Intergovernmental Panel on Climate Change establishes beyond any reasonable doubt the correlation between carbon in the atmosphere and climate change
2015 The Paris Agreement	The Paris Agreement, adopted by 195 nations, resolved to hold the global average temperature to below 2°C above preindustrial levels
2018 The Incheon Report	The Paris Agreement included a commitment to further reports. This, the first, urged a downward revision of the threshold from 2°C to 1.5°C, recognizing that this would require "rapid, far-reaching and unprecedented changes in all aspects of society"

Figure 4.2: Landmark publications [2] [Ashby, 2021, p.89]

4.1 Policy making as a tool

Policymaking is a very complex procedure. Depending on the desired result, different strategies and policy instruments can be applied. Many different groups of people can be included in the process: civil servants and politicians, technocrats from different fields (e.g. law, policy, trade, procedure), and stakeholders from different sectors. The more urgent a topic is considered to be (e.g. in terms of otherwise negative impacts on society or the environment) the more strict the chosen strategy will probably be. [Sterner, 2003] The same applies to the scale of the intervention, which can form local, regional, and national, up to supra-national or global cooperations. Examples of the different scales are; municipal, provincial, national/government, EU, and the UN. Bigger unions following the same guidelines and working towards the same goal will probably allow for bigger achievements. It is important to know when to use which combination of policy instruments, which can be understood as "a set of techniques by which governmental authorities wield their power in attempting to ensure support and affect or prevent social change." [Vedung, 1998, p.21] This section now gives a short overview of different policy instruments in general as well as related to a sustainable built environment.

4.1.1 Typologies of policy instruments

There are different classification methods for policy instruments. This section briefly presents two different approaches. The first one (see Fig. 4.3) separates different policy instruments into three groups: regulatory instruments, economic instruments, and informative instruments [Vedung, 1998]. The second one (see Fig. 4.4), which was developed specifically in regard to a sustainable built environment by Kibert [2002], separates them into five groups: Regulatory instruments, economic instruments, information tools, voluntary tools, and research and development.

Carrots, sticks, and sermons

The classification developed by Vedung [1998] is the most commonly used one today [Bucci Ancapi et al., 2022]. The three groups can also be referred to as carrots (economic instruments, e.g. giving or taking away money), sticks (regulatory instruments, e.g. binding regulations), and sermons (informative instruments), and thanks to this conceptualisation the assignment of instruments to the different groups can be quite easy to understand.

Figure 4.3: Sticks, carrots, and sermons

Policy instruments related to the Sustainable Built Environment

The classification from Kibert [2002] adds two more groups: voluntary tools and research and development. Figure 4.4 gives a more detailed overview of the different instruments within the groups. Related to the BE, regulatory instruments listed are technology- or performance-based standards. For economic instruments, examples are charges or taxes (emission or product), permits or fees, as well as liability payments or environmental subsidies, which include financial assistance in all forms (grants, soft loans, tax breaks, accelerated depreciation). Information tools can include public information campaigns, technological information diffusion programs, as well as environmental labelling schemes. Unilateral commitments or declarations from enterprises, negotiated agreements between public organizations and business groups, and selective regulations form the group of voluntary tools, while research and development conclude the list. [Kibert, 2002] Different instruments can be combined to work towards a specific goal.

policy instruments	
Regulatory instruments	**Technology-based standards:** mandatory, describe approved technology for process or problem, greatly emphasize design and use of preventive methods **Performance-based standards:** mandatory, define problems to solve or goals to achieve, focus on outcome, avoid overt prescription
Economic instruments	**Emission charges and taxes:** direct payments based on quantity and quality of pollutant **Product charges and taxes:** payments applied to products that create pollution when manufactured, consumed or disposed **User charges:** cost of collective services (finance local authorities, e.g. collection and treatment of solid waste and sewage water) **Marketable (tradable, transferable) permits:** environmental quotas, permits, maximum rights allocated to economic agents **Deposit-refund systems:** payments made when purchasing a product (e.g. packaging), fully or partially reimbursed when returned **Non-compliance fees:** payments imposed under civil law on polluters who do not comply with environmental or natural resource management requirements and regulations, can be proportional **Performance bonds:** payment of a deposit ("bond"), defunded when compliance is achieved **Liability payments:** compensate for damage caused, can be made to "victims" or to the government **Environmental subsidies:** all forms of explicit financial assistance (e.g. grants, soft loans, tax breaks, accelerated depreciation), in general in contradiction with the polluter-pays principle
Information tools	**Public information campaign:** a campaign that aims to raise public awareness of environmental issues **Technological information diffusion programs:** provision of technological information for producers with the aim to change the behavior of firms **Environmental labeling schemes:** provision of information on the performance of products, certified by third parties or producers
Voluntary tools	**Unilateral commitment or declaration:** program created by enterprise and/or business without any public organization involved **Negotiated agreement or commitment:** program involving contractual arrangement between a public organization and an enterprise or business group **Selective regulation or public voluntary program:** program in which governments provide the framework for the policy, but leave participation up to the judgment of enterprises
Research + development	**Research and development tools:** support for research and development in private sector, direct commitment to R&D activities or establishment of a partnership with the private sector

Figure 4.4: Policy instruments in the built environment (Adapted from Kibert [2002])

4.1.2 Top-down and Bottom-up approach

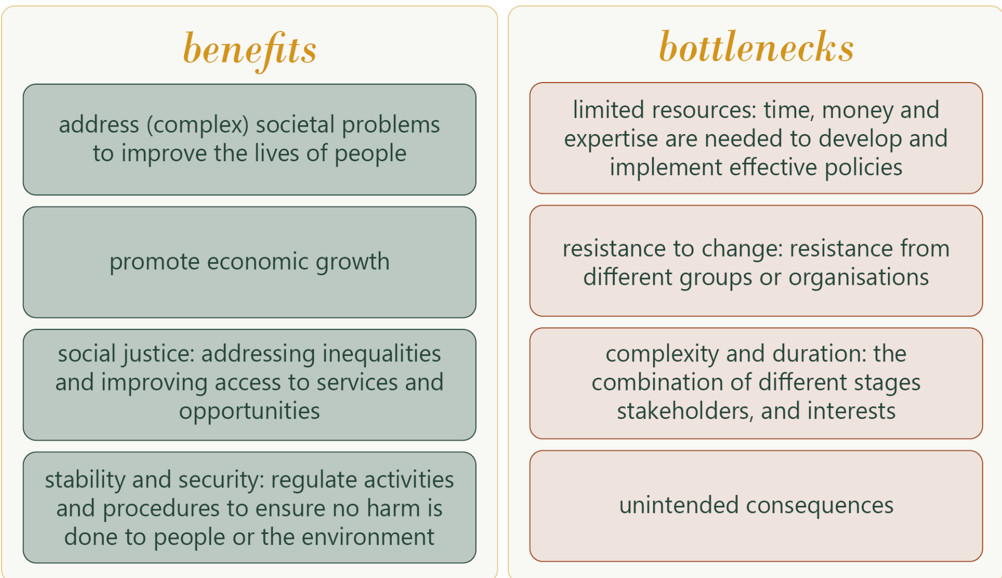
One topic that can often be found in discussions around policy implementation is the differentiation between top-down compared to bottom-up approaches. [Cerna, 2013] Top-down approaches try to have clear and generalisable policy structures, with the policy designer as the central decision-maker and the policies following consistent patterns. Bottom-up approaches on the other hand are considered less generic, as they are developed through e.g. networking techniques with central actors, in order to gain insight into their activities, strategies, or goals. This provides a type of flexibility that allows the strategy to react to contextual factors, but the strong focus on local autonomy has also been criticised. [Cerna, 2013]

It might depend on the type of intervention, whether a top-down or bottom-up approach is applied. In areas of little conflict combined with a disagreement about the right means of implementation, bottom-up approaches are more likely. When the goal is connected with high conflict but the measures of implementation are quite clear, top-down approaches are more common. This can for instance apply to educational disadvantages (= bottom-up) versus taxation issues (= top-down). [Cerna, 2013] The right choice of an implementation strategy towards the desired outcome is therefore always dependent on the specific topic and policy type.

4.1.3 Policy making: Benefits and Bottlenecks

A well-executed average policy can be better than a poorly executed well-crafted policy. [Patel, 2020, p.24]

Policymaking takes place in a field of trade-offs and tensions. When defining specific goals, certain aspects will be prioritised over others. Figure 4.5 lists some of the different benefits and bottlenecks mentioned in the literature. For example, while policies can address complex societal problems to improve the lives of people, or ensure stability and security for people and the environment, the resistance to change of different groups can just as well present as a bottleneck and there is always the risk for unintended consequences. [Patel, 2020][Kraft and Furlong, 2015][Fischer et al., 2007]



Sources: Patel (2020), Kraft and Furlong (2015), Fischer et al. (2007)

Figure 4.5: Different benefits and bottlenecks related to policymaking [Patel, 2020][Kraft and Furlong, 2015][Fischer et al., 2007]

4.2 Regulations in the EU which impact the built environment and/or circularity

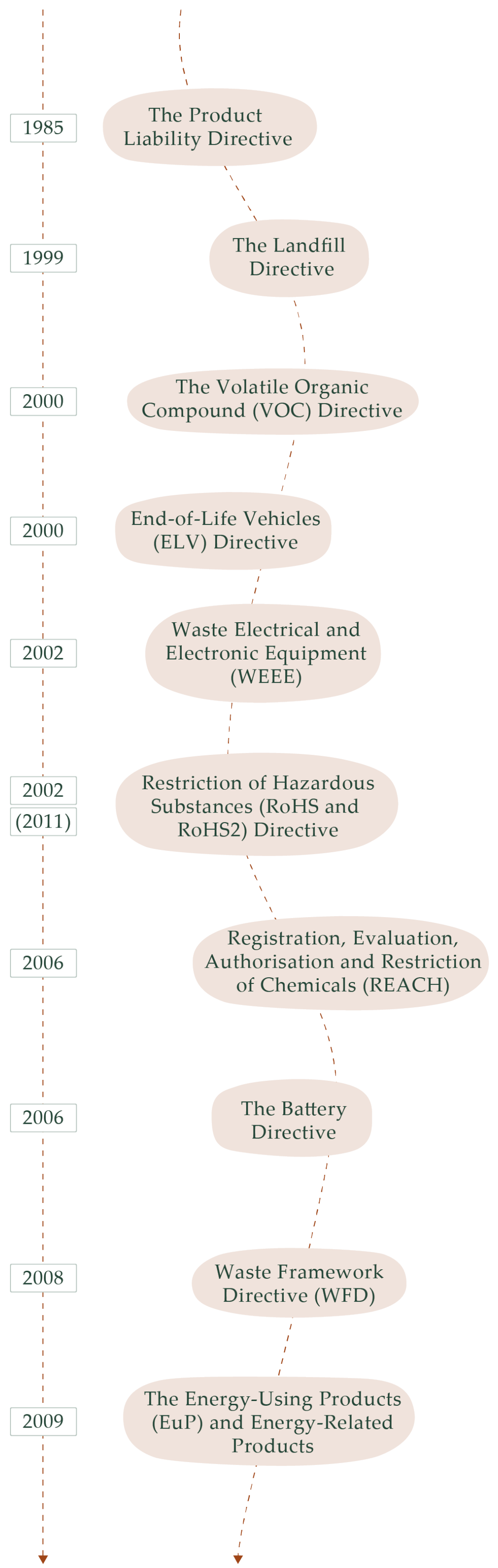


Figure 4.6: Directives on the restriction of material use [Ashby, 2021]

As mentioned before, policies can be implemented on different scales. Looking at policies related to sustainable development in general, and starting from the global scale, we have the UN SDGs, which have already been mentioned at the beginning of this thesis. In Europe, there is the European Green Deal, but in regard to circularity also the EU circular economy action plan and with it also the Horizon Europe project.

4.2.1 Directives concerning material restrictions

Figure 4.6 shows some of the many EU directives about the restriction of certain materials over the last decades. These directives aimed for harmonization through the Member States, by being turned into Member State law. These directives impact the choice of materials, not components. So from the view of the BE, these directives influence the contents of building components to a certain level, but there are no policies covering the scale of building components or products specifically, for example in terms of overall material consumption, manufacturing processes or circular potentials. Listed examples are *The Product Liability Directive (1985)* which introduces liability responsibility related to defective products when damage is caused, *Restriction of Hazardous Substances (RoHS)(2002)* define a ban on equipment which contains higher than allowed levels of different materials, like lead, cadmium, or mercury.

The *Energy-Using Products Directives (Energy-Using Products (EuP))(2003)* formulates eco-design requirements for energy-using products (e.g. appliances, electronic equipment, motors) and energy-related products (e.g. double glazing, showers). Manufacturers should ensure consideration throughout a product's life.

4.3 Newest developments in the European Union

The awareness from the policymaker side has been growing over the last years in regard to critical materials and circularity. However, both fields are still barely discussed together. In cases where both concepts were mentioned together, it was mostly done from the critical materials side, and even less the other way around. Examples, where the topics were mentioned together, were the open EdX course 'Critical Raw Materials: Managing Resources for a Sustainable Future' [TU Delft (Producer), 2021] - while discussing the need for circular strategies related to critical materials concern - and the 'Circularity for Educators' online course by the CBE Hub.

There have been new policy developments recently, and this section will now discuss some of them in more detail to assess how they address CRMs and circularity related to the building products and the built environment.

4.3.1 Critical Raw Materials Act

The CRMA was published by the EC in March 2023 and addresses the importance of critical raw materials for the EU and the risks related to the EU's huge dependence on imports for many CRMs. The main objectives of the act (see Figure 4.7) refer to the strengthening of the value chain, the diversification of EU imports, the monitoring and mitigation of supply disruptions and free movement on the single market combined with improved circularity and sustainability. [European Commission, 2023a]

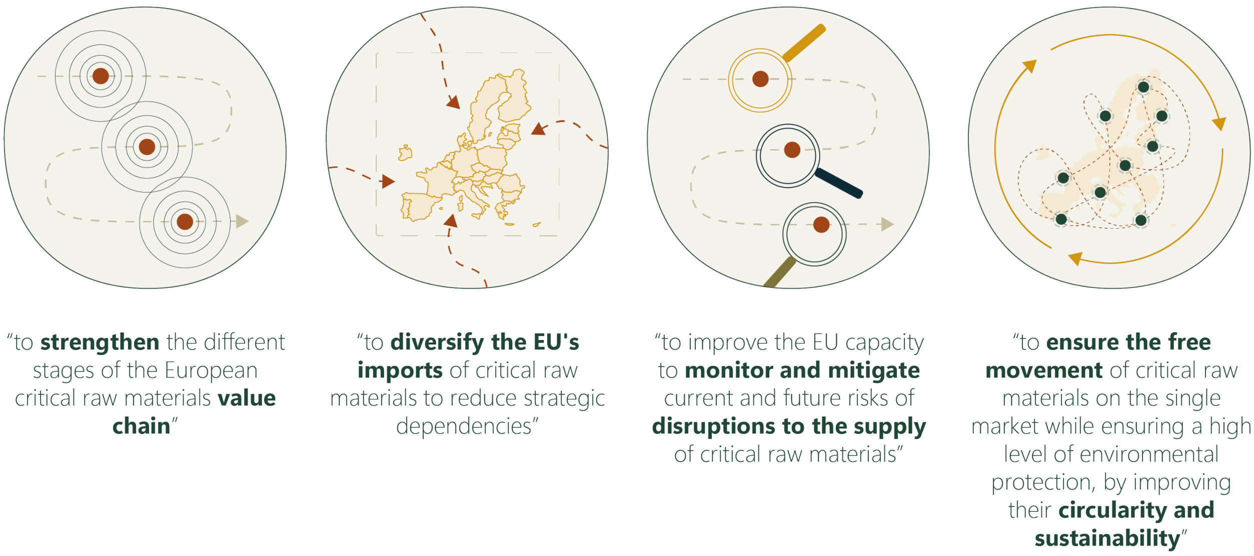


Figure 4.7: Main objectives of the CRMA [European Commission, 2023a, p.2]

The act again highlights the importance of CRMs for the green and digital transition and defence and space applications. Supply disruptions would have impacts across all industry levels; the EU's competitiveness would be in danger, working conditions and wages affected and jobs at stake, and the whole functioning of the single market at risk. [European Commission, 2023a] For the different objectives, some are more clearly defined than others. The objective to strengthen the value chain sets specific percentages as goals; the capacity for extraction, processing, and recycling is to produce 10%, 40%, and 15% respectively for the total annual production of the Union. The same clarity is found for the diversification of EU imports, as no more than 65% of annual consumption should be provided by any third country. [European Commission, 2023a] For the other two objectives, however, no specific numbers are set to achieve, the goal is to improve. Specifically relevant for this research is the question of how the CRMA views circularity as a mitigation strategy, and how detailed it sets its targets in that regard.

The CRMA and circularity

Circularity has its own section in the chapter 'Sustainability' in the CRMA, but compared to the specific percentages set for the first objective, the aim here is to *increase*. 'Increase the collection of waste', 'increase the re-use of products and components', 'increase the use of secondary critical raw materials', and 'increase the technological maturity of recycling technologies' [European Commission, 2023a, p.37-38].

The key product groups mentioned here are again waste electrical and electronic equipment and permanent magnets, mostly in regard to recycling.

The circular strategies covered in the CRMA are mostly related to recycling and recovering. Referring back to the R-strategies (see Figure 2.4), these two strategies together form the part of 'useful applications of materials', which is the least effective measure within the circular economy, compared to 'product life extension' as well as 'smarter product use and manufacture'.

4.3.2 Net Zero Industry Act

Figure 4.8: Main objectives of the NZIA [European Commission, 2023b]

The NZIA was published together with the CRMA and together they aim to support the transition towards climate neutrality. Figure 4.8 lists the main objectives, covering the simplification of the regulatory framework, the scale-up of manufacturing and the fostering of competitiveness and resilience regarding net-zero technologies and industry. It aims to stimulate investment into net-zero technologies through different actions which can then help to create a more resilient net-zero industry in Europe [European Commission, 2023b]:

Net-Zero Strategic Projects Prioritisation of essential projects

CO2 injection capacity target Support of carbon capture and storage projects

Facilitating access to markets Sustainability and resilience criteria

Enhancing skills Net-Zero Industry Academies

Cutting red tape and accelerated permitting Help development of net-zero manufacturing projects

Attracting investment Net-Zero Europe Platform, European Hydrogen Bank

Innovation Regulatory sandboxes for development and testing

DEPENDENCIES Currently, the EU imports a big portion of its net-zero technology from China; e.g. more than 90% of solar photovoltaics (PVs) technology and related components and more than 25% of electric cars and batteries. European Commission [2023b]

OBJECTIVES By 2030, at least 40% of the Union's annual deployment needs for strategic net-zero technologies should be produced through the Union's manufacturing capacity. Permit-granting processes should be facilitated and coordinated by only one competent authority per Member State in order to reduce administrative burden. The act also defines duration limits for permit-granting processes (12 or 18 months, depending on manufacturing capacity). Net-zero strategic projects are discussed in terms of their priority status; processes (like permits and authorisations related to planning, design and construction) should "be treated in the most rapid way possible" [European Commission, 2023c, p.44]

Skills and job creation are also mentioned and especially focus on the required training, education, and skills as well as professional qualifications, as the sector is expected to grow rapidly. Figure 4.9 shows some trends regarding net-zero technologies, e.g. expecting the deployment of renewables to quadruple by 2050. [European Commission, 2023b]

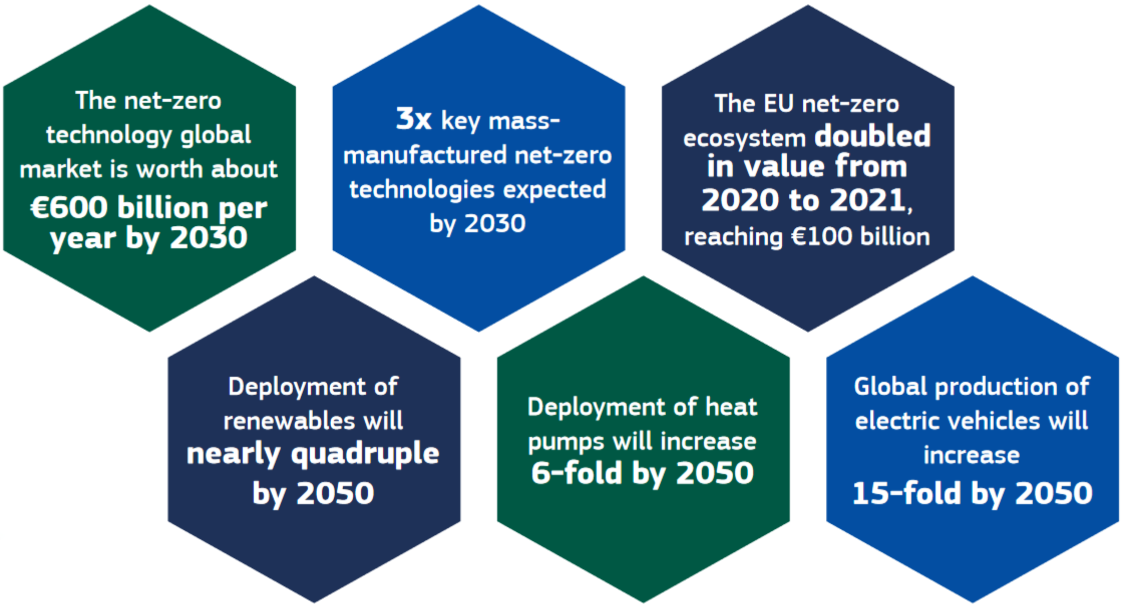


Figure 4.9: Net-Zero Technology Trends [European Commission, 2023b]

4.3.3 Eco-Design Directive

The Eco-Design Directive of the EU was first published in 2002 and addressed energy-using products, with the objective to reduce energy consumption along with other environmental impacts throughout the whole life cycle of a product. The new Eco-Design Directive from 2022 then extended the scope to cover a broader range, also with the aim to help achieve a circular economy as well as in the long run to reach the EU's goals regarding climate, environment and energy. [European Commission, 2022]

The regulation aims to address aspects related to sustainability and circularity of products such as "product durability, reusability, upgradeability and reparability, the presence of substances of concern in products, product energy and resource efficiency, the recycled content of products, product remanufacturing and high-quality recycling, and for reducing products' carbon and environmental footprints." [European Commission, 2022, p.1]

Possible supplementing delegating acts are mentioned, these could include e.g. that manufacturers are required to make technical documentation digitally available, that products placed on the market need to measure energy consumption or performance, or also that these measurement/data needs to be collected and (anonymised) reported to the EC, to only mention a few. Figure 4.10 gives some keywords on ecodesign requirements for products, ranging from durability, over energy use/efficiency, to the expected recovery or waste materials. [European Commission, 2022]

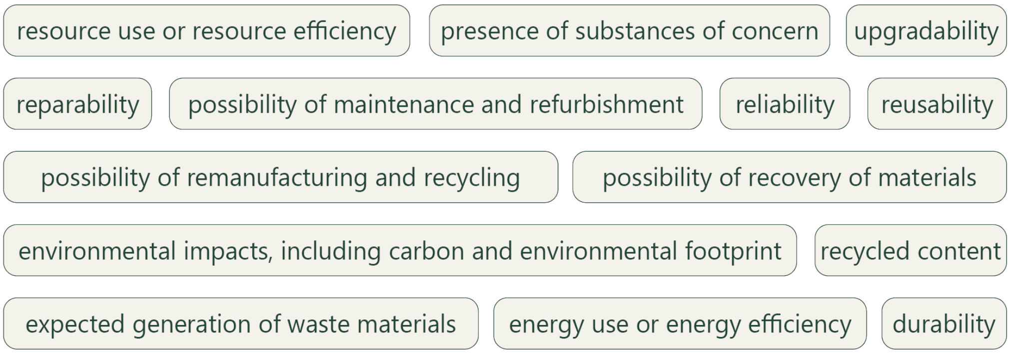


Figure 4.10: Ecodesign requirements for relevant product groups, source: European Commission [2022]

The Eco-Design Directive does not extensively address building products. It covers construction products which are also energy-related products but otherwise, it refers to the revised 'Construction Products Regulation', which neither mentions circular strategies nor critical materials.

4.3.4 Urgency + need for action

> **[...] the current transition from fossil fuels to renewable energy sources is a complex policy-led process with time goals.** [Kügerl et al., 2023, p.1]

Overall it can be said, that the CRMA, the NZIA and the Eco-Design Directive define clear targets, but they do not come with a clear path on how to reach these goals. The objectives also set specific time frames for the enforcement of the mentioned goals, mostly ranging between three to five years. This can be linked to the importance to move fast regarding the climate crisis, as [Kügerl et al., 2023, p.1] also state; "[...] the current transition from fossil fuels to renewable energy sources is a complex policy-led process with time goals." The urgency to develop clear guidelines and strategies to reach the different objectives in time is quite evident in that sense.

As the research of this thesis has its focus on façades, the lack of product-specific policies, not just regarding the façade sector but also the whole BE, can be defined as a gap. The same goes for policies regarding the circular built environment; as mentioned before (see Fig. 4.4), there is an existent framework for policy instruments regarding the sustainable built environment, but a focus on circularity in the built environment is still missing.

4.4 Chapter conclusion

In conclusion, policymaking is also a rather complex and dynamic process, which is shaped by social, economic, and political factors. It is used to address challenges, through the implementation of different policy instruments, and people or groups involved range from civil servants and politicians to technocrats and stakeholders from different sectors.

POLICYMAKING AND IMPLEMENTATION The implementation of new policies requires a certain level of public support, and policymaking then reflects specific social and economic developments and also demonstrates the role of government within a society. For the successful implementation of policies, policymakers must not only clarify the ambitions but also translate them into concrete actions, in order to bridge the gap between targets and implementation. Policy interventions can happen at various scales, ranging from local to global.

MATERIALS AND RESOURCE LIMITATIONS The discussion regarding resource limitations was first initiated by the Club of Rome in 1972, and in 1987, the Brundtland Report gave the first definition of sustainability. Together they set the foundation for many subsequent policies regarding material restrictions. Over the last few decades, numerous regulations have been developed to address material restrictions, e.g. the End-of-Life Vehicles Directive, the Waste Electrical and Electronic Equipment Directive, and the Energy-Using Products Directive.

POLICY INSTRUMENTS, APPROACHES, AND RESTRICTIONS Different combinations of different policy instruments can be used as techniques, and they can generally be grouped into regulatory, economic, and informative instruments. While top-down approaches provide clear and generalizable policy structures, bottom-up approaches respond to contextual factors. Policies bring both benefits and bottlenecks. They address societal problems and promote economic growth, social justice, stability, and security. However, limited resources (time, money, and expertise), resistance to change, complexity, duration, and unintended consequences can pose challenges.

CRMS, CE, AND THE FAÇADE SECTOR The newest developments in the EU regarding CRMs and the built environment (and with that the façade sector), recent developments such as the CRMA, the NZIA and the Eco-Design Directive set different specific targets, but do not have a clear path on how to reach them. Clear guidelines (or product-specific policies) regarding the façade sector are not included, just like different applications of CRMs in the BE are also not discussed so far. The awareness of the need for widely employed circular strategies in the BE is already quite high in professional and academic circles, but it lacks a solid policy foundation.

OUTLOOK This chapter described policymaking in general as well as existing policies. The next chapter will now conclude the previous chapters and consequently formulate policy recommendations related to the discussed fields of CRMs within the façade sector, and how circular strategies can be implemented as mitigation strategies in this regard.

5 Policy recommendations

This chapter starts with a summary of the main findings and identified problems discussed throughout the previous chapters and subsequently formulates recommendations on how to address the reduction of critical raw materials use and life extension of products with critical raw material content.

The proposed recommendations address seven different topics within four fields; *Material and Products*, *Company and Strategy*, *Geopolitical* and *Environmental and Social*. A first assessment of possible policy instruments to implement the recommendations is made by linking the different parts of the recommendations to the policy instruments for the sustainable built environment by Kibert [2002].

5.1 Identified problems

CRMs

- assessment of criticality: supply risk + economic importance
- importance for energy transition
- EU import dependency
- mitigation strategies and challenges
- material extraction and environmental, social and economic injustice

Circularity and the façade sector

- CE principles: design out waste, keep products in use, regenerate natural systems
- increasing awareness regarding the need for implementation circular strategies
- 100% circular economy will never be possible
- curtain wall façades: toolbox of components, environmental control, smart systems
- CRMs in façades as of yet not discussed

chapter conclusions

CRMs in façades

- analysis of aluminium curtain wall panel: 23 different CRM
- assessment difficult for sensors, motors, magnets, etc.; quantification not possible
- high % of criticality assessed for aluminium alloys (typical main material for curtain walls)
- high import reliance for respective CRMs

Policies: CRMs and CE

- awareness is rising for CRMs and CE concerns, but still lacking solid policy foundations
- CRMs, CE and façade (building) components not yet discussed together
- CE still mostly reduced to recycling and recovery
- CRMA, NZIA, and Eco-Design Directive set targets but no clear path on how to reach them

Figure 5.1: Keypoint summary of the previous chapters

Figure 5.1 gives a summary of the main takeaways from the previous chapters:

CHAPTER 1: CRITICAL RAW MATERIALS The literature review described in chapter 1 gives a general introduction to CRMs, including the definition of criticality (combination of high supply risk and high economic importance) and the importance of CRMs related to the climate crisis and the associated need of the energy transition. However, CRMs are connected to various challenges: On an EU level, high import dependency is problematic. Globally, material extraction - and the needed scale-up of renewable technologies etc. demands also an increase in raw material mining - is connected to environmental, social and economic injustice. Known mitigation strategies (e.g. substitution or recycling) then again come with their own limitations.

CHAPTER 2: CIRCULARITY AND THE FAÇADE SECTOR In chapter 2, the principles of a circular economy are discussed. In order to transition to a more circular economy, waste needs to be reduced through design, and products should be kept in use as long as possible, while also regenerating natural systems. An increasing awareness regarding the need to implement more circular strategies can be observed, although it is also clear, that a completely circular economy will never be achievable, due to stock dynamics, as well as loss of quantity and quality. The chapter then also introduces curtain wall façades and their components, and establishes a first connection to CRMs. From the literature review, it can be stated, that CRMs are so far not discussed in combination with the façade sector, or also the built environment in general.

CHAPTER 3: ANALYSIS: CRITICAL MATERIALS IN FAÇADES Chapter 3 shows the results of the analysis of the curtain wall element, as described in the methodology. The analysis demonstrates the complexity of a criticality assessment within systems and components and provides a list of 23 different CRMs included in the element. The assessment was done for (aluminium) alloys, magnets within motors, and sensors, which already displays the difficulty regarding the quantification of CRMs.

CHAPTER 4: MATERIAL POLICIES AND THE BUILT ENVIRONMENT Lastly, chapter 4 studies existing policies in regard to CRMs, circularity and the façade sector, which then reveals a lack of a solid policy foundation for these fields. The fields are in general not yet discussed together - also resulting in a lack of product-specific policies-, and strategies regarding a CE are mostly reduced to recycling and recovery. Clear paths and guidelines on how to reach the defined targets are missing.

To summarise all previous findings, the following statement can be made:

IDENTIFIED NEED:
(1) the use of CRMs should be reduced wherever possible
and
(2) CRMs used in products should be kept in the loop as long as possible

From the identified issues related to critical raw materials, it becomes clear, that **the use of critical raw materials should be reduced as much as possible**. They are, however, crucial for some applications in the façade sector, e.g. alloys and components related to 'smart systems' which are seen as important tools for the energy transition - due to the specific characteristics and functionalities added by CRMs to a specific product or component. This results in a big tension, as Figure 5.2 on the next page shows: smart buildings, meant to help mitigate the climate crisis, are highly dependant on CRMs, which can then again be linked to an increase in primary mining, geopolitical tensions and global injustice. If the use of CRMs cannot be reduced, **the lifespan of CRMs used in products should be prolonged as long as possible**, which demonstrates the importance of a wider implementation of (highly effective) circular strategies.

industry will not solve the problem; clear policies are needed - both product-specific and regarding the implementation of circular strategies.

From the current awareness for the connection of CRMs, the CE, and the façade (or building) sector, the statement can be made that **it is unlikely for the industry to solve the related problems by itself**; clear policies and guidelines are therefore regarded as crucial, especially as the topic comes with an inherent urgency related to the climate crisis.

The following recommendations were therefore formulated to show mitigation strategies related to different aspects and problems mentioned.

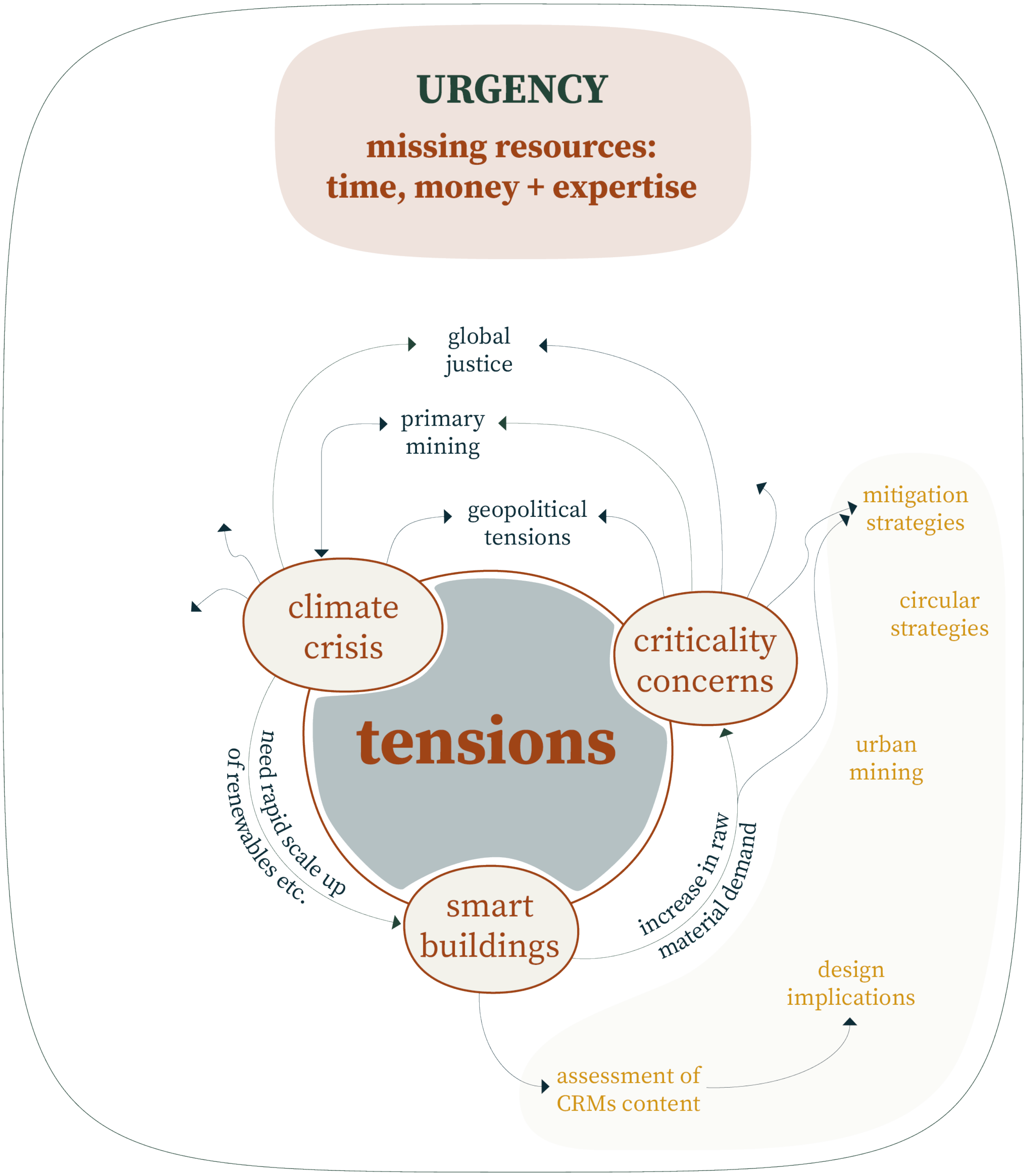


Figure 5.2: Identified tensions regarding smart buildings as mitigation strategies for the climate crisis

5.2 Recommendations

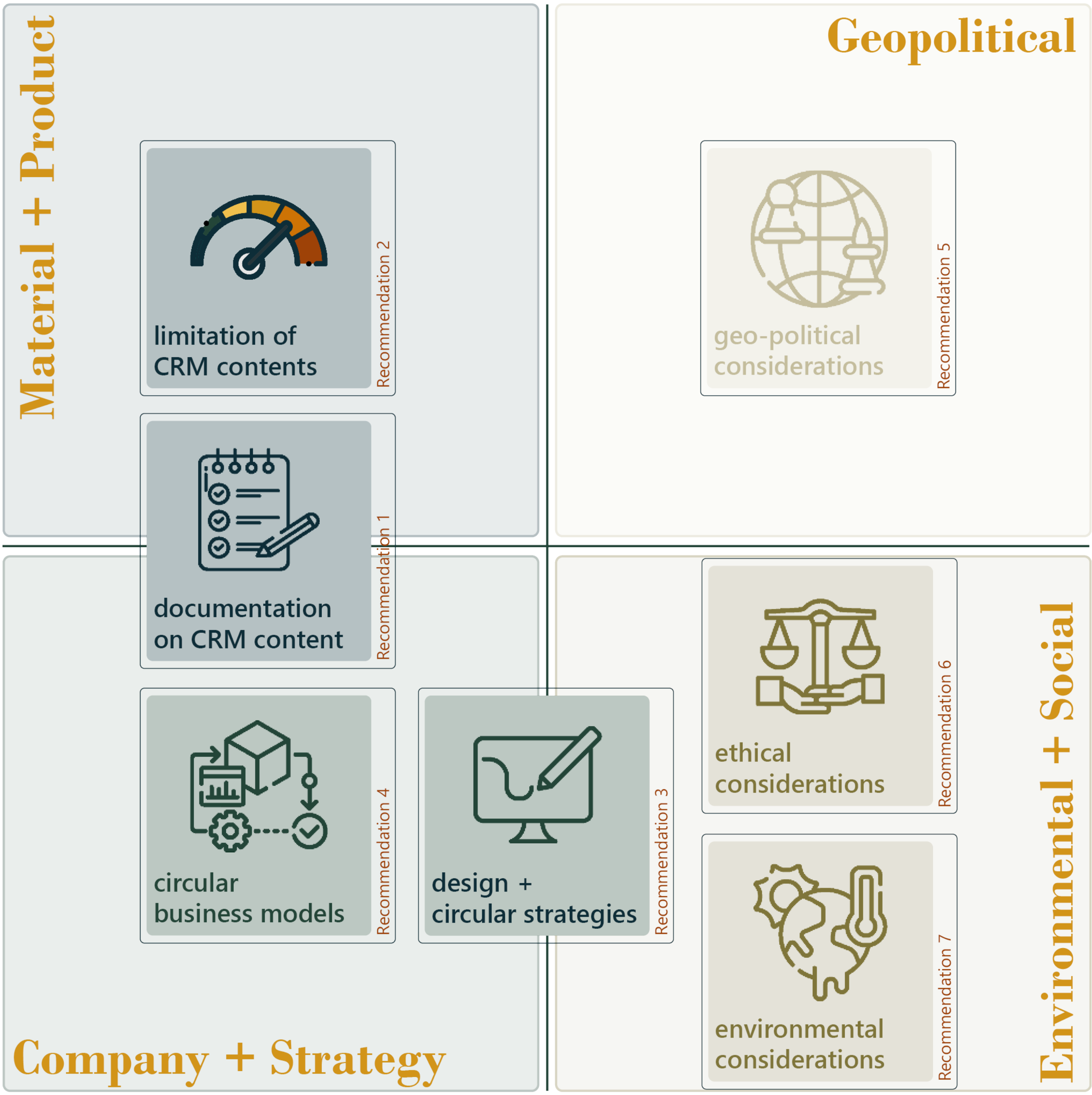


Figure 5.3: The defined recommendations for future policymaking (matrix after Peck [2016] and Ashby [2016])

Within the four different fields (*Material and Products*, *Company and Strategy*, *Geopolitical* and *Environmental and Social*), the seven different recommendations include (1) the documentation on CRM content, (2) the limitation of CRM content, (3) circular business models, (4) design and circular strategies, (5) geo-political considerations, (6) ethical considerations, as well as (7) environmental considerations. This section now demonstrates a first attempt to link different aspects within the recommendations to specific policy instruments and by that shows up the possibilities or limitations in that regard.

A short comparison of the formulated recommendations with the newly introduced CRMA and NZIA shows very few overlaps. Referring back to Figure 5.3, the two documents have their focus on *Material and Product* (CRMA) and *Company and Strategy* (NZIA). However, from the defined recommendations only *Recommendation 1: Documentation on CRM content* is represented with a strong focus, and circular strategies are discussed in regard to recycling. *Environmental and Social* and *Geopolitical* considerations are still missing.

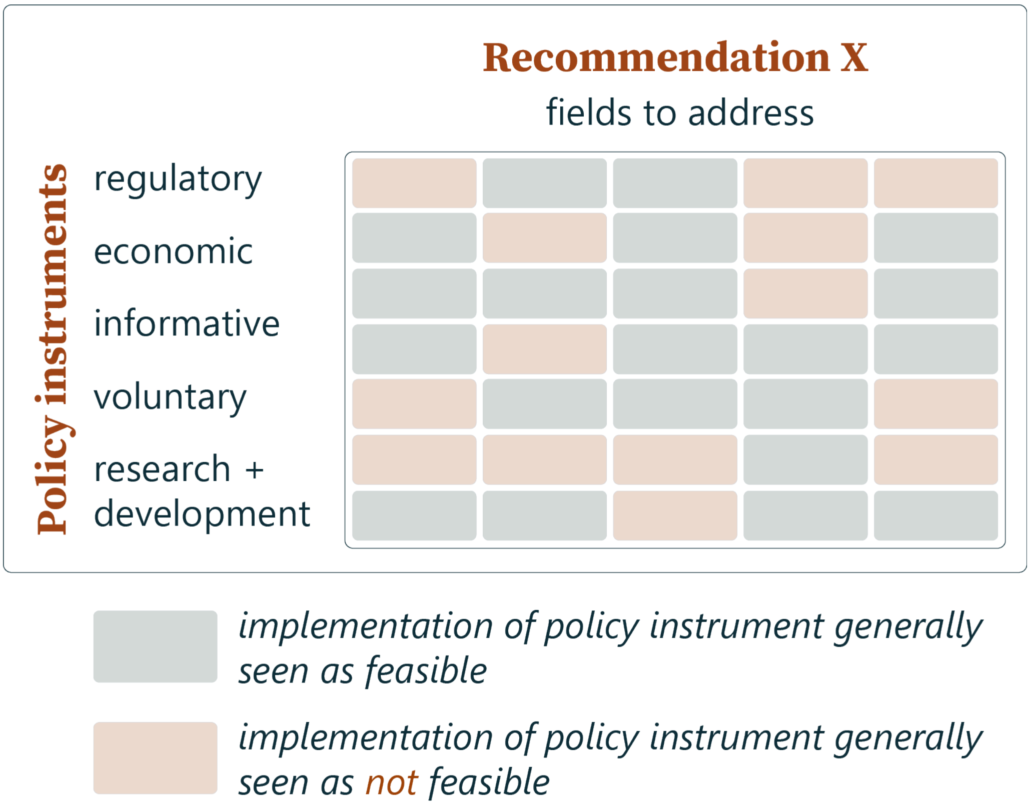


Figure 5.4: Simplifications of evaluation tables for the different recommendations related to policy instruments

In order to give more depth to the proposed recommendations, they were cross-checked with the list of policy instruments for the sustainable built environment by Kibert [2002], as that was regarded to be the most closely linked listing available in regard to the analysed fields. It should, however, be noted, that the *sustainable* built environment and the *circular* built environment are two different concepts. It can, therefore, already be assumed, that a comprehensive list of policy instruments for the circular built environment - and also with a focus on a more product-specific approach towards the façade sector - the introduction of further policy instruments is likely needed.

Figure 5.4 shows a simplified version of the tables made for cross-checking policy instruments with aspects of the recommendations. The table does not indicate, whether a specific policy instrument should be used for a certain aspect within a recommendation. It is simply a first assessment, of whether the instrument is seen as a possible tool to enforce or achieve a certain field or target within the recommendations.

5.2.1 Recommendations 1: Documentation on CRMs content in building products

Without quantifying the material composition within components, products, or whole façades, it is impossible to properly assess how these perform in regard to critical materials. Therefore, the first step must be the detailed documentation of all the different parts included. A first possible method to do so was already demonstrated with the analysis within this research in Chapter 3, as outlined in the methodology in the methodology.

Recommendation 1 : documentation on CRM content

General Information

- Product description - Production year - Manufacturer information - Installation instruction	- Responsibilities (business model / take back agreement, ownership) - Operation and functionality (user guide, maintenance)	- environmental impact for each phase (extraction, production, use, EoL) / LCA

Composition (CRMs)

- Product components - Bill of materials (description of material content and composition of a product): list and weight, identification of CRMs	- Origin of the materials used in the product - Processing information / manufacturing process (how are materials constructed, joined, treated, coated; feasibility of material recovery)	- Reason why this material was chosen (purpose / functionality) - Product design specification, environmental design aspects

Figure 5.5: Subpoints considered within recommendation 1 (list of targets after Building Product Passport summary by Meyer [2018], see Figure in the appendix)

Figure 5.5 lists the different subpoints included in *Recommendation 1: documentation on CRM content*. It is split into two fields; general information and composition, and based on a summary of possible information included in a Building Product Passport (BPP) by Meyer [2018] (see Figure 1 in the appendix).

The general information asks e.g. for basic information like a product description, production year, manufacturer information and installation instruction, while the composition then includes documentation related to the components and sub-components of a product or system: which components there are and how many of them, what is their volume or weight, but also on the specific material composition of these components and how they perform in regard to a criticality assessment.

Required tools and data

In regard to the mentioned objectives, it is important to facilitate their implementation as much as possible. Data collection concerning building components and materiality, as well as calculation strategies for criticality assessments, should therefore not pose a threat to this goal.

In that sense, manufacturers and suppliers should provide information on the material composition of their products along with their products. One way how this could be done was demonstrated by Meyer [2018], who researched how Building Information Modelling (BIM) could be used for the assessment of CRMs in buildings. Databases and protocols can be seen as possible useful tools regarding documentation of CRMs content.

Assessment protocols

The concept of building product passports was briefly introduced in Section 2.2. In addition to the information mentioned there, and in regard to a comprehensive analysis of critical materials within a system, the following indicators should be considered:

WHAT which materials are there and in what quantity

WHY which purpose or functionality do these materials serve and why are they necessary in the specific product or component

WHEN how long are these materials in use and when will they be available for recovery, at what stage should there be a new assessment of the materials in use in regard to possible future applications

HOW what was the manufacturing process and how feasible is material recovery

WHERE what is the exact location of materials in regard to components and systems

WHO who is responsible for the availability of which type of information as well as the different stages of a product's life

Assessment of policy instruments

In general, it is seen as feasible to use regulatory instruments to enforce the documentation on CRMs content in products. The question is, whether the two listed regulatory instruments (technology- and performance-based standards) are applicable, as the recommendation is about the documentation of the subpoints mentioned in Figure 5.5 (e.g. in the form of a DPP and not necessarily about the assessment of the therein documented aspects. The introduction of additional regulatory instruments might be helpful here.

A lack of documentation can be addressed through different economic instruments, like charges or non-compliance fees, while user charges or deposit-refund systems are less applicable.

Information tools, like information/awareness campaigns, voluntary policy tools, like commitments and agreements, as well as research and development, are generally seen as applicable. Although these are less effective, as they are non-binding. As the documentation is the crucial first step, on which all the following recommendations and strategies build up on, it is seen as necessary to make documentation as extensive as possible.

5.2.2 Recommendation 2: Define % limit of CRMs in new products or components

The way we look at resources needs to change. We cannot keep building without a general understanding of the materials we use and what their impacts - related to environmental, economic, social, or political fields - might be. Referring back to the definition of what makes materials critical (see Chapter 1), one main objective must be to reduce the use of CRMs as much as possible. A reduction of critical materials in products or applications where they are not absolutely necessary is therefore highly recommended.

This then raises the question of on what a limitation of critical raw material content should be based on. This is especially complicated as the definition and assessment of criticality is very complex by itself. Each material ranges differently in the assessment of the CRMs list, however, it seems unrealistic to include these differences in the criticality assessment of specific products or components, also because the assessment need to be seen as dynamic, as the factors used for the criticality assessment of the CRMs list are changing constantly.

It is therefore still an open question, whether the limitations are more effective (or relevant?) when e.g. based on the volume of critical materials compared to on the number of different critical materials.

Recommendation 2: limitation of CRM content

limits per components	limits per system	thresholds (%)	ranges (%-%)
- quickly reached when main material critical	- different components can balance out others	- define definite limit for acceptable CRM content, link to mitigation strategies	- different ranges can be linked to different mitigation strategies or policy instruments

Figure 5.6: Fields considered within recommendation 2

The higher the level of criticality, the higher ranking the required circular strategy should be.

Figure 5.6 lists four different ways of dealing with limitations of critical materials: when considering limitations per components, it is likely that these limits are quickly reached (as can be seen with the mullions and transoms analysed in chapter 3, as the main material was defined as critical). On the other hand, defining limitations per system could result in components with a high level of criticality being balanced out by components with a lower level.

The other aspect is the limitation itself; a maximum % limit can be set per different critical material or per group of critical materials, which can then be seen as a threshold. Another way would be to define ranges or % which can then be connected to different strategies to compensate, as well as different policy instruments (regulatory, economic, informational). The higher the %, the higher/lower the applied instruments (e.g. material charges, fees, subsidies) can be.

Assessment of policy instruments

Standards or norms are seen as possible instruments to limit the content of CRMs in products. The question here is rather what to base the specific %-number on. Only by solving this, an effective regulation can be put in place, which could then also be combined with economic instruments like product charges or taxes, non-compliance fees, or liability payments.

5.2.3 Recommendation 3: Design and circular strategies

Design plays a crucial role throughout all life stages of a product. Therefore, it is important to consider the role of the design when it comes to the limitation of material use and product life extension, especially related towards the implementation of more effective circular strategies.

The awareness for concerns around CRMs already at the beginning of a project is important as the chances are then still higher to design out critical materials (e.g. through substitution) or at least consider possible circular strategies as possible scenarios at the end of the product's life. The impact of design decisions on material use should also be further investigated e.g. in regard to curtain wall facades, as it was shown that different frame-to-glass ratios impact the level of criticality per element. Design optimisation also plays a role in that sense.

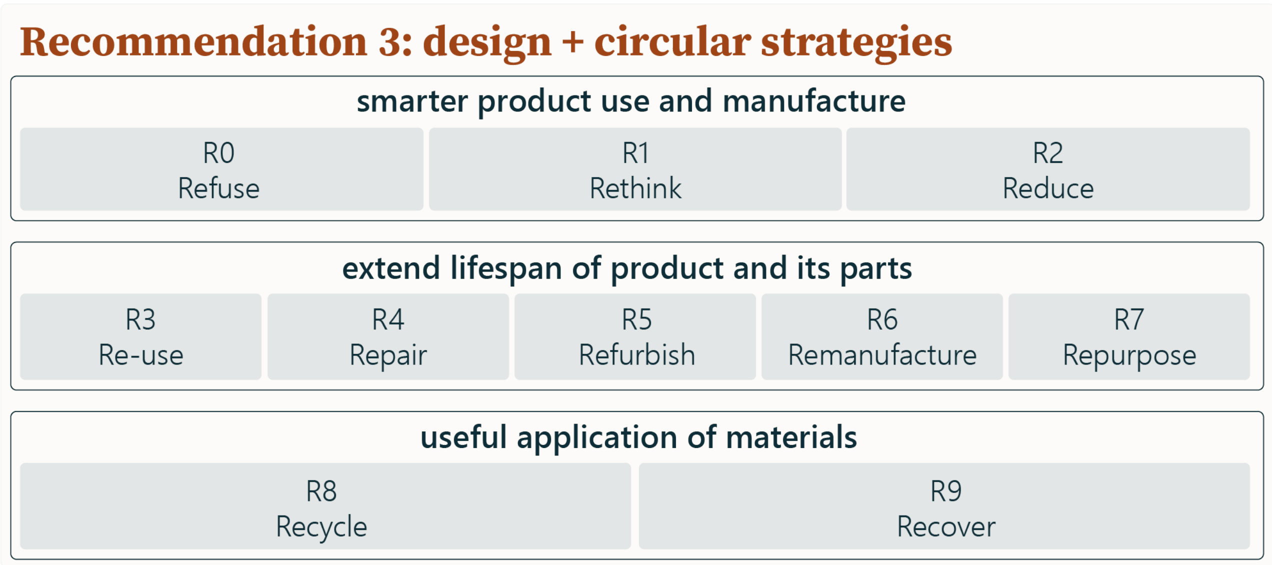
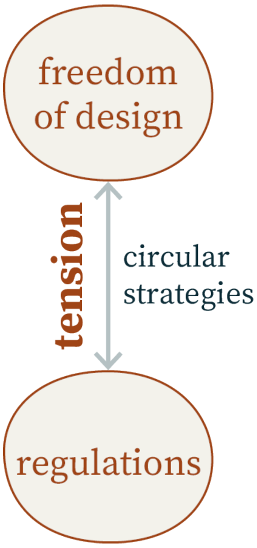


Figure 5.7: R-strategies, adapted from PBL [2018]

For this recommendation, the R-strategies were considered in regard to possible enforcement through different policy instruments. This was considered important, as circularity in policies is still mainly focusing on recycling, although there are many more effective circular strategies.

Related to Recommendation 2, if a certain % of critical materials is exceeded, it is proposed that circular strategies are enforced, or have to be examined as possible mitigation strategies. This could help to either reduce critical material content or else ensure that the critical materials are kept within the economy after the end of their first life.

Aesthetical decisions can also be discussed, or compared, in regard to CRMs concerns. This then opens the discussion about another tension; the one between freedom of design and regulations toward a certain goal - which can be defined as the mitigation of the climate crisis. A 100% circular economy is not possible to achieve from a material perspective, as was mentioned before. On the other hand, a 100% circular economy from a built environment perspective, when strictly executed and focussed on the most effective R-strategies and principles, would consequently result in modularised and prefabricated standardised design. However, public - and professional or also academic - acceptance, which is still an important factor for the successful implementation of policies (as discussed in Chapter 4), in that regard is highly unlikely.



The aim must still be to aim for the highest ranking R-strategy considered feasible.

Assessment of policy instruments

The enforcement of the strategies in the group of *smarter product use and manufacture* through regulations is considered not feasible, as both technology-based as well as performance-based standards need to be somehow measurable, or quantifiable. Refusing, rethinking, and reducing critical materials within products must therefore rather come through voluntary practices so far. However, further research should be done to investigate possible additional policy instruments which specifically address these fields.

Standards and norms can be implemented regarding the strategies within *extend lifespan of product and its parts*, to ensure that the ability for e.g. re-use, repair, or remanufacture is accounted for. These can also be combined with selected economic instruments, like tax exemptions or non-compliance fees. Information tools can be seen as valuable in regard to public awareness and possible societal change of values in regard to products and materials. The same goes for voluntary tools, e.g. in the form of agreements or commitments.

5.2.4 Recommendation 4: Circular business models and building regulations

It can be understood that circular strategies work most effectively if they are clearly defined and prepared for within the design phase of a product or system. If a product is produced and handled with regard to a future circular strategy from the very beginning, it is more likely, that that approach is actually followed through, rather than figuring out which circular strategy could be followed once a product has reached its end-of-life. In that sense, business models can help to accelerate the transition towards a circular built environment. Specific business models can be implemented in order to focus on certain aspects of a product's value chain.

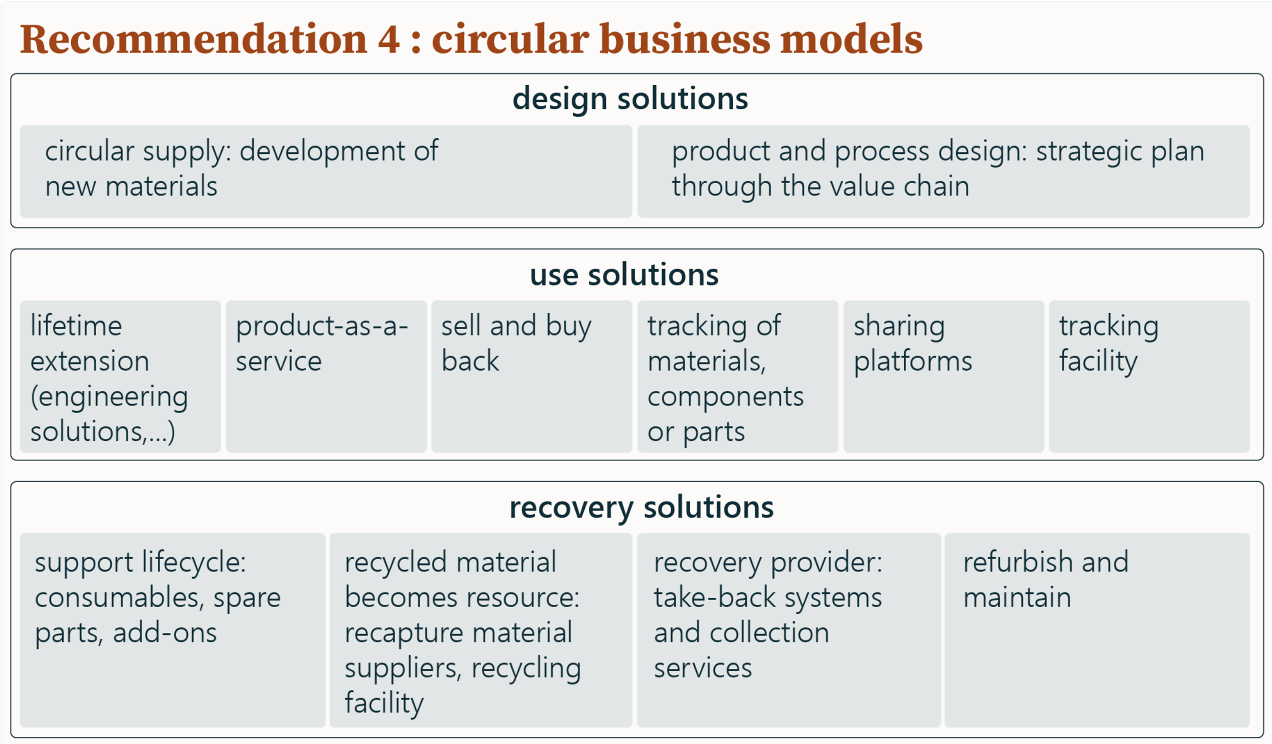


Figure 5.8: Fields considered within recommendation 4 (based on Arup and BAM [2018]

Figure 5.8 shows different examples for Circular Business Model (CBM)s which can be implemented within a circular built environment according to Arup and BAM [2018]. They are divided in three fields (*design*, *use*, and *recovery* solutions) and range from the development of new materials, over product-as-a-service, to recovery providers.

Assessment of policy instruments

Standards and norms are seen as important tools towards the implementation of new business models, e.g. regarding new materials, product design, lifetime extension possibilities, or recycled materials as resources. As the different CBMs focus on different stages within a product's lifecycle, the applicability of economic instruments also varies.

In order to increase the number of companies or manufacturers complying with circular strategies, the implementation of circular business models should be incentivised. This can also be of help for small and local-scale circular business models to lower the risk factors which can be part of transitioning from one business model to another or facilitate market entry by reducing barriers e.g. related to financial factors.

Information and voluntary tools as well as further research into each specific CBM are also seen as important.

5.2.5 Recommendation 5, 6, and 7: Geopolitical, ethical and environmental considerations

The extraction of critical materials often takes place in a problematic context, e.g. in regard to environmental, societal, social or cultural aspects (see Section 1.1). Assuming that everyone has a certain responsibility to work towards a more just and sustainable world, building product design should not happen without considering resource consumption and its respective impacts on other societies or cultures.

Different aspects should be considered in that regard. These include e.g. considerations about the extraction and processing of CRMs; not only where the critical materials used in products are mined, and processed, but also by whom, or under what conditions for the workers and with which consequences for the environment. Due to time limitations and the scope of these recommendations, they were not explored in more detail but, as they are closely intertwined with the topic of critical materials, further research should be done to deepen these aspects.

As a first assessment of possible policy instruments, the implementation of e.g. certification schemes is seen as valuable. This can include the different stages of the value chain, whether the process is clearly traceable and how they comply with existing EU standards.

Linking back to Figure 5.2, more research needs to be done to further analyse the tension between the rising demand for CRMs related to mitigation strategies for the climate crisis.

5.3 Chapter conclusion

MAIN GOALS This chapter started with a conclusion of the findings from the previous chapters and subsequently formulated the need to (1) reduce the use of critical raw material content in products as much as possible and (2) if the reduction of critical raw materials is not possible, it is important to keep them in the loop as long as possible.

TENSIONS The tension between the strategy to make buildings smart as a mitigation strategy for the climate crisis and the concomitant rise in demand for raw critical raw materials was identified. Specific policies to implement circular strategies are therefore seen as necessary, and the chapter gives an overview of recommendations in that regard. Another tension was stated regarding *Recommendation 3: Design and circular strategies*: the question of how much regulations are allowed to interfere with the freedom of design. In the sense of crisis mitigation, stricter regulation is needed, as the topic is unlikely to solve itself due to its complexity.

THE RECOMMENDATIONS AND POLICY INSTRUMENTS The recommendations range over the fields of Material and Product, Company and Strategy, Environmental and Social, and Geopolitical. By cross-checking the subpoints of the different recommendations with existing policy instruments for the sustainable built environment, it can be stated that the policy instruments generally show potential to address the mentioned challenges. However, as the policy instruments are aimed at a sustainable, not a circular built environment, the introduction of additional policy instruments is seen as beneficial. Further research could e.g. be done regarding implementation strategies for highest ranking circular strategies (refuse, rethink, reduce), as their implementation through the mentioned regulatory instruments is not regarded as feasible as of yet.

Conclusion

The thesis demonstrated the need for rapid uptake in mitigation strategies and the possibility of future policies to facilitate this transition. More and more attention has been paid to critical material concerns related to the energy transition, but the use of critical materials within façade (or building) systems and components has not been discussed so far. Hence, one main conclusion is, that there is not enough information and knowledge available yet in regard to the combination of critical raw materials, the built environment, and the circular economy. It did become clear, however, that critical materials also play an important role in the built environment regarding different scales; aluminium alloys as big structural components provide certain application possibilities through the specific material composition. On a much smaller scale, critical materials are seen as crucial for sensors and motors, and their sub-components, which are key technologies for 'smart' technologies or buildings.

The analysis showed that critical materials are indeed present in aluminium curtain wall systems, although a complete quantification was not possible due to the lack of available information on sensor and motor components. Some questions remain open, for example how exactly the results of the analysis can or should be read, as e.g. the quantification of critical materials contents and the number of different critical materials used within a system or component, for now, does not consider the different levels of criticality for different critical materials and is therefore still rather superficial.

In regard to material policies, it was found that although new policies have been developed e.g. about CRMs concerns, these do not discuss the BE at all, and circularity is only briefly mentioned in regard to recycling possibilities. Certain targets are set but no clear paths are defined on how to achieve them. In order to prevent future bottlenecks in the façade (or building construction) sector, it is deemed necessary to increase the number of mitigation strategies, as well as their strictness. The use of critical raw materials needs to be reduced, and their lifespan extended for as long as possible.

Simply optimising existing processes will not be enough in the long run. The different recommendations, therefore, discuss different fields and aspects to prevent possible bottleneck occurrences through documentation, limitation, circular strategies and circular business models while also pointing out the importance to consider environmental, ethical and geopolitical implications of critical raw material concerns.

Reflection

The relation between the graduation topic, the master's track, and the master's programme: The thesis was carried out at the Delft University of Technology in the field of *Façade + Product Design (Circular Building Product)* and *Climate Design* within the department of *Architectural Engineering + Technology* at the Faculty of Architecture and the Built Environment.

The overall topic of the thesis is the circular environment and circular strategies related to critical raw material concerns in façades. Circularity is an important research topic within the architecture faculty and specifically the Building Technology master track, with its focus on sustainability and innovation in the built environment. Critical materials on the other hand are as of yet not discussed in regard to the BE. The research identified this lack of awareness and the related lack of knowledge as a notable seed of future bottlenecks and aimed to set some impulses on how to prepare for and prevent those. During the research, the need for future research became clear, which will be further addressed in the following discussion.

The relevance of the graduation work in the larger social, professional and scientific framework: The awareness of the role of the built environment in regard to the needed energy transition is very high at the Faculty of Architecture and the Built Environment of the TU Delft, as well as in the BE in general. There is therefore a big focus on decarbonising the building stock and reducing the operational energy demand of buildings. There is a considerable amount of focus on researching ways to optimize energy consumption in buildings. As a result, there are numerous smart application options available. But as mentioned before, these systems rely on the use of critical materials and the awareness of this connection is very low to non-existent in this area.

The available literature on critical materials today mostly discusses the concern in fields related to low carbon, e-mobility or security and defense, while there is a gap in research and knowledge of critical materials in the built environment. By focusing on smart applications as solutions for issues related to the climate crisis, however, primary mining is accepted as a solution. This then opens up new fields of discussion concerning social, environmental and geopolitical concerns.

From a scientific perspective, the goal of this research was to demonstrate the need for more information and knowledge in this field as a clear gap can be identified. On a professional level, critical material concerns are likely to pose a threat to companies, including façade companies as well as other companies within the BE sooner or later, which should be addressed as early and as precisely as possible. Social issues can be linked to the different stages of the supply chain of different materials or products, e.g. companies will (from a current forecast) encounter supply and demand imbalances which can affect their workers in terms of job security. Especially the mining of raw materials can affect and pose a threat to local communities and their environments. This links to the big tension in regard to the topics discussed: the mitigation of the climate crisis through smart applications and renewable energy technologies vs. CRMs-related issues.

Approach, methods, and methodology: The analysis of this research focused on one specific aluminium façade element and followed a clear step-by-step process. The same analysis set-up could therefore also be used for different systems, and within different sectors of the BE.
One weak point of the research can be identified in terms of the followed analysis, as it did not strictly follow a case study analysis design and method as e.g. defined by [Yin, Robert K., 2009].

For the research, the focus was put on the three fields of (aluminium) alloys, motors and sensors. Two aspects can be discussed in that regard:
(1) as for the results, there was - and that was anticipated - a big difference in the available information on components and material composition of the additional features like motors and sensors compared to the basic curtain wall system. Finding information in regard to elements or materials contained in 'smart systems' was found to be very difficult, and therefore also made it impossible to provide a holistic and complete quantification of CRMs in aluminium curtain wall façade system. This problem can then again be linked to the approach for the research as it was specifically looked for information on motors or sensors *within façade systems*.
(2) Aluminium alloys identify as materials, while motors and sensors are components of systems and they consist of many sub-components. With a different approach, it might have been possible to produce more output. As an example, compared to the chosen analysis - which looked at a *generic* curtain wall element - a more pre-defined element with clearly specified smart applications could have given a more holistic overview of the critical materials contained within it.

With the chosen approach, a lot of time was spent on the search for and comparison of different systems (different window opening mechanisms, different sensor types and functionalities) and the attempt to define a mean application from that, which then in the end could not be thoroughly investigated but instead resulted in a very superficial overview of possibly included CRMs within motors and sensors.
In general, it can be stated, that the results of this research can be seen as a first introduction of CRMs within facade systems, but much more and deeper research should be done into this field, in order to create a more extensive understanding for CRMs content within these systems.

Transferability of project results: The case study analysis showed results for one specific aluminium façade element with pre-defined measurements. As façades can vary greatly in terms of design, materiality, and functionality, the resulting percentages of criticality cannot simply be applied to other façade compositions. On a component level, however, it can be noted that the material compositions can give general indications of how different components rank in terms of criticality. The role of design and its implications for CRMs will be further discussed in the following *Discussion* chapter.

The policy recommendations were formulated in the context of the façade sector. It is assumed, that similar approaches can also be applied to other sectors within the built environment.

Discussion

Circularity is more than recycling When we talk about the built environment, we talk about many quite different sectors at the same time. And when we talk about building products, we talk about groups of products which can have very different scales and lifespans. This was one of the reasons, to choose the facade sector for the analysis, as it already represents the combination of big-scale to small-scale and long lifespans to short lifespans. What we learned through the research, however, was that:

Circularity is often talked about in combination with recycling, neglecting the fact, that this is a rather low-ranking strategy compared to others. Recycling might be the most comfortable strategy, as it still counts as a way of keeping materials in the loop, without really influencing common practices in terms of new product design too much. Developing a new product with recycled materials still leaves a lot more freedom compared to developing a new product using remanufactured components or reusing parts. If we talk about a circular economy, we should talk about trade-offs, as well as priorities and, in a best-case scenario, also find a way to make them measurable and comparable. The purpose of architecture, freedom of design, and so on can be discussed on and on, but the question can be raised whether resource concerns should function as additional design criteria.

The role of design The different results of S1 and S2 can also be read from a design perspective. In the system with the openable window, there are also two more transoms included. This changes the overall proportionalities of the different components; more structural components and less glass area. As the previous analysis defined the structural elements as those with CRMs contents, it would be easy to argue for bigger spans between the separate mullions and transoms, as that would lead to more glass area and therefore to a lower overall percentage of CRMs content. However, bigger spans would most likely require bigger profiles so the next question would then ask for the optimal ratio between element and profile sizes.

In general, it can be assumed that design can have a big impact when it comes to the conscious application of a more material-aware application of different systems, once the required knowledge in that regard is established. As the analysis showed, that is not the case as of now.

Level of 'smartness' and trade-offs
The decision on how 'smart' a building or a façade is going to be is also part of the design process. It would be impulsive to argue, that because of the high number of different critical materials within smart facades, it might be better to not use these systems within facades. However, that could then lead to higher usage of smart systems within the building itself.

In general, CRMs concerns can pose threats to companies or manufacturers in the form of possible imbalances of supply and demand. This can lead to price fluctuations which can then be hard to balance. It is, therefore, important to achieve strategic autonomy in regard to supply and security also within companies.

Even when considering that the undertaken analysis only represents a small part of the building industry, even within the façade industry, it clearly demonstrates that there is a lack of awareness when it comes to CRMs in this field as there was basically no information found in this regard beforehand.
In terms of policy implementation, it is important that the public understands the importance of the transition to a circular economy. Society needs to participate, and so do academia, industry, and government, as - like mentioned before - resources (time, money, and expertise) are limited.

Recommendations for further research

Topics for further research:

Use of critical raw materials in all sectors of the built environment The lack of available information and knowledge observed for the façade sector also applies to the other sectors of the built environment. This thesis has demonstrated the urgency to have a deeper understanding in these regards, while the analysis only looked at one product (one specific type of curtain wall element), in one sector (the façade industry) within the built environment. It can be argued that critical materials play a seemingly much more important role in other sectors e.g. in the building services sector, due to that sector's range of products which are largely motor-operated or sensor-controlled.

The role of design It was only shortly discussed in the thesis that design decisions likely also have a big impact on the final critical material content within a product. This connection needs to be further investigated, e.g. through decision-making analyses.

Lifetime expansion vs. supply and demand The thesis formulates the need to keep materials and products in the loop, as a mitigation strategy for critical materials-related challenges. However, it still needs to be further investigated how lifetime expansion actually affects supply and demand in the long term.

Policymaking and additional policy instruments The policy recommendations formulated in this thesis could be used as a starting point for further discussions. The first step should be to test them with policymakers and other stakeholders to assess their actual feasibility, strengths, and weaknesses. In that sense, the recommendations should be further investigated and worked out.

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Appendix

1 Building Product Passport

Building Product Passport

General information

- Product description
  - Identification code / article number
  - Intended use
- Production year
- Manufacturer information
- Installation instruction
- Exact location of the building
- Number of building elements (within building)
- Responsibilities
  - Business model/take back agreement
  - Ownership
- Operation and functionality
  - Use guide
  - Mainenance
- Environmental impact for each phase / LCA (extraction, production, use, EoL)

Composition of building component/product

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

Circularity

- Expected lifetime
- Description of the end-of-life possibilities
  - Recyclability/reuse rate or potential
    - next opportunities or previous application
  - Recycled/reused components
- Disassembly/removal manual
  - Joining techniques used
  - Guidelines EoL treatment
- Maintenance
- Replaced parts during use
- CRM parameter

Figure 1: Adapted from Meyer [2018]

2 Modelling

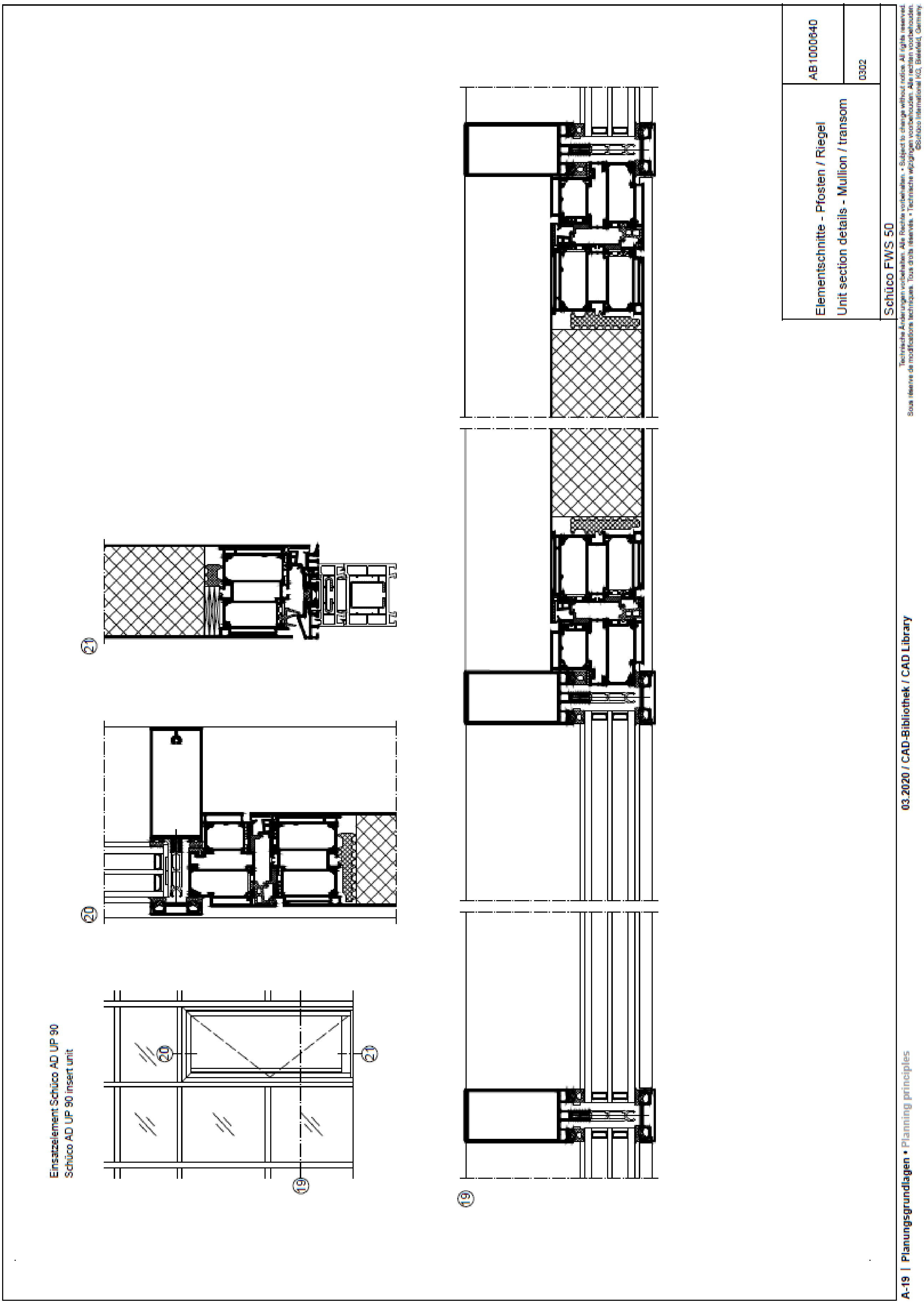

Figure 2: Detail drawing by Schüco, used as the starting point for the modelling

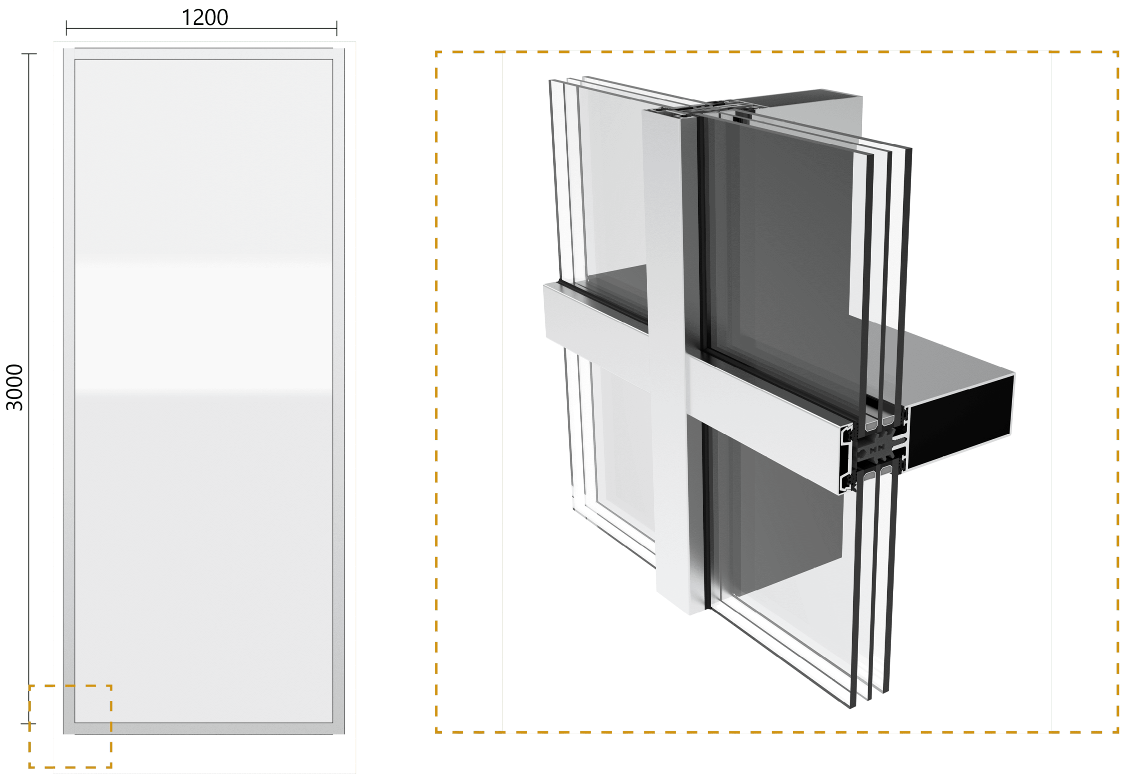

Figure 3: System 1: fully glazed (based on Fig. 2)

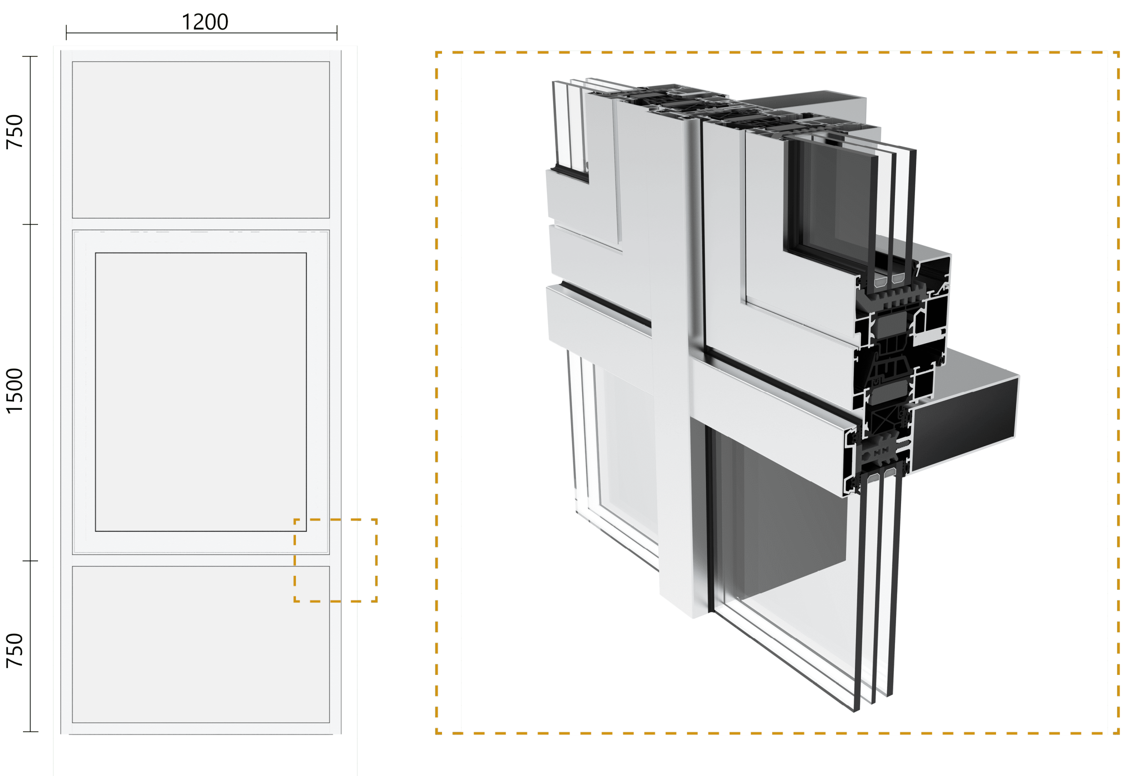

Figure 4: System 2: openable window (based on Fig. 2)

Figure 5: Exploded view of curtain wall components (based on Fig. 2)

3 Analysis: Excel calculations

Part		System 1						System 2					
Component	Sub-Component	Section/Area mm³	Length mm	Volume mm³	Nr.	Volume mm³	Total Volume m³	Section/ Area mm³	Length mm	Volume m³	Nr.	Volume mm³	Total Volume m³
				or volume from Rhino model	esti-mated		/1000000000			or volume from Rhino model			/1000000000
Structure	Mullion	979	3000	2986958	1	2986958	0,003875863	979	3000	2986958	1	2986958	0,005653673
	Transom	768	1150	888905	1	888905		768	1150	888905	3	2666715	
Pressure plate	Pressure plate mullion	170	3000	510000	1	510000	0,0007055	170	3000	510000	1	510000	0,0010965
	Pressure plate transom	170	1150	195500	1	195500		170	1150	195500	3	586500	
Cover cap	Cover cap mullion	112	3000	336000	1	336000	0,00044295	112	3000	336000	1	336000	0,00065685
	Cover cap transom	93	1150	106950	1	106950		93	1150	106950	3	320850	
Connection	transom to mullion connection piece	656	102	66860	2	133720	0,00013372	656	102	66860	6	401160	0,00040116
Window frame	Aluminium - fixed part							401	-	2032768	1	2032768	0,005153063
	Aluminium - openable part							541	-	3120295	1	3120295	
Window frame - thermal break	thermal break - fixed part							671	-	3383210	1	3383210	0,004879181
	thermal break - openable part							318	-	1495971	1	1495971	
Gasket - curtain wall system	mullion - inside gaskets fixed fixed curtain wall	96	-	292824	4	1171296	0,002667768	96	-	292824	4	1171296	0,003219416
	transom - inside gaskets fixed fixed curtain wall	42	-	48851	4	195404		42	-	48851	8	390808	
	mullion - outside gaskets fixed fixed curtain wall	77	-	236206	4	944824		77	-	236206	4	944824	
	transom - outside gaskets fixed fixed curtain wall	77	-	89061	4	356244		77	-	89061	8	712488	
Gasket - openable window	openable window - gasket fixed part							31	-	160881	1	160881	0,000749117
	openable window - gasket openable part							130	-	588236	1	588236	
Insulation	mullion - insulation (half)	206	-	627510	4	2510040	0,00422183	206	-	627510	4	2510040	0,00540109
	transom - insulation (half)	207	-	243535	4	974140		207	-	243535	8	1948280	
	mullion - insulation outside	87	-	266265	2	532530		87	-	266265	2	532530	
	transom - insulation outside	87	-	102560	2	205120		87	-	102560	4	410240	
Insulation - openable window	openable window - fixed part							369	-	1870667	1	1870667	0,005585374
	openable window - openable part							816	-	3714707	1	3714707	
Triple Glazing	6mm glass pane - fixed	3495625	6	20973750	2	41947500	0,052434375	853050	6	5118300	4	20473200	0,044238375
	3mm glass pane - fixed	3495625	3	10486875	1	10486875		853050	3	2559150	2	5118300	
	6mm glass pane - openable							1243125	6	7458750	2	14917500	
	3mm glass pane - openable							1243125	3	3729375	1	3729375	
	Gas infill - fixed	3421249	11	37633739	2	75267478	0,075267478	819864	11	9018504	4	36074016	0,062538894
	Gas infill - openable							1202949	11	13232439	2	26464878	
Glass Edge	Outer sealant -fixed	37	-	306908	2	613816	0,000613816	37	-	140261	4	561044	0,00089283
	Outer sealant - openable							37	-	165893	2	331786	
	Desiccant - fixed	47	-	388498	2	776996	0,000776996	47	-	176843	4	707372	0,001126294
	Desiccant - openable							47	-	209461	2	418922	
	Aluminium bar - fixed	15	-	123097	2	246194	0,000246194	15	-	55998	4	223992	0,000356654
	Aluminium bar - openable							15	-	66331	2	132662	
Connection	Glass setting block alu	126	100	12600	2	25200	0,0000252	126	100	12600	6	75600	0,0000756
Connection	Glass setting block soft					0	0					0	0
Window fixings / hardware [simplified assumption]	frame connections inside corners									51630	4	206520	0,00020652
	hardware frame (inside + outside + hinges = simplified as one continuous edge)									787457	1	787457	0,000787457
Screws	Calculated in other sheet directly!												

Figure 6: Volume calculations of systems A

Part		System 1						System 2					
Component	Sub-Component	Section/Area mm³	Length mm	Volume mm³	Nr.	Volume mm³	Total Volume m³	Section/Area mm³	Length mm	Volume m³	Nr.	Volume mm³	Total Volume m³
				or volume from Rhino model	esti-mated		/1000000000			or volume from Rhino model			/1000000000
Structure	Mullion	979	3000	2986958	1	2986958	0,003875863	979	3000	2986958	1	2986958	0,005653673
	Transom	768	1150	888905	1	888905		768	1150	888905	3	2666715	
Pressure plate	Pressure plate mullion	170	3000	510000	1	510000	0,0007055	170	3000	510000	1	510000	0,0010965
	Pressure plate transom	170	1150	195500	1	195500		170	1150	195500	3	586500	
Cover cap	Cover cap mullion	112	3000	336000	1	336000	0,00044295	112	3000	336000	1	336000	0,00065685
	Cover cap transom	93	1150	106950	1	106950		93	1150	106950	3	320850	
Connection	transom to mullion connection piece	656	102	66860	2	133720	0,00013372	656	102	66860	6	401160	0,00040116
Window frame	Aluminium - fixed part							401	-	2032768	1	2032768	0,005153063
	Aluminium - openable part							541	-	3120295	1	3120295	
Window frame - thermal break	thermal break - fixed part							671	-	3383210	1	3383210	0,004879181
	thermal break - openable part							318	-	1495971	1	1495971	
Gasket - curtain wall system	mullion - inside gaskets fixed fixed curtain wall	96	-	292824	4	1171296	0,002667768	96	-	292824	4	1171296	0,003219416
	transom - inside gaskets fixed fixed curtain wall	42	-	48851	4	195404		42	-	48851	8	390808	
	mullion - outside gaskets fixed curtain wall	77	-	236206	4	944824		77	-	236206	4	944824	
	transom - outside gaskets fixed curtain wall	77	-	89061	4	356244		77	-	89061	8	712488	
Gasket - openable window	openable window - gasket fixed part							31	-	160881	1	160881	0,000749117
	openable window - gasket openable part							130	-	588236	1	588236	
Insulation	mullion - insulation (half)	206	-	627510	4	2510040	0,00422183	206	-	627510	4	2510040	0,00540109
	transom - insulation (half)	207	-	243535	4	974140		207	-	243535	8	1948280	
	mullion - insulation outside	87	-	266265	2	532530		87	-	266265	2	532530	
	transom - insulation outside	87	-	102560	2	205120		87	-	102560	4	410240	
Insulation - openable window	openable window - fixed part							369	-	1870667	1	1870667	0,005585374
	openable window - openable part							816	-	3714707	1	3714707	
Triple Glazing	6mm glass pane - fixed	3495625	6	20973750	2	41947500	0,052434375	853050	6	5118300	4	20473200	0,044238375
	3mm glass pane - fixed	3495625	3	10486875	1	10486875		853050	3	2559150	2	5118300	
	6mm glass pane - openable							1243125	6	7458750	2	14917500	
	3mm glass pane - openable							1243125	3	3729375	1	3729375	
	Gas infill - fixed	3421249	11	37633739	2	75267478	0,075267478	819864	11	9018504	4	36074016	0,062538894
	Gas infill - openable							1202949	11	13232439	2	26464878	
Glass Edge	Outer sealant -fixed	37	-	306908	2	613816	0,000613816	37	-	140261	4	561044	0,00089283
	Outer sealant - openable							37	-	165893	2	331786	
	Desiccant - fixed	47	-	388498	2	776996	0,000776996	47	-	176843	4	707372	0,001126294
	Desiccant - openable							47	-	209461	2	418922	
	Aluminium bar - fixed	15	-	123097	2	246194	0,000246194	15	-	55998	4	223992	0,000356654
	Aluminium bar - openable							15	-	66331	2	132662	
Connection	Glass setting block alu	126	100	12600	2	25200	0,0000252	126	100	12600	6	75600	0,0000756
Connection	Glass setting block soft					0	0					0	0
Window fixings / hardware [simplified assumption]	frame connections inside corners									51630	4	206520	0,00020652
	hardware frame (inside + outside + hinges = simplified as one continuous edge)									787457	1	787457	0,000787457
Screws	Calculated in other sheet directly!												

Figure 7: Volume calculations of systems A

Measurements: outer edge of mullion/transom							
	Unit size:	height	width	nr.	mm²	m²	m²
S	element size	3050	1250	1	3812500	3,81	
S1	Glazing	2950	1150	1	3392500	3,39	
S2	Glazing	700	1150	2	1610000	1,61	2,79
S2	Glazing	945	1245	1	1176525	1,18	

Figure 8: S1+S2a measurements

Measurements: calculation scale-up / middle of mullion/transom							
	Unit size:	height	width	nr.	mm²	m²	m²
S	element size	3050	1250	1	3812500	3,81	
S1	Glazing	2950	1150	1	3392500	3,39	
S2	Glazing	700	1150	2	1610000	1,61	2,79
S2	Glazing	945	1245	1	1176525	1,18	

Figure 9: S1+S2b measurements

SYSTEM LEVEL							ELEMENT LEVEL													
									Granta Edupack			Calculation numbers								
System	Part	Sub-part	Volume per unit (m³)	Unit Volume (m³)	Unit Weight (kg)	Function	|Sensor |Motor |Alloy	Material	Elements	%	Density kg/m³	%	Density (kg/m³)	Amount per element/unit kg	EC CRM list 2023	Unit criticality ~%	Main EU supplier	%	Import reliance %	(main) processing country (%) ?
S1 basis stick and beam system	frame	mullion	0,003	0,005	13,85	horizontal structural element	A	**Aluminium alloy** 6000 series: Al + 1.2% Mg + 0.25% Zn + Si, Fe, Mn) e.g.: 6063-T5 aluminum-magnesium-silicon alloy [a]	Al (aluminium)	97,5 - 99,4	2660 - 2710 kg/m³ [a]	98,45	2685	13,63	YES	99,68	Guinea	63	55	
		transom	0,001			vertical structural element			Cr (chromium)	0,0 - 0,1					NO					
	pressure plate	pressure plate (mullion, transom)	0,001						Cu (copper)	0,0 - 0,1		0,05		0,01	YES (SRM)		Poland	19	48	
	frame	covercap (mullion, transom)	0,000			cover, design			Fe (iron)	0,0 - 0,35					NO					
									Mg (magnesium)	0,45 - 0,9		0,675		0,09	YES		China	97	100	
	connection	transom to mullion connection piece	0,000			connection piece			Mn (manganese)	0,0 - 0,1		0,05		0,01	YES		South Africa	41	96	
									Si (silicon)	0,2 - 0,6		0,4		0,06	YES		Norway	35	64	
	setting block	glass setting block stiff	0,000						Ti (titanium)	0,0 - 0,1		0,05		0,01	YES		Kazakhstan	36	100	
									Zn (zinc)	0,0 - 0,1					NO					
									Other	0,0 - 0,15					-					
	sealants	gaskets	0,003	0,003	2,32	(air)tightness	-	EPDM	Carbon	-	860 - 880 kg/m³	-	870	-	NO	0,00				
									Hydrogen	-		-		-	NO					
	setting block	glass setting block soft cover	0,000																	
		insulation	0,004	0,004	0,46	thermal	-	Extruded polyethylene foam	(CO-(C6H4)-CO-O-(CH2)2-O)n		101 - 115 kg/m³		108		NO	0,00				
	fixings	screws: fixing the transom-to-mullion connection-piece	4 per piece = 16		2,18	fixing (pressure plates on frame)	A	**Stainless steel** AISI 304 (1/8) [a]	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m³	0,04	7955		NO	10,57				
	fixings	screws: fixing transom to mullion + connection piece	4 per piece = 16						-	-		-								
	fixings	screws: pressure plates to frame	~every 20cm = ~40						Cr (chromium)	18 - 20		19			NO					
	fixings	screws: fixing the glass-settingblock to the transom	2 pieces with 2 = 4						Fe (iron)	65,8 - 74		69,9			NO					
									Mn (manganese)	0 - 2		1		0,02	YES		South Africa	41	96	
									Ni (nickel)	8 - 11		9,5		0,21	YES (SRM)		Finland	38	75	
									P (phosphorus)	0 - 0,045		0,0225		0,00	YES		Kazakhstan	65	100	
									S (sulfur)	0 - 0,03		0,015			NO					
									Si (silicon)	0 - 1		0,05		0,00	YES		Norway	35	64	
	insulated glass unit	glazing	0,052	0,052	129,25	visual, aesthetic	-	**Glass pane** Low-e glass / soda-lime glass	SiO2	73	2440 - 2490 kg/m³	73	2465	94,35	-	0,00				
									Al2O3	1		1		1,29	-					
									Na2O	17		17		21,97	NO					
									MgO	4		4		5,17	-					
									CaO	5		5		6,46	NO					
	insulated glass unit	gas filling	0,075			thermal insulation	-	Argon gas	Ar (argon)						NO	0,00				
	insulated glass unit	thermobar aluminium spacer tube	0,0002	0,0002	0,67	edge fixing, spacer	A	**Aluminium alloy** 3004, H19	Al (aluminium)	95,6 - 98,2	2690 - 2750 kg/m³	96,9	2720	0,65	YES	99,48	Guinea	63	55	
									Cu (copper)	0 - 0,25		0,125		0,0008	YES (SRM)		Poland	19	48	
									Fe (iron)	0 - 0,7		0,35			NO					
									Mg (magnesium)	0,8 - 1,3		1,05		0,01	YES		China	97	100	
									Mn (manganese)	1 - 1,5		1,25		0,01	YES		South Africa	41	96	
									Si (silicon)	0 - 0,3		0,15		0,00	YES		Norway	35	64	
									Zn (zinc)	0 - 0,25		0,125			NO					
									Residuals	0 - 0,15		0,075			NO					
	window edge	primary/secondary sealant	0,001	0,001	0,57	sealant	-	Silicon, polyisobutylene	(CH2-C(CH3)-CH-(CH2)2-C(CH3)2)n		910 - 950		930		NO	0,00				
	window edge	desiccant	0,001	0,001	0,70	absorb moisture	-	Silica pellets		SiO2	?		900		-					

	Volume m³	Weight: kg
Total	0,07	150,00

Figure 10: Criticality assessment of System S1a

SYSTEM LEVEL								ELEMENT LEVEL												
									Granta Edupack			Calculation numbers								
System	Part	Sub-part	Volume per unit (m³)	Unit Volume (m³)	Unit Weight (kg)	Function	Sensor / Motor / Alloy	Material	Elements	%	Density kg/m³	%	Density (kg/m³)	Amount per element/unit kg	EC CRM list 2023	Unit criticality ~%	Main EU supplier	%	Import reliance %	(main) processing country (%) ?
S1 basis stick and beam system	frame	mullion	*0,003*	*0,008*	*20,96*	horizontal structural element	A	**Aluminium alloy** 6000 series: Al + 1.2% Mg + 0.25% Zn + Si, Fe, Mn) e.g.: **6063-T5** aluminum-magnesium-silicon alloy [a]	Al (aluminium)	97,5 - 99,4	2660 - 2710 kg/m³ [a]	98,45	2685	20,64	YES	99,68	Guinea	63	55	
		transom	*0,003*			vertical structural element			Cr (chromium)	0,0 - 0,1					NO					
	pressure plate	pressure plate (mullion, transom)	*0,001*						Cu (copper)	0,0 - 0,1		0,05		0,01	YES (SRM)		Poland	19	48	
	frame	covercap (mullion, transom)	*0,001*			cover, design			Fe (iron)	0,0 - 0,35					NO					
									Mg (magnesium)	0,45 - 0,9		0,675		0,14	YES		China	97	100	
	connection	transom to mullion connection piece	0,000			connection piece			Mn (manganese)	0,0 - 0,1		0,05		0,01	YES		South Africa	41	96	
									Si (silicon)	0,2 - 0,6		0,4		0,08	YES		Norway	35	64	
	setting block	glass setting block stiff	0,000						Ti (titanium)	0,0 - 0,1		0,05		0,01	YES		Kazakhstan	36	100	
									Zn (zinc)	0,0 - 0,1					NO					
									Other	0,0 - 0,15					-					
	sealants	gaskets	0,003	0,003	2,80	(air)tightness	-	EPDM	Carbon	-	860 - 880 kg/m³	-	870	-	NO	0,00				
									Hydrogen	-		-		-	NO					
	setting block	glass setting block soft cover	0,000																	
		insulation	0,005	0,005	0,58	thermal	-	Extruded polyethylene foam	(CO-(C6H4)-CO-O-(CH2)2-O)n		101 - 115 kg/m³		108		NO	0,00				
	fixings: stick beam system	screws: fixing the transom-to-mullion connection-piece	4 per piece = 32		2,88	fixing (pressure plates on frame)	A	**Stainless steel** AISI 304 (1/8) [a]	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m³		7955		NO	10,57				
		screws: fixing transom to mullion + connection piece	4 per piece = 32						-	-										
		screws: pressure plates to frame	~every 20cm = ~40+10						Cr (chromium)	18 - 20					NO					
		screws: fixing the glass-	6 pieces						Fe (iron)	65,8 - 74					NO					
									Mn (manganese)	0 - 2		1		0,03	YES		South Africa	41	96	
									Ni (nickel)	8 - 11		9,5		0,27	YES (SRM)		Finland	38	75	
									P (phosphorus)	0 - 0,045		0,0225		0,0006	YES		Kazakhstan	65	100	
									S (sulfur)	0 - 0,03					NO					
									Si (silicon)	0 - 1		0,05		0,00	YES		Norway	35	64	
S1 + S2	insulated glass unit **fixed glazing + openable window**	glazing	0,044	0,044	109,05	visual, aesthetic	-	**Glass pane** Low-e glass / soda-lime glass	SiO2	73	2440 - 2490 kg/m³		2465		-	0,00				
									Al2O3	1					-					
									Na2O	17					NO					
									MgO	4					-					
									CaO	5					NO					
		gas infill	0,063			thermal insulation	-	Argon gas	Ar (argon)						NO	0,00				
		thermobar aluminium spacer tube	0,0004	0,0004	0,97	edge fixing, spacer	A	**Aluminium alloy** 3004, H19	Al (aluminium)	95,6 - 98,2	2690 - 2750 kg/m³	96,9	2720	0,94	YES	99,48	Guinea	63	55	
									Cu (copper)	0 - 0,25		0,125		0,00	YES (SRM)		Poland	19	48	
									Fe (iron)	0 - 0,7					NO					
									Mg (magnesium)	0,8 - 1,3		1,05		0,01	YES		China	97	100	
									Mn (manganese)	1 - 1,5		1,25		0,01	YES		South Africa	41	96	
									Si (silicon)	0 - 0,3		0,15		0,00	YES		Norway	35	64	
									Zn (zinc)	0 - 0,25					NO					
									Residuals	0 - 0,15					NO					
		primary/secondary sealant	0,001	0,001	0,83	sealant	-	Silicon, polyisobutylene	(CH2-C(CH3)-CH-(CH2)2-C(CH3)2)n		910 - 950		930		NO	0,00				
		desiccant	0,001	0,001	1,01	absorb moisture	-	Silica pellets		SiO2	?		900		-					
S2	frame openable window; aluminium	fixed part	0,002	0,005	13,84		A	**Aluminium alloy** 6000 series: Al + 1.2% Mg + 0.25% Zn + Si, Fe, Mn) e.g.: **6063-T5** aluminum-magnesium-silicon alloy [a]	Al (aluminium)	97,5 - 99,4	2660 - 2710 kg/m³ [a]	98,45	2685	13,62	YES	99,68	Guinea	63	55	
		openable part	0,003						Cr (chromium)	0,0 - 0,1					NO					
									Cu (copper)	0,0 - 0,1		0,05		0,01	YES (SRM)		Poland	19	48	
									Fe (iron)	0,0 - 0,35					NO					
		(window handle)							Mg (magnesium)	0,45 - 0,9		0,675		0,09	YES		China	97	100	
									Mn (manganese)	0,0 - 0,1		0,05		0,01	YES		South Africa	41	96	
									Si (silicon)	0,2 - 0,6		0,4		0,06	YES		Norway	35	64	
									Ti (titanium)	0,0 - 0,1		0,05		0,01	YES		Kazakhstan	36	100	
									Zn (zinc)	0,0 - 0,1					NO					
									Other	0,0 - 0,15					-					
	frame openable window	thermal break	0,005	0,005	5,12	separating inner and outer sash, thermal performance	-	PUR (Polyurethane plastic) (PUR®	(NH-R-NH-CO-O-R'-O-CO)n		1040 - 1060		1050		NO					
	sealants	gaskets	0,001	0,001	0,65	(air)tightness	-	EPDM	Carbon	-	860 - 880 kg/m³	-	870	-	NO	0,00				
									Hydrogen	-		-		-	NO					
	setting block	glass setting block soft cover	0,000																	
	window frame	insulation	0,006	0,006	0,60	thermal	-	Extruded polyethylene foam	(CO-(C6H4)-CO-O-(CH2)2-O)n		101 - 115 kg/m³		108		NO	0,00				
	window hardware (simplified)	corners - connections window frame	0,0002065	0,000994	7,91		A	**Stainless steel** AISI 304 (1/8) [a]	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m³		7955		NO	10,57				
									Cr (chromium)	18 - 20					NO					
									Fe (iron)	65,8 - 74					NO					
		hardware frame (inside + outside + hinges = simplified as one continuous edge)	0,0007875						Mn (manganese)	0 - 2		1		0,08	YES		South Africa	41	96	
									Ni (nickel)	8 - 11		9,5		0,75	YES (SRM)		Finland	38	75	
		screws: window frame corners	*for now included in overall hardware assumption*		0,00	fixing connections,			P (phosphorus)	0 - 0,045		0,0225		0,00	YES		Kazakhstan	65	100	
		screws: window to stick system							S (sulfur)	0 - 0,03					NO					
		screws: handle fixing							Si (silicon)	0 - 1		0,05		0,00	YES		Norway	35	64	
		screws: fixing hardware to frame																		

	Volume	Weight:
	m³	kg
Total	0,08	167,21

Figure 11: Criticality assessment of System S2a

SYSTEM LEVEL								ELEMENT LEVEL												
										Granta Edupack			Calculation numbers							
System	Part	Sub-part	Volume per unit (m^3)	Unit Volume (m^3)	Unit Weight (kg)	Function	|Sensor |Motor |Alloy	Material	Elements	%	Density kg/m^3	%	Density (kg/m^3)	Amount per element/unit kg	EC CRM list 2023	Unit criticality ~%	Main EU supplier	%	Import reliance %	(main) processing country (%) ?
S1 basis stick and beam system	frame	mullion	0,003	0,005	13,85	horizontal structural element	A	**Aluminium alloy** 6000 series: Al + 1.2% Mg + 0.25% Zn + Si, Fe, Mn) e.g.: 6063-T5 aluminum-magnesium-silicon alloy [a]	Al (aluminium)	97,5 - 99,4	2660 - 2710 kg/m^3 [a]	98,45	2685	13,63	YES	99,68	Guinea	63	55	
		transom	0,001			vertical structural element			Cr (chromium)	0,0 - 0,1					NO					
	pressure plate	pressure plate (mullion, transom)	0,001						Cu (copper)	0,0 - 0,1		0,05		0,01	YES (SRM)		Poland	19	48	
	frame	covercap (mullion, transom)	0,000			cover, design			Fe (iron)	0,0 - 0,35					NO					
									Mg (magnesium)	0,45 - 0,9		0,675		0,09	YES		China	97	100	
	connection	transom to mullion connection piece	0,000			connection piece			Mn (manganese)	0,0 - 0,1		0,05		0,01	YES		South Africa	41	96	
									Si (silicon)	0,2 - 0,6		0,4		0,06	YES		Norway	35	64	
	setting block	glass setting block stiff	0,000						Ti (titanium)	0,0 - 0,1		0,05		0,01	YES		Kazakhstan	36	100	
									Zn (zinc)	0,0 - 0,1					NO					
									Other	0,0 - 0,15					-					
	sealants	gaskets	0,003	0,003	2,32	(air)tightness	-	EPDM	Carbon	-	860 - 880 kg/m^3	-	870	-	NO	0,00				
									Hydrogen	-		-		-	NO					
	setting block	glass setting block soft cover	0,000																	
		insulation	0,004	0,004	0,46	thermal	-	Extruded polyethylene foam	(CO-(C6H4)-CO-O-(CH2)2-O)n		101 - 115 kg/m^3		108		NO	0,00				
	fixings	screws: fixing the transom-to-mullion connection-piece	4 per piece = 16		2,18	fixing (pressure plates on frame)	A	**Stainless steel** AISI 304 (1/8) [a]	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m^3	0,04	7955		NO	10,57				
	fixings	screws: fixing transom to mullion + connection piece	4 per piece = 16						-	-		-								
	fixings	screws: pressure plates to frame	~every 20cm = ~40						Cr (chromium)	18 - 20		19			NO					
	fixings	screws: fixing the glass-settingblock to the transom	2 pieces with 2 = 4						Fe (iron)	65,8 - 74		69,9			NO					
									Mn (manganese)	0 - 2		1		0,02	YES		South Africa	41	96	
									Ni (nickel)	8 - 11		9,5		0,21	YES (SRM)		Finland	38	75	
									P (phosphorus)	0 - 0,045		0,0225		0,00	YES		Kazakhstan	65	100	
									S (sulfur)	0 - 0,03		0,015			NO					
									Si (silicon)	0 - 1		0,05		0,00	YES		Norway	35	64	
	insulated glass unit	glazing	0,052	0,052	129,25	visual, aesthetic	-	**Glass pane** Low-e glass / soda-lime glass	SiO_2	73	2440 - 2490 kg/m^3	73	2465	94,35	-	0,00				
									Al_2O_3	1		1		1,29	-					
									Na_2O	17		17		21,97	NO					
									MgO	4		4		5,17	-					
									CaO	5		5		6,46	NO					
	insulated glass unit	gas filling	0,075			thermal insulation	-	Argon gas	Ar (argon)						NO	0,00				
	insulated glass unit	thermobar aluminium spacer tube	0,0002	0,0002	0,67	edge fixing, spacer	A	**Aluminium alloy** 3004, H19	Al (aluminium)	95,6 - 98,2	2690 - 2750 kg/m^3	96,9	2720	0,65	YES	99,48	Guinea	63	55	
									Cu (copper)	0 - 0,25		0,125		0,0008	YES (SRM)		Poland	19	48	
									Fe (iron)	0 - 0,7		0,35			NO					
									Mg (magnesium)	0,8 - 1,3		1,05		0,01	YES		China	97	100	
									Mn (manganese)	1 - 1,5		1,25		0,01	YES		South Africa	41	96	
									Si (silicon)	0 - 0,3		0,15		0,00	YES		Norway	35	64	
									Zn (zinc)	0 - 0,25		0,125			NO					
									Residuals	0 - 0,15		0,075			NO					
	window edge	primary/secondary sealant	0,001	0,001	0,57	sealant	-	Silicon, polyisobutylene	(CH2-C(CH3)-CH-(CH2)2-C(CH3)2)n		910 - 950		930		NO	0,00				
	window edge	desiccant	0,001	0,001	0,70	absorb moisture	-	Silica pellets		SiO_2	?		900		-					

	Volume m^3	Weight: kg
Total	0,07	150,00

Figure 12: Criticality assessment of System S1b

SYSTEM LEVEL							ELEMENT LEVEL													
									Granta Edupack			Calculation numbers								
System	Part	Sub-part	Volume per unit (m³)	Unit Volume (m³)	Unit Weight (kg)	Function	Sensor / Motor / Alloy	Material	Elements	%	Density kg/m³	%	Density (kg/m³)	Amount per element/unit kg	EC CRM list 2023	Unit criticality ~%	Main EU supplier	%	Import reliance %	(main) processing country (%) ?
S1 basis stick and beam system	frame	mullion	*0,003*	*0,008*	*20,96*	horizontal structural element	A	**Aluminium alloy** 6000 series: Al + 1.2% Mg + 0.25% Zn + Si, Fe, Mn) e.g.: **6063-T5** aluminum-magnesium-silicon alloy [a]	Al (aluminium)	97,5 - 99,4	2660 - 2710 kg/m³ [a]	98,45	2685	20,64	YES	99,68	Guinea	63	55	
		transom	*0,003*			vertical structural element			Cr (chromium)	0,0 - 0,1					NO					
	pressure plate	pressure plate (mullion, transom)	*0,001*						Cu (copper)	0,0 - 0,1		0,05		0,01	YES (SRM)		Poland	19	48	
	frame	covercap (mullion, transom)	*0,001*			cover, design			Fe (iron)	0,0 - 0,35					NO					
									Mg (magnesium)	0,45 - 0,9		0,675		0,14	YES		China	97	100	
	connection	transom to mullion connection piece	0,000			connection piece			Mn (manganese)	0,0 - 0,1		0,05		0,01	YES		South Africa	41	96	
									Si (silicon)	0,2 - 0,6		0,4		0,08	YES		Norway	35	64	
	setting block	glass setting block stiff	0,000						Ti (titanium)	0,0 - 0,1		0,05		0,01	YES		Kazakhstan	36	100	
									Zn (zinc)	0,0 - 0,1					NO					
									Other	0,0 - 0,15					-					
	sealants	gaskets	0,003	0,003	2,80	(air)tightness	-	EPDM	Carbon	-	860 - 880 kg/m³	-	870	-	NO	0,00				
	setting block	glass setting block soft cover	0,000						Hydrogen	-		-		-	NO					
		insulation	0,005	0,005	0,58	thermal	-	Extruded polyethylene foam	(CO-(C6H4)-CO-O-(CH2)2-O)n		101 - 115 kg/m³		108		NO	0,00				
	fixings: stick beam system	screws: fixing the transom-to-mullion connection-piece	4 per piece = 32		2,88	fixing (pressure plates on frame)	A	**Stainless steel** AISI 304 (1/8) [a]	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m³		7955		NO	10,57				
		screws: fixing transom to mullion + connection piece	4 per piece = 32						-	-										
		screws: pressure plates to frame	~every 20cm = ~40+10						Cr (chromium)	18 - 20					NO					
		screws: fixing the glass-settingblock to the transom	6 pieces with 2 = 12						Fe (iron)	65,8 - 74					NO					
									Mn (manganese)	0 - 2		1		0,03	YES		South Africa	41	96	
									Ni (nickel)	8 - 11		9,5		0,27	YES (SRM)		Finland	38	75	
									P (phosphorus)	0 - 0,045		0,0225		0,0006	YES		Kazakhstan	65	100	
									S (sulfur)	0 - 0,03					NO					
									Si (silicon)	0 - 1		0,05		0,00	YES		Norway	35	64	
S1 + S2	insulated glass unit **fixed glazing + openable window**	glazing	0,044	0,044	109,05	visual, aesthetic	-	**Glass pane** Low-e glass / soda-lime glass	SiO2	73	2440 - 2490 kg/m³		2465		-	0,00				
									Al2O3	1					-					
									Na2O	17					NO					
									MgO	4					-					
									CaO	5					NO					
		gas infill	0,063			thermal insulation	-	Argon gas	Ar (argon)						NO	0,00				
		thermobar aluminium spacer tube	0,0004	0,0004	0,97	edge fixing, spacer	A	**Aluminium alloy** 3004, H19	Al (aluminium)	95,6 - 98,2	2690 - 2750 kg/m³	96,9	2720	0,94	YES	99,48	Guinea	63	55	
									Cu (copper)	0 - 0,25		0,125		0,00	YES (SRM)		Poland	19	48	
									Fe (iron)	0 - 0,7					NO					
									Mg (magnesium)	0,8 - 1,3		1,05		0,01	YES		China	97	100	
									Mn (manganese)	1 - 1,5		1,25		0,01	YES		South Africa	41	96	
									Si (silicon)	0 - 0,3		0,15		0,00	YES		Norway	35	64	
									Zn (zinc)	0 - 0,25					NO					
									Residuals	0 - 0,15					NO					
		primary/secondary sealant	0,001	0,001	0,83	sealant	-	Silicon, polyisobutylene	(CH2-C(CH3)-CH-(CH2)2-C(CH3)2)n		910 - 950		930		NO	0,00				
		desiccant	0,001	0,001	1,01	absorb moisture	-	Silica pellets		SiO2	?		900		-					
S2	frame openable window; aluminium	fixed part	0,002	0,005	13,84		A	**Aluminium alloy** 6000 series: Al + 1.2% Mg + 0.25% Zn + Si, Fe, Mn) e.g.: **6063-T5** aluminum-magnesium-silicon alloy [a]	Al (aluminium)	97,5 - 99,4	2660 - 2710 kg/m³ [a]	98,45	2685	13,62	YES	99,68	Guinea	63	55	
		openable part	0,003						Cr (chromium)	0,0 - 0,1					NO					
									Cu (copper)	0,0 - 0,1		0,05		0,01	YES (SRM)		Poland	19	48	
									Fe (iron)	0,0 - 0,35					NO					
		(window handle)							Mg (magnesium)	0,45 - 0,9		0,675		0,09	YES		China	97	100	
									Mn (manganese)	0,0 - 0,1		0,05		0,01	YES		South Africa	41	96	
									Si (silicon)	0,2 - 0,6		0,4		0,06	YES		Norway	35	64	
									Ti (titanium)	0,0 - 0,1		0,05		0,01	YES		Kazakhstan	36	100	
									Zn (zinc)	0,0 - 0,1					NO					
									Other	0,0 - 0,15					-					
	frame openable window	thermal break	0,005	0,005	5,12	separating inner and outer sash, thermal performance	-	PUR (Polyurethane plastic) (PUR®	(NH-R-NH-CO-O-R'-O-CO)n		1040 - 1060		1050		NO					
	sealants	gaskets	0,001	0,001	0,65	(air)tightness	-	EPDM	Carbon	-	860 - 880 kg/m³	-	870	-	NO	0,00				
	setting block	glass setting block soft cover	0,000						Hydrogen	-		-		-	NO					
	window frame	insulation	0,006	0,006	0,60	thermal	-	Extruded polyethylene foam	(CO-(C6H4)-CO-O-(CH2)2-O)n		101 - 115 kg/m³		108		NO	0,00				
	window hardware (simplified)	corners - connections window frame	0,0002065	0,000994	7,91		A	**Stainless steel** AISI 304 (1/8) [a]	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m³		7955		NO	10,57				
									Cr (chromium)	18 - 20					NO					
									Fe (iron)	65,8 - 74					NO					
		hardware frame (inside + outside + hinges = simplified as one continuous edge)	0,0007875						Mn (manganese)	0 - 2		1		0,08	YES		South Africa	41	96	
									Ni (nickel)	8 - 11		9,5		0,75	YES (SRM)		Finland	38	75	
		screws: window frame corners	*for now included in overall hardware assumption*		0,00	fixing connections,			P (phosphorus)	0 - 0,045		0,0225		0,00	YES		Kazakhstan	65	100	
		screws: window to stick system							S (sulfur)	0 - 0,03					NO					
		screws: handle fixing							Si (silicon)	0 - 1		0,05		0,00	YES		Norway	35	64	
		screws: fixing hardware to frame																		

	Volume	Weight:
	m³	kg
Total	0,08	167,21

Figure 13: Criticality assessment of System S2b

kg	Aluminium	Antimony	Arsenic	Baryte	Beryllium	Bismuth	Boron/borate	Cobalt	Coking coal	Feldspar	Fluorspar	Gallium	Germanium
System 1	14,28	-	-	-	-	-	-	-	-	-	-	-	-
System 2	35,20	-	-	-	-	-	-	-	-	-	-	-	-

kg	LREE	Magnesium	Manganese	Natural Graphite	Niobium	PGM	Phosphate rock	Phosphorus	Scandium	Silicon metal	Strontium	Tantalum	Titanium metal
System 1	-	0,10	0,04	-	-	-	-	0,0005	-	0,06	-	-	0,01
System 2		0,25	0,14	-	-	-	-	0,0024	-	0,15	-	-	0,02

	COMPLETE SYSTEM		
	Total weight	CRMs weight	CRMs %
	kg	kg	%
System 1	150,00	14,70	9,80
System 2	167,21	36,79	22,00

Glass
kg
129,25
109,05

WITHOUT GLASS		
Total	CRMs	CRMs %
kg	kg	%
20,75	14,70	70,86
58,16	36,79	63,26

Figure 14: S1+S2a results

kg	Aluminium	Antimony	Arsenic	Baryte	Beryllium	Bismuth	Boron/borate	Cobalt	Coking coal	Feldspar	Fluorspar	Gallium	Germanium
System 1	14,28	-	-	-	-	-	-	-	-	-	-	-	-
System 2	35,20	-	-	-	-	-	-	-	-	-	-	-	-

kg	LREE	Magnesium	Manganese	Natural Graphite	Niobium	PGM	Phosphate rock	Phosphorus	Scandium	Silicon metal	Strontium	Tantalum	Titanium metal
System 1	-	0,10	0,04	-	-	-	-	0,0005	-	0,06	-	-	0,01
System 2		0,25	0,14	-	-	-	-	0,0024	-	0,15	-	-	0,02

	COMPLETE SYSTEM		
	Total weight	CRMs weight	CRMs %
	kg	kg	%
System 1	150,00	14,70	9,80
System 2	167,21	36,79	22,00

Glass
kg
129,25
109,05

WITHOUT GLASS		
Total	CRMs	CRMs %
kg	kg	%
20,75	14,70	70,86
58,16	36,79	63,26

Figure 15: S1+S2b results

4 Policy instruments X Recommendations

POLICY x product passport		Recommendation 1: documentation on CRM content					
		General information			Composition (CRMs)		
Policy instruments		- Product description - Production year - Manufacturer information - Installation instruction	- Responsibilities (business model / take back agreement, ownership) - Operation and functionality (user guide, maintenance)	- environmental impact for each phase / LCA (extraction, production, use, EoL)	- Product components - Bill of materials (description of **material content and composition** of a product): list and weight, identification of CRMs	- Origin of the materials used in the product - Processing information / **manufacturing process** (how are materials constructed, joined, treated, coated; **feasibility of material recovery**)	- Reason why this material was chosen (**purpose / functionality**) - Product design specification, environmental design aspects
Regulatory Instruments	Technology-based standards [1], Revising existing norms and standards [2]	×	-	-	-	-	-
	Performance-based standards [1], Revising existing norms and standards [2]	×	-	-	-	-	-
Economic Instrument	Emission charges and taxes [1], carbon taxes [2], tax exemptions [2]	×	✓	✓	×	✓	✓
	Product charges and taxes [1], tax exemptions [2]	×	✓	✓	×	✓	✓
	User charges [1]	×	×	×	×	×	×
	Marketable (tradable, transferable) permits [1]	×	✓	×	×	×	×
	Deposit-refund systems [1]	×	✓	✓	×	×	×
	Non-compliance fees [1]	×	✓	✓	✓	✓	✓
	Performance bonds [1]	×	✓	✓	×	×	×
	Liability payments [1]	×	✓	✓	✓	✓	✓
	Environmental subsidies [1]	×	✓	✓	✓	✓	✓
Information tools	Public information campaign [1], awareness campaigns [2]	✓	✓	✓	✓	✓	✓
	Technological information diffusion programs [1], knowledge transfer and redesign [2]	✓	✓	✓	✓	✓	✓
	Environmental labeling schemes [1]	✓	✓	✓	✓	✓	✓
	Free information exchange [2]	✓	✓	✓	✓	✓	✓
Voluntary policy tools	Unilateral commitment of declaration [1]	✓	✓	✓	✓	✓	✓
	Negotiated agreement or commitment [1]	✓	✓	✓	✓	✓	✓
	Selective regulation or public voluntary program [1]	✓	✓	✓	✓	✓	✓
Research + development	Support for research and development in the private sector, direct commitment [1]	✓	✓	✓	✓	✓	✓

[1] Kibert (2002)
[2] Bucci Ancapi et al. (2022)
Source product passport: Meyer (2018)

Figure 16: Checklist policy instruments and Recommendation 1

POLICY x limitations		Recommendation 2: limitation of CRM content			
Policy instruments		**limits per components**	**limits per system**	**thresholds (%)**	**ranges (%-%)**
Regulatory Instruments	Technology-based standards [1], Revising existing norms and standards [2]	-	-	-	-
	Performance-based standards [1], Revising existing norms and standards [2]	✓	✓	✓	✓
Economic Instrument	Emission charges and taxes [1], carbon taxes [2], tax exemptions [2]	-	-	-	-
	Product charges and taxes [1], tax exemptions [2]	✓	✓	✓	✓
	User charges [1]	×	×	×	×
	Marketable (tradable, transferable) permits [1]	×	×	×	×
	Deposit-refund systems [1]	×	×	×	×
	Non-compliance fees [1]	✓	✓	✓	✓
	Performance bonds [1]	×	×	×	×
	Liability payments [1]	✓	✓	✓	✓
	Environmental subsidies [1]	✓	✓	✓	✓
Information tools	Public information campaign [1],	✓	✓	✓	✓
	Technological information diffusion programs [1], knowledge transfer and redesign [2]	✓	✓	✓	✓
	Environmental labeling schemes [1]	✓	✓	✓	✓
	Free information exchange [2]	✓	✓	✓	✓
Voluntary policy tools	Unilateral commitment of declaration [1]	✓	✓	✓	✓
	Negotiated agreement or commitment [1]	✓	✓	✓	✓
	Selective regulation or public voluntary program [1]	✓	✓	✓	✓
Research + development	Support for research and development in the private sector, direct commitment [1]	✓	✓	✓	✓

[1] Kibert (2002)
[2] Bucci Ancapi et al. (2022)

Figure 17: Checklist policy instruments and Recommendation 2

POLICY x R-STRATEGIES		Recommendation 3: design + circular strategies									
Policy instruments		smarter product use and manufacture			extend lifespan of product and its parts					useful applications of materials	
		R0 Refuse	R1 Rethink	R2 Reduce	R3 Re-use	R4 Repair	R5 Refurbish	R6 Remanufacture	R7 Repurpose	R8 Recycle	R9 Recover
Regulatory Instruments	Technology-based standards [1], Revising existing norms and standards [2]	×	×	×	✓	✓	✓	✓	✓	✓	×
	Performance-based standards [1], Revising existing norms and standards [2]	'×	'×	'×	✓	✓	✓	✓	✓	✓	'×
Economic Instrument	Emission charges and taxes [1], carbon taxes [2], tax exemptions [2]	×	×	✓	✓	✓	✓	✓	✓	✓	✓
	Product charges and taxes [1], tax exemptions [2]	×	×	✓	✓	✓	✓	✓	✓	✓	✓
	User charges [1]	×	×	×	×	×	×	×	×	×	×
	Marketable (tradable, transferable) permits [1]	×	×	×	×	×	×	×	×	✓	×
	Deposit-refund systems [1]	×	×	×	✓	✓	✓	✓	✓	✓	×
	Non-compliance fees [1]	×	×	×	×	✓	✓	✓	×	✓	×
	Performance bonds [1]	×	×	×	×	×	×	×	×	×	×
	Liability payments [1]	×	×	×	×	×	×	×	×	×	×
	Environmental subsidies [1]	×	×	×	×	×	×	×	×	×	×
Information tools	Public information campaign [1], awareness campaigns [2]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Technological information diffusion programs [1], knowledge transfer and redesign [2]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Environmental labeling schemes [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Free information exchange [2]	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Voluntary policy tools	Unilateral commitment of declaration [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Negotiated agreement or commitment [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Selective regulation or public voluntary program [1]	-	-	-	✓	✓	✓	✓	✓	✓	✓
Research + development	Support for research and development in the private sector, direct commitment [1]	×	✓	✓	✓	✓	✓	✓	✓	✓	✓

[1] Kibert (2002)
[2] Bucci Ancapi et al. (2022)
Source R-strategies: PBL (2018)

Figure 18: Checklist policy instruments and Recommendation 3

POLICY x business models		Recommendation 4: circular business models											
		design solutions (extend lifespan of product and its parts)		use solutions						recovery solutions			
Policy instruments		circular supply: development of new materials	product and process design: strategic plan through the value chain	lifetime extension (engineering solutions like dis-/reassembly, repair, maintenance, upgrade	product-as-a-service	sell and buy back	tracking of materials, components or parts	sharing platforms	tracking facility	support lifecycle: consumables, spare parts, add-ons	recycled material becomes resource: recapture material suppliers, recycling facility	recovery provider: take back systems and collection services	refurbish and maintain
Regulatory Instruments	Technology-based standards [1], Revising existing norms and standards [2]	✓	✓	✓	✓	-	×	×	×	✓	✓	×	×
	Performance-based standards [1], Revising existing norms and standards [2]	✓	✓	✓	✓	-	✓	×	×	✓	✓	×	✓
Economic Instrument	Emission charges and taxes [1], carbon taxes [2], tax exemptions [2]	✓	✓	✓	✓	×	×	×	×	×	×	×	×
	Product charges and taxes [1], tax exemptions [2]	✓	✓	✓	✓	×	×	×	×	×	×	×	✓
	User charges [1]	×	×	×	✓	✓	-	-	-	-	×	✓	✓
	Marketable (tradable, transferable) permits [1]	×	×	✓	✓	-	-	-	✓	✓	✓	✓	✓
	Deposit-refund systems [1]	×	×	×	×	✓	×	×	×	×	×	✓	×
	Non-compliance fees [1]	✓	✓	✓	✓	✓	×	×	×	✓	✓	✓	✓
	Performance bonds [1]	✓	✓	✓	-	-	-	-	-	✓	-	-	✓
	Liability payments [1]	✓	✓	✓	-	-	-	-	-	-	-	-	-
	Environmental subsidies [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Information tools	Public information campaign [1],	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Technological information diffusion programs [1], knowledge transfer and redesign [2]	✓	✓	✓	✓	✓	-	-	✓	✓	✓	✓	✓
	Environmental labeling schemes [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Free information exchange [2]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Voluntary policy tools	Unilateral commitment of declaration [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Negotiated agreement or commitment [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Selective regulation or public voluntary program [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Research + development	Support for research and development in the private sector, direct commitment [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

[1] Kibert (2002)
[2] Bucci Ancapi et al. (2022)
Source CBMs: Arup and BAM (2018)

Figure 19: Checklist policy instruments and Recommendation 4