GRADUATION PRESENTATION

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

Alexandra Fröwis | 5594774

26th June 2023

Mentors: Dr. Olga Ioannou, FPD | Dr. David Peck, CD

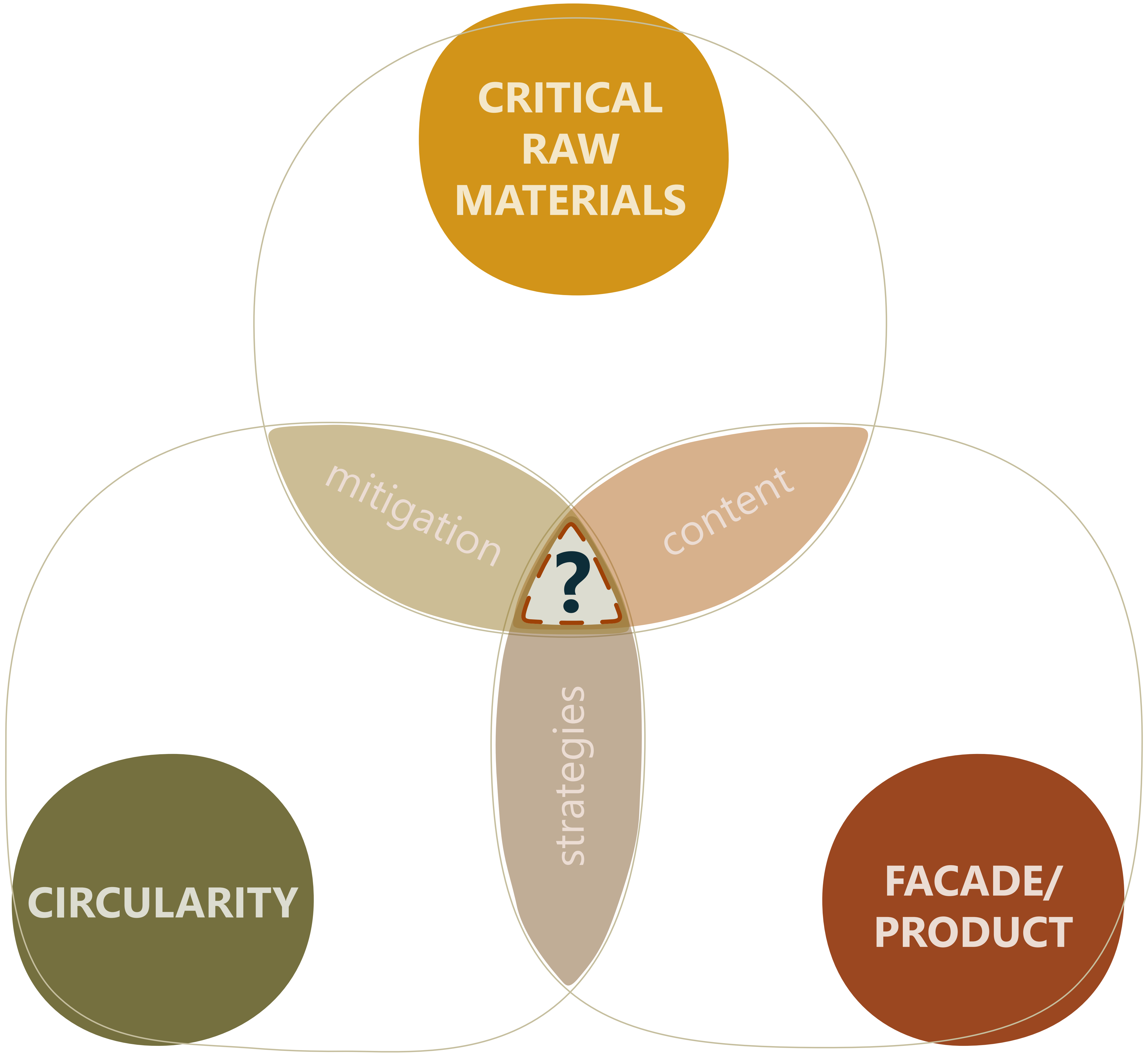
Delegate: Dr. Arie Romein

DELFT UNIVERSITY OF TECHNOLOGY

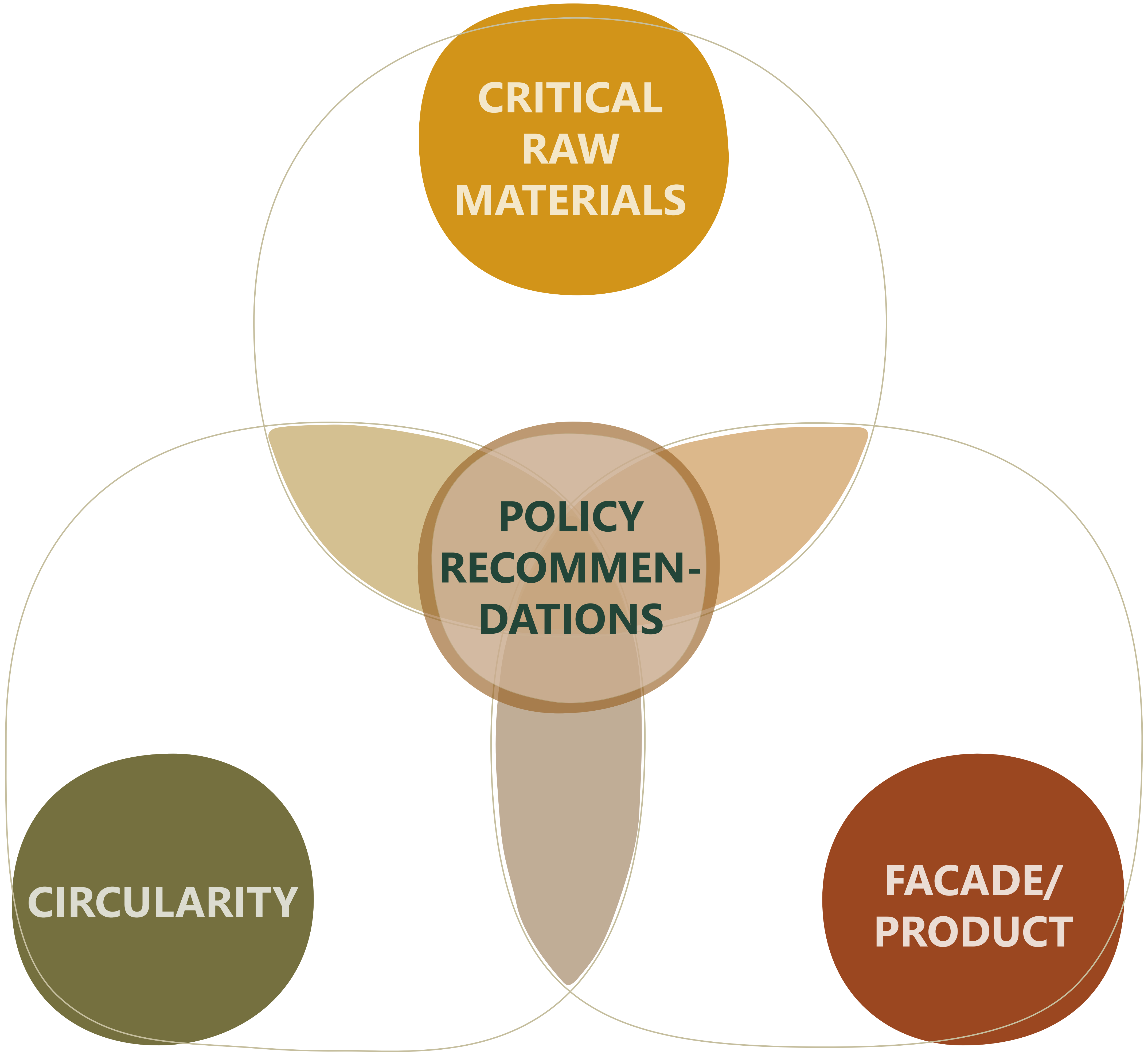
Faculty of Architecture and the Built Environment

MSc Building Technology

Introduction
Fields



Introduction
Goal



Overview
Presentation content

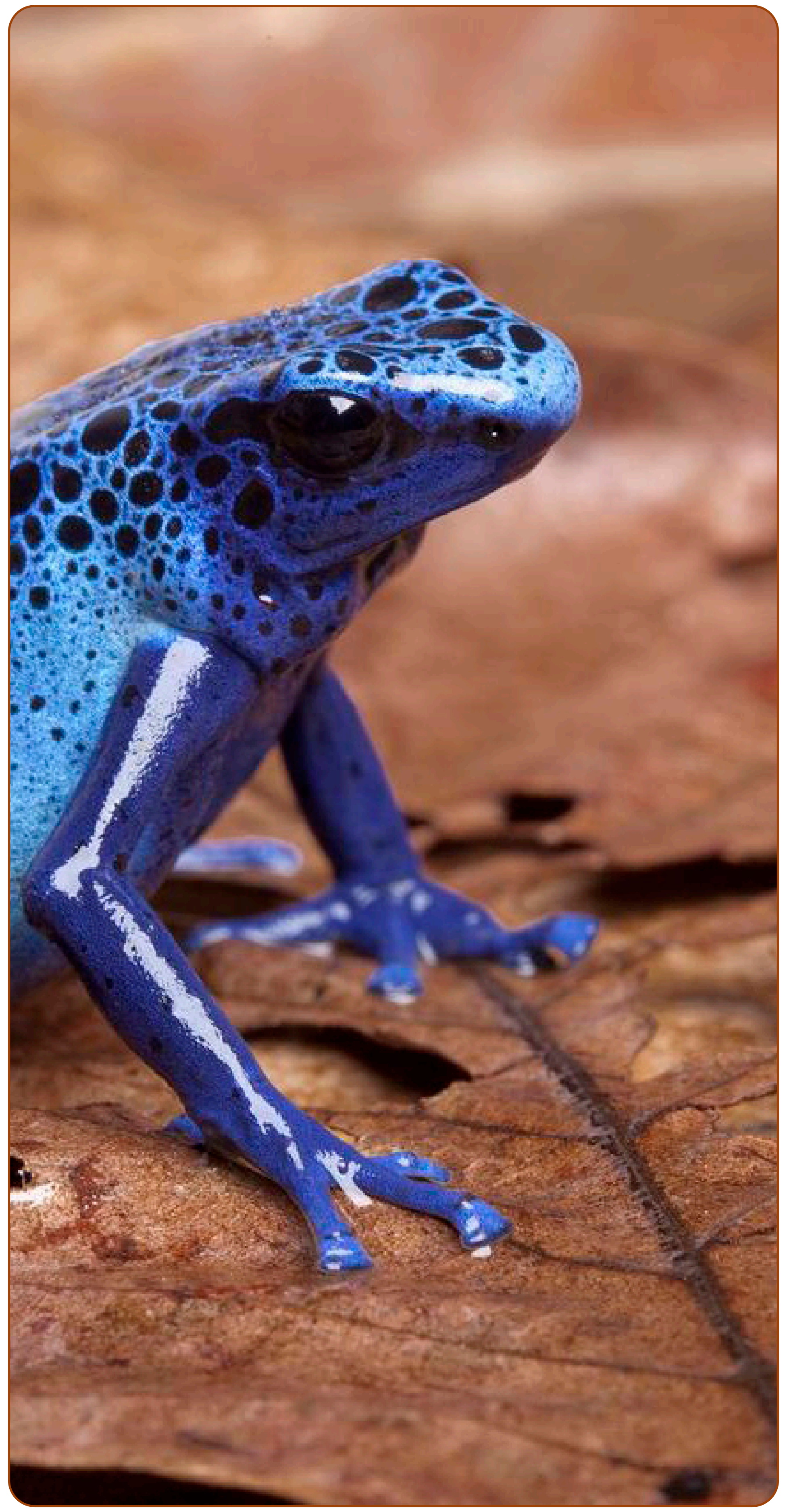
content

INTRO + LITERATURE	background research overview literature review
FAÇADE ANALYSIS	ANALYSIS: method ANALYSIS: results
POLICY	overview policymaking material policies newest developments
RECOMMEN-DATIONS	chapter conclusions recommendations reflection, conclusion, outlook

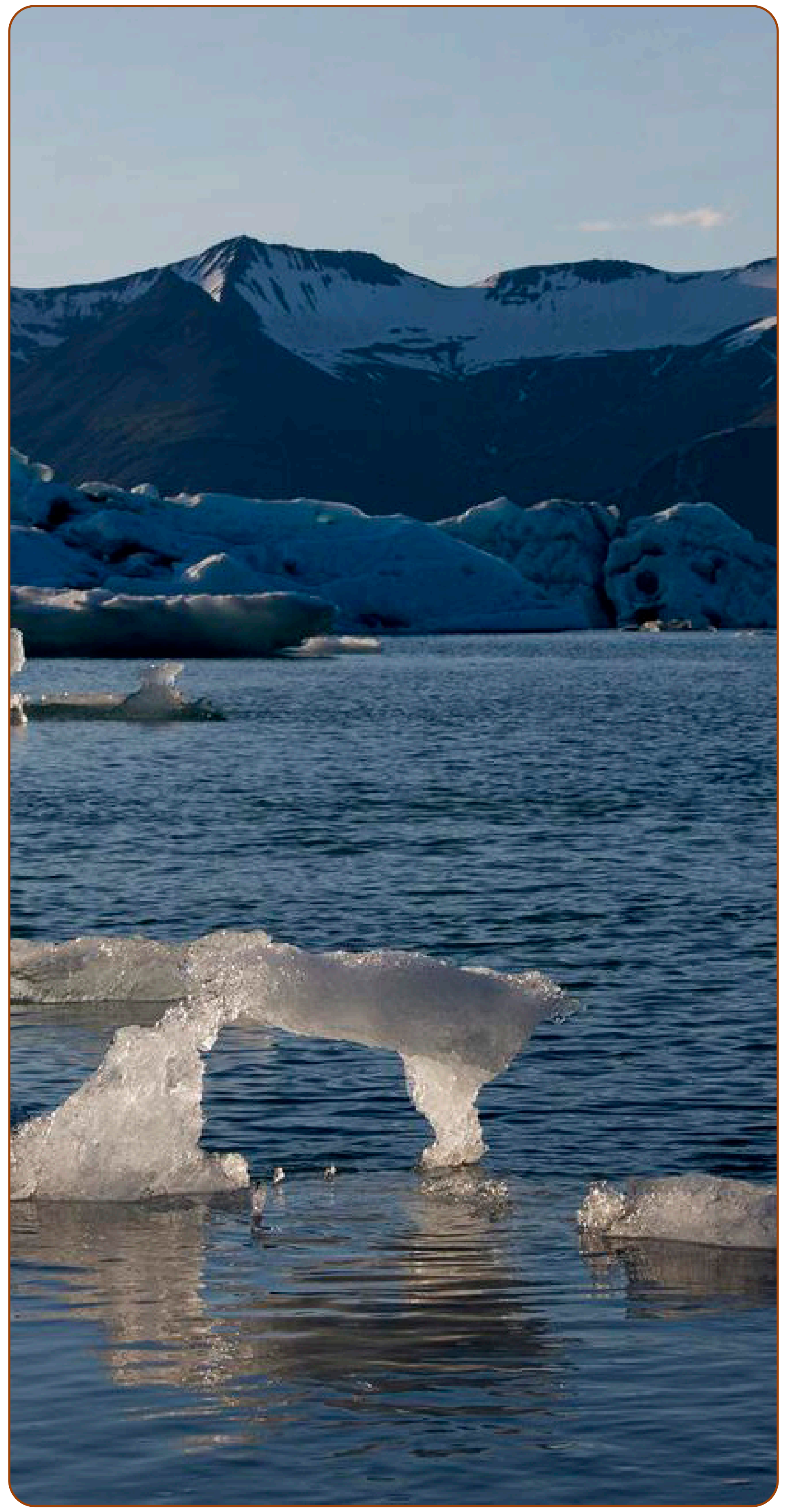
introduction
+ literature

Coffee plants destroyed by frost, São Paulo

Wildfire smoke in Multnomah County, Oregon



Threatened by habitat loss: poison dart frog

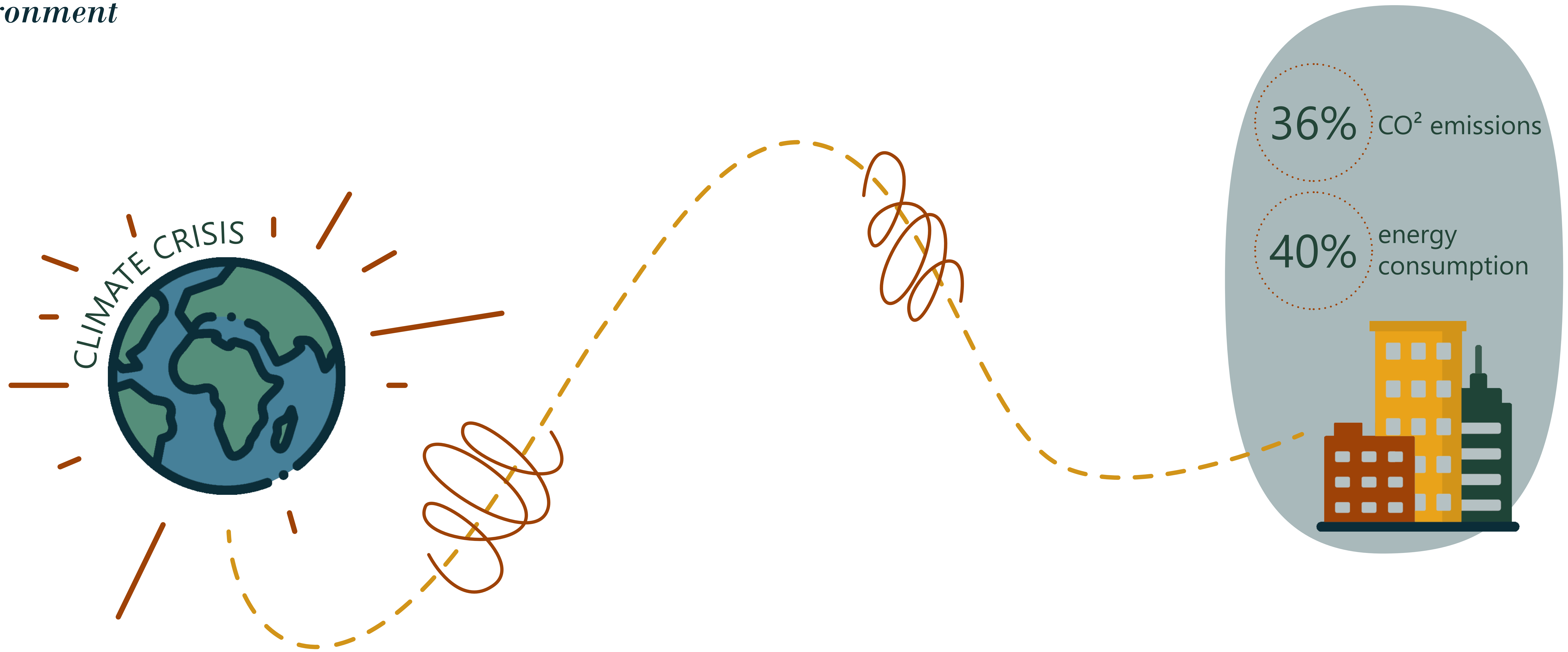


Lake at Jökulsárlón, Iceland, growing because of glacial melting

Flood following Super Typhoon Noru, Bulancan Province, Philippines

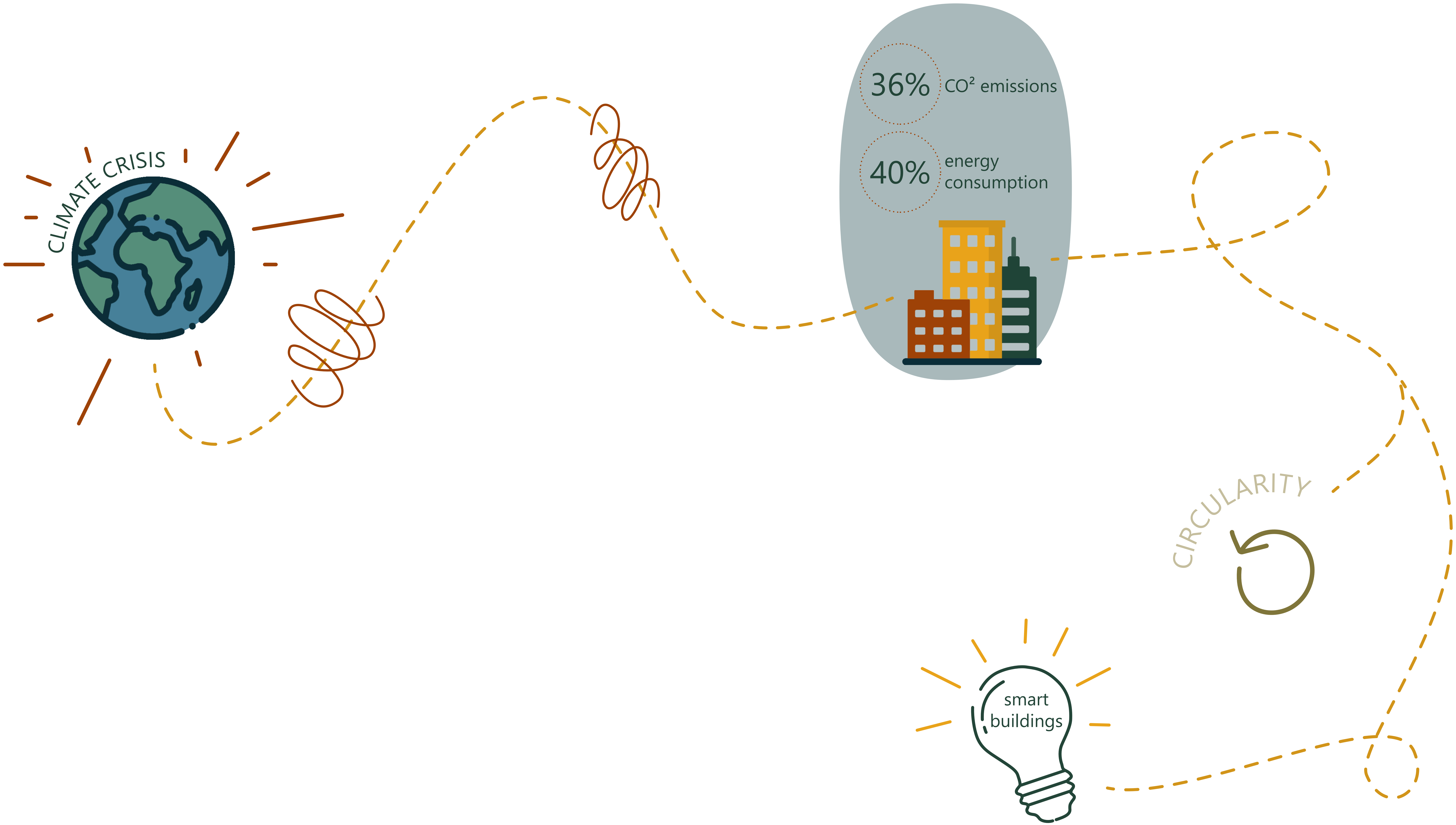
Lindwall, C. (n.d.). *What Are the Effects of Climate Change? NRDC.* https://www.nrdc.org/stories/what-are-effects-climate-change

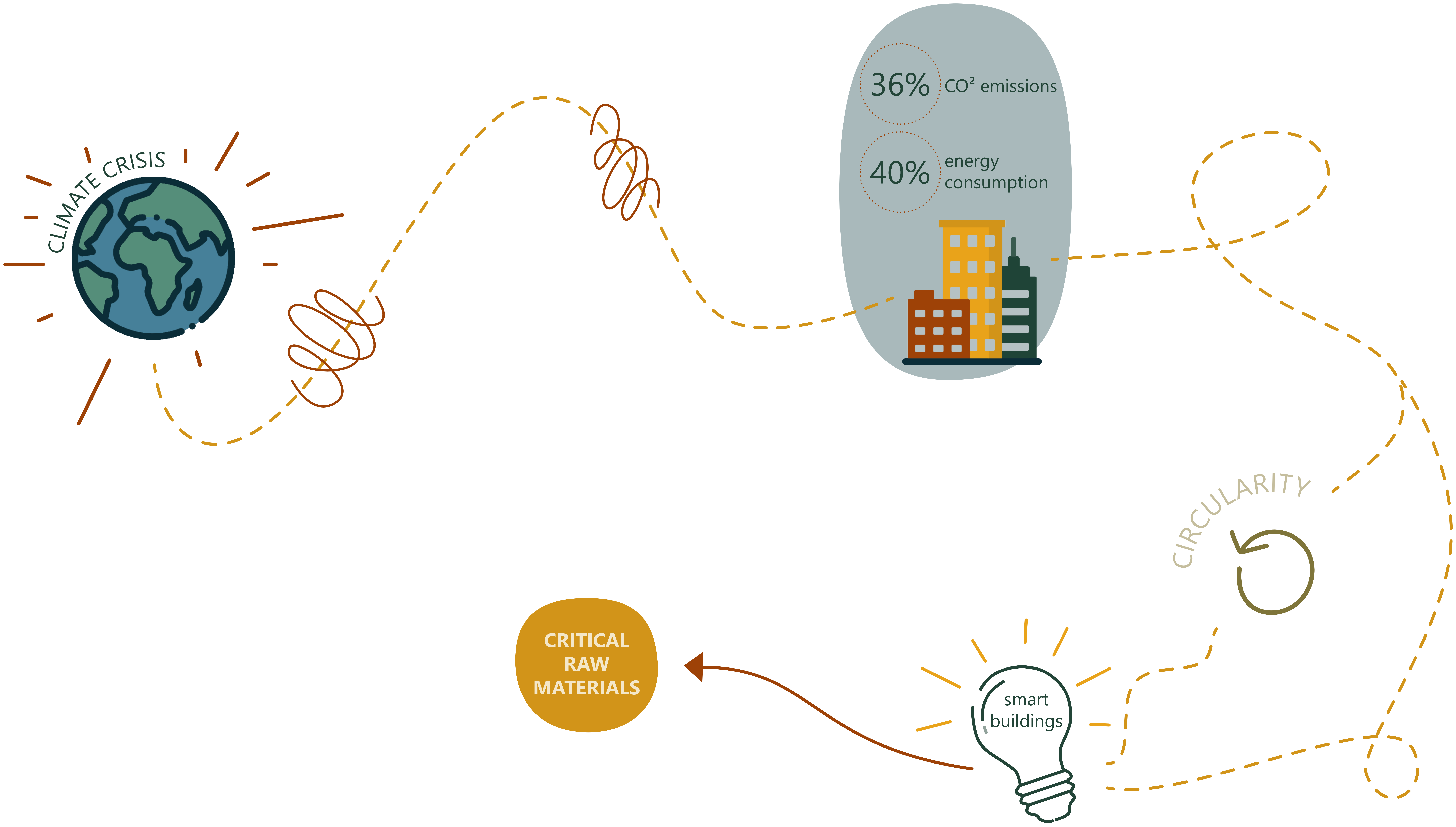
Background
Built Environment



Background

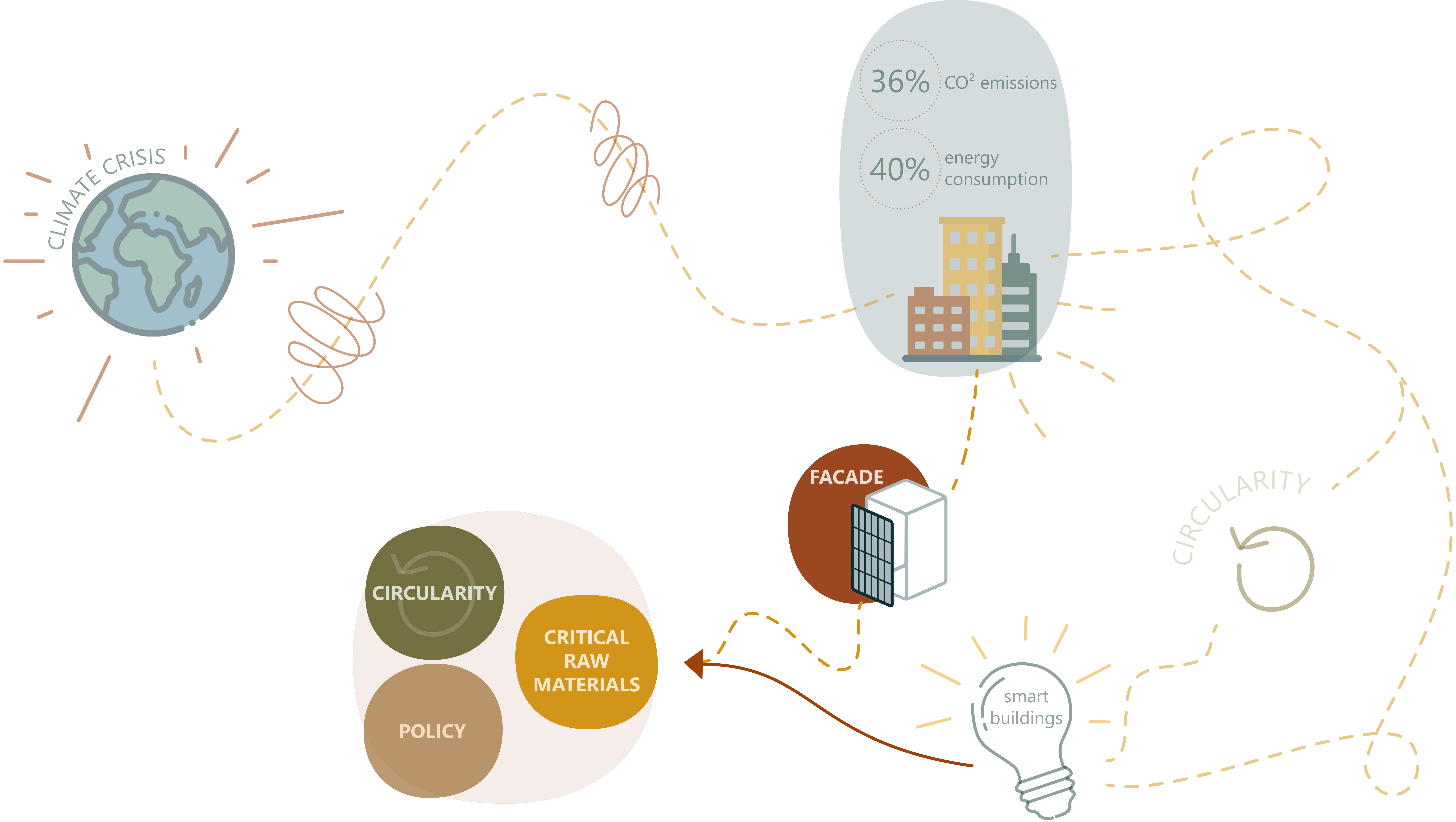
Strategies





CLIMATE CRISIS
36% CO^2 emissions
40% energy consumption
CIRCULARITY
smart buildings
CRITICAL RAW MATERIALS

Background
Topic



main question

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

sub-questions

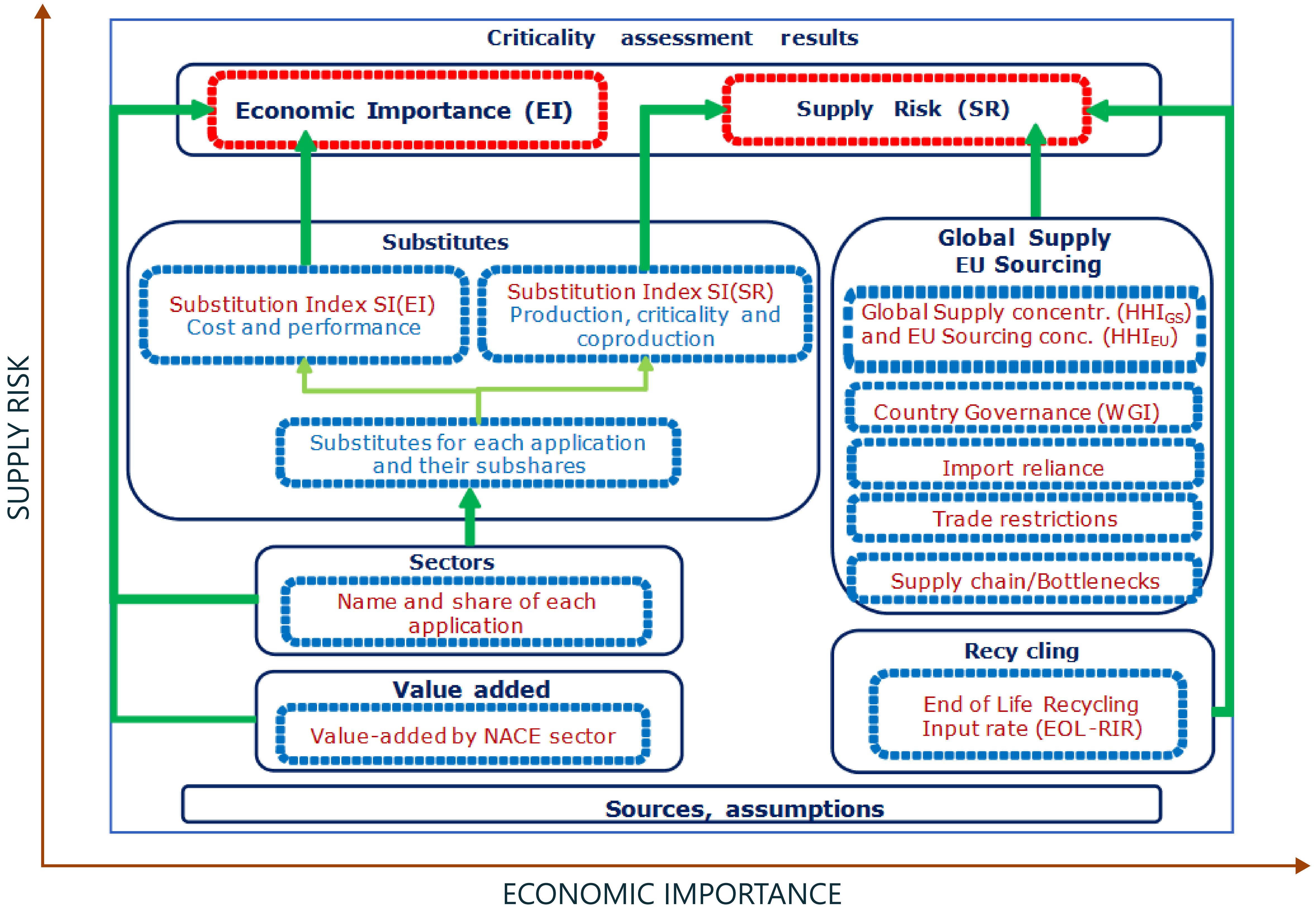
| What role do critical materials play in the built environment?
| How are critical materials related to the circular built environment?
| What policies regarding critical raw materials and circularity in the built environment already exist?

goal

| Develop recommendations to help policy makers with decision making in critical material concerns in building products *to prevent future material bottlenecks* in façade companies.

critical materials

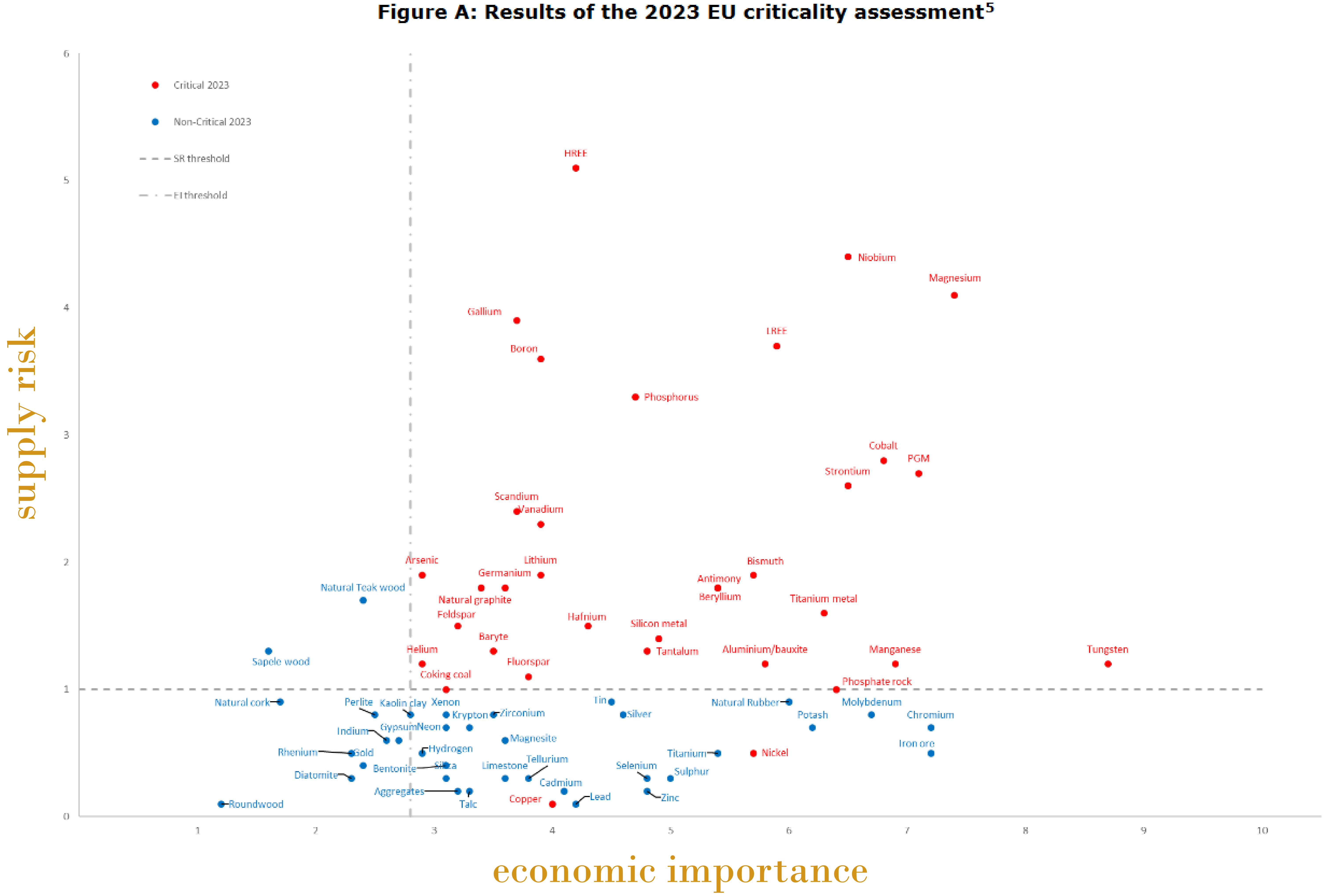
SUPPLY RISK
critical materials
ECONOMIC IMPORTANCE



SUPPLY RISK
ECONOMIC IMPORTANCE
Criticality assessment results
Economic Importance (EI)
Supply Risk (SR)
Substitutes
Substitution Index SI(EI)
Cost and performance
Substitution Index SI(SR)
Production, criticality and coproduction
Substitutes for each application and their subshares
Global Supply
EU Sourcing
Global Supply concentr. (HHIGS) and EU Sourcing conc. (HHIEU)
Country Governance (WGI)
Import reliance
Trade restrictions
Supply chain/Bottlenecks
Sectors
Name and share of each application
Value added
Value-added by NACE sector
Recy cling
End of Life Recycling Input rate (EOL-RIR)
Sources, assumptions

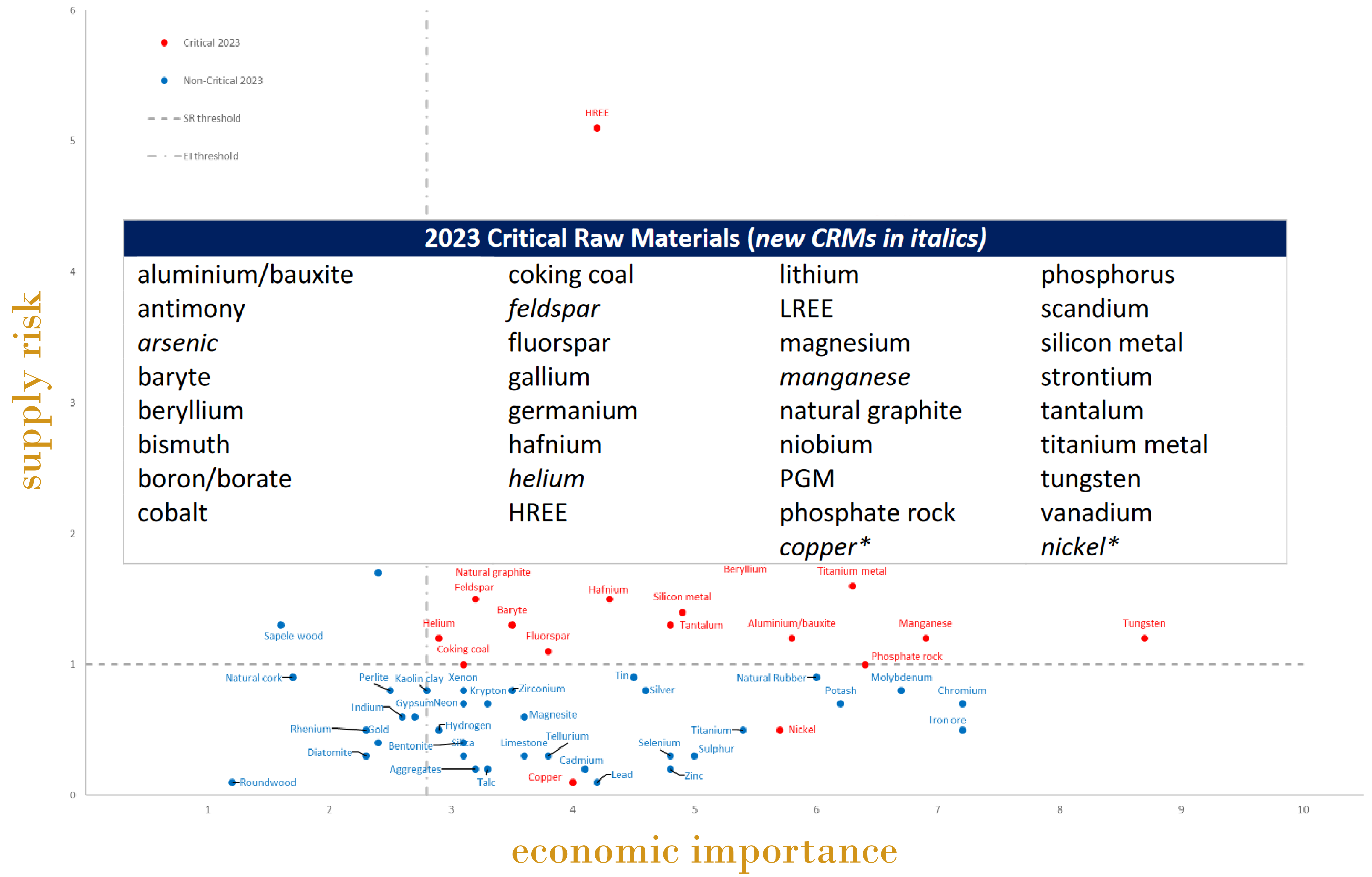
Literature review

Critical Raw Materials | EU CRM List 2023



economic importance

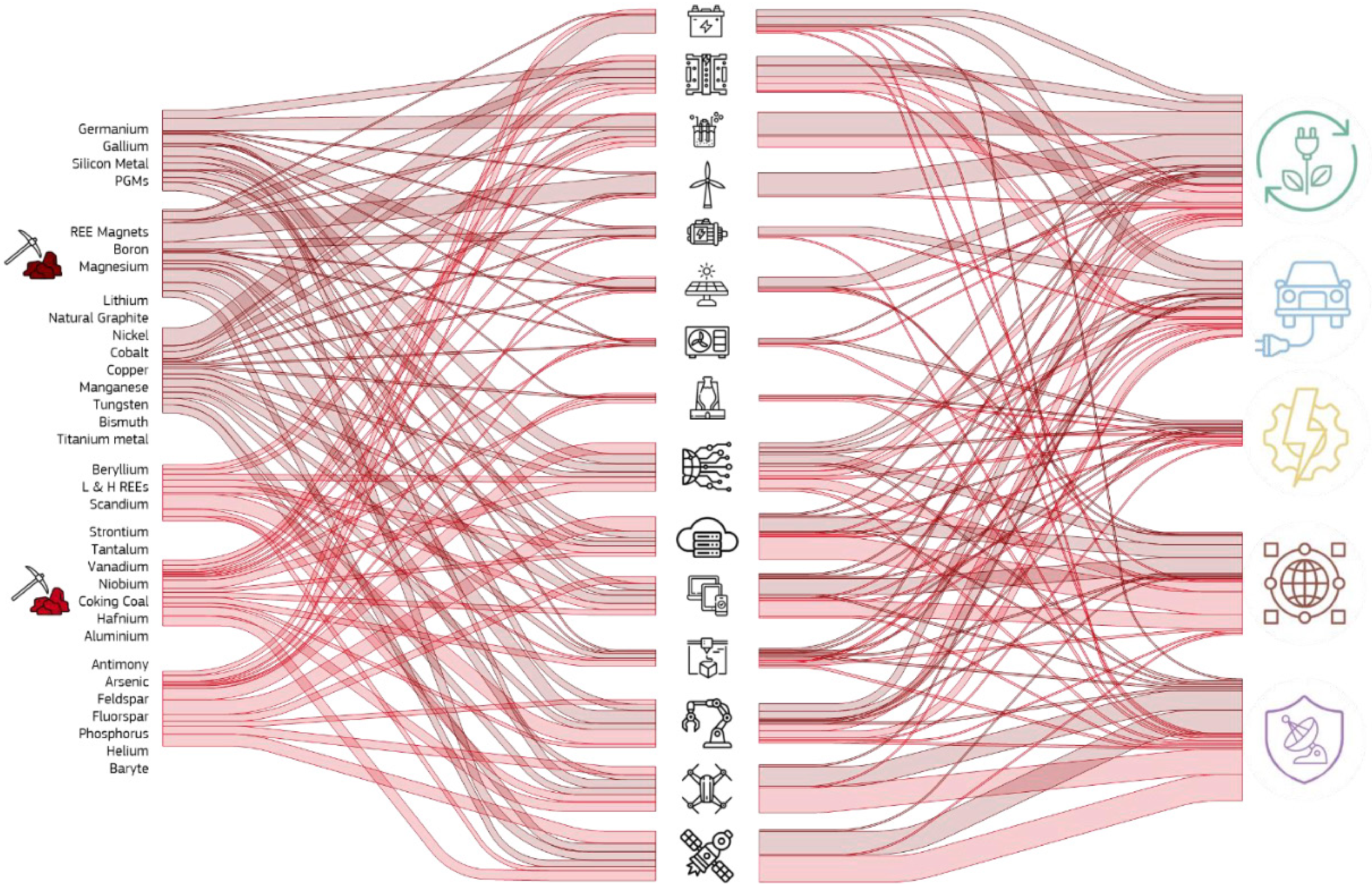
Figure A: Results of the 2023 EU criticality assessment[5]



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**

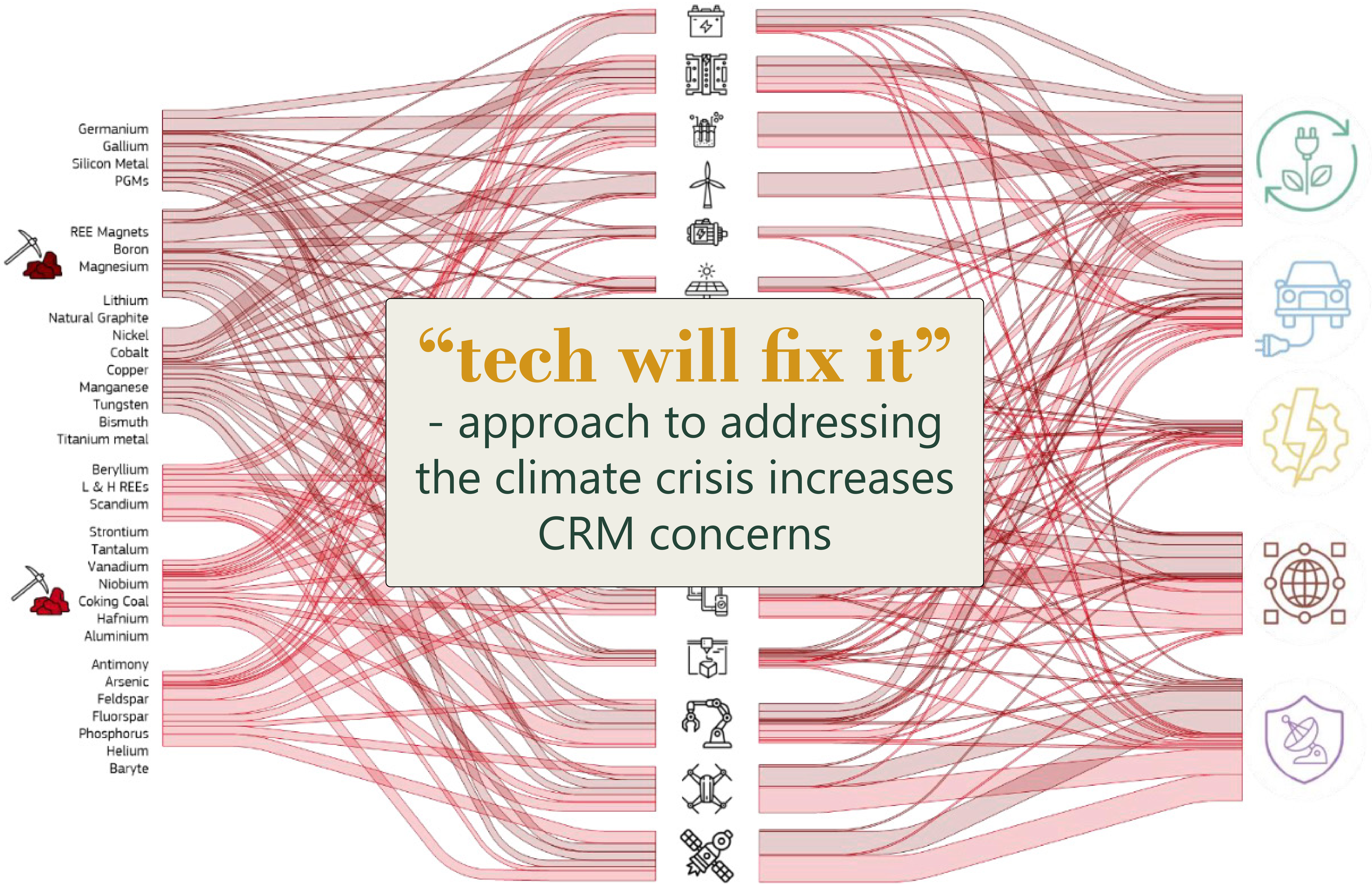
Literature review
Critical Raw Materials | energy transition



CRMs for Strategic Technologies and Sectors in the EU 2023 (European Commission, 2023)

Literature review

Critical Raw Materials | energy transition



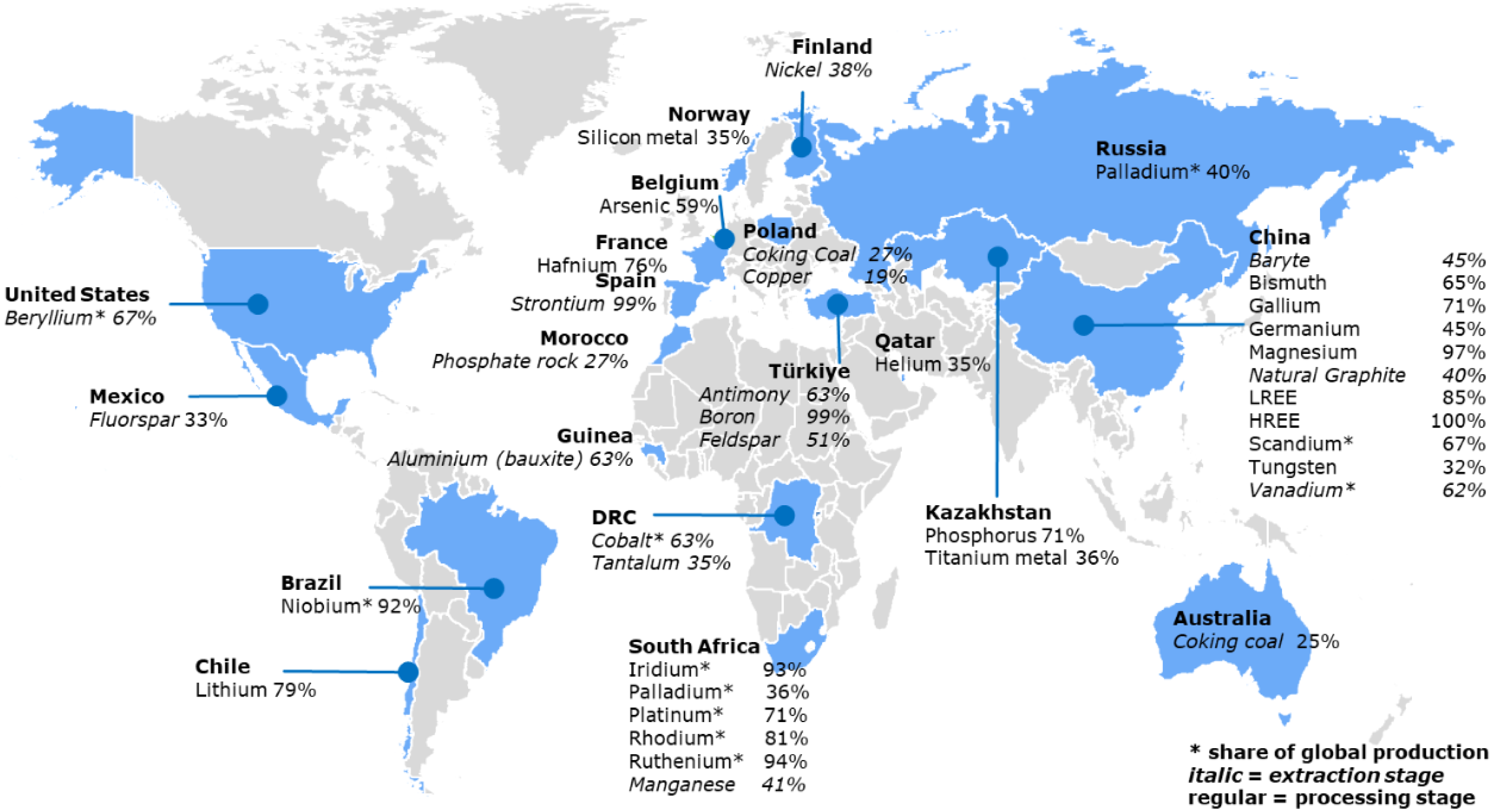
"tech will fix it"

- approach to addressing the climate crisis increases CRM concerns

CRMs for Strategic Technologies and Sectors in the EU 2023 (European Commission, 2023)

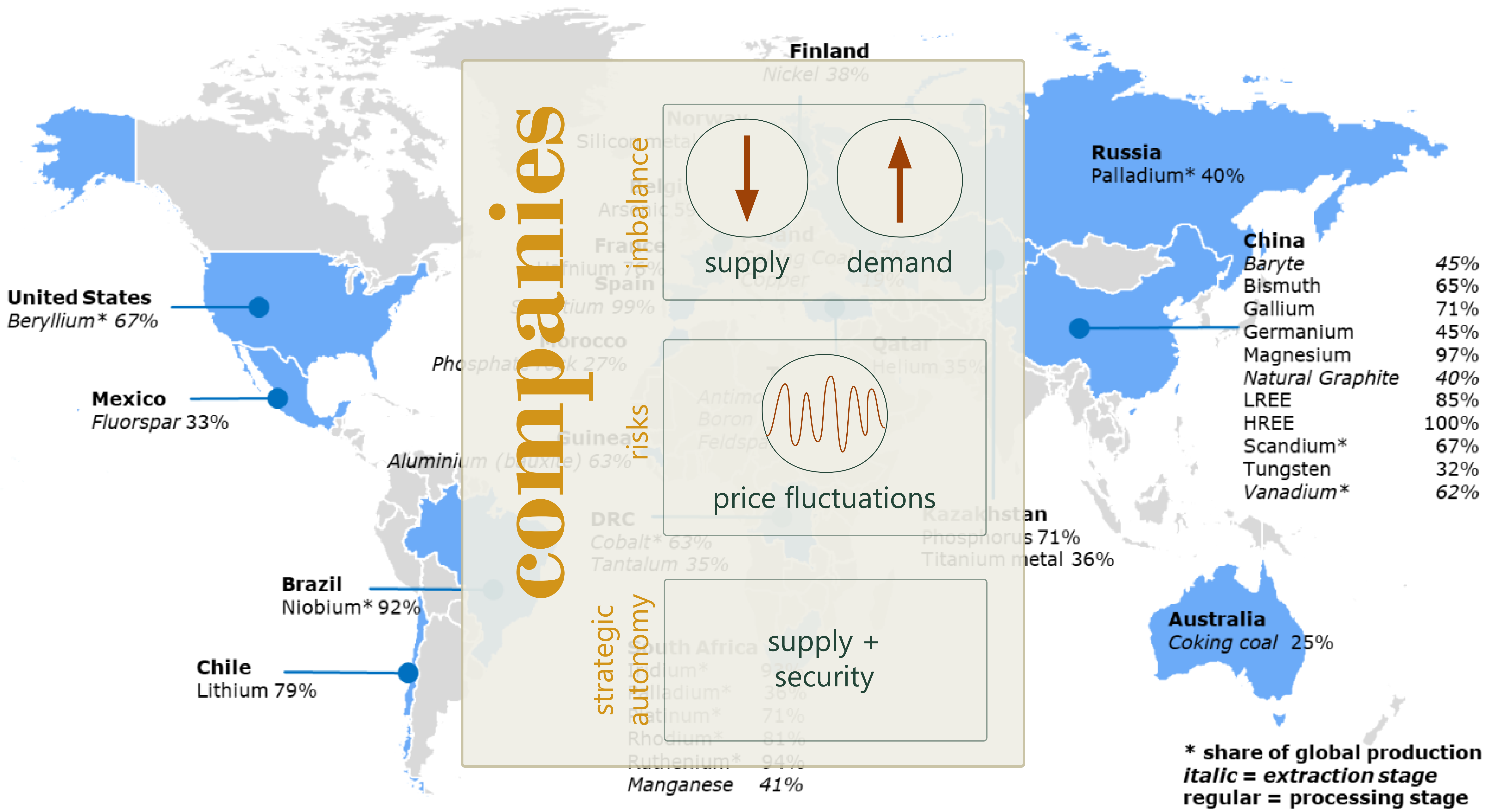
Literature review

Critical Raw Materials | geopolitical, social, environmental



Countries accounting for the largest share of EU sourcing of CRMs (European Commision, 2023)

Literature review
Critical Raw Materials | threat of bottlenecks



Countries accounting for the largest share of EU sourcing of CRMs (European Commision, 2023)

mitigation strategies

- IMPROVE RESOURCE EFFICIENCY
- SUBSTITUTION
- SUSTAINABLE MINING
- MINIMIZE EMBODIED ENERGY
- CIRCULAR PRODUCT DESIGN
- URBAN MINING AND RECYCLING

mitigation strategies

- IMPROVE RESOURCE EFFICIENCY
- SUBSTITUTION
  - substance for substance
  - service for product
  - process for process
  - new technology for substance
- SUSTAINABLE MINING
- MINIMIZE EMBODIED ENERGY
- CIRCULAR PRODUCT DESIGN
- URBAN MINING AND RECYCLING
  - from waste to resource
  - large unexploided stocks of rare and critical metals e.g. in vehicles

mitigation strategies

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restrictions

Substitution:
- influence a product's performance, cost , and reliability
- extensive testing needed to ensure technical and legal reliability

Urban mining and recycling:
- missing infrastructure + technologies
- missing economic viability
- demand growth consequently leads to im-balance of End-of-Life recycling rates and re-cycled input rates

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circularity

from LINEAR (*take-make-use-dispose)*
to CIRCULAR *(keep materials in the loop)*

1. ***design out*** *waste and pollution*
2. ***keep*** *products and materials* ***in use***
3. ***regenerate*** *natural systems*

[Ellen MacArthur Foundation, 2017]

Literature review

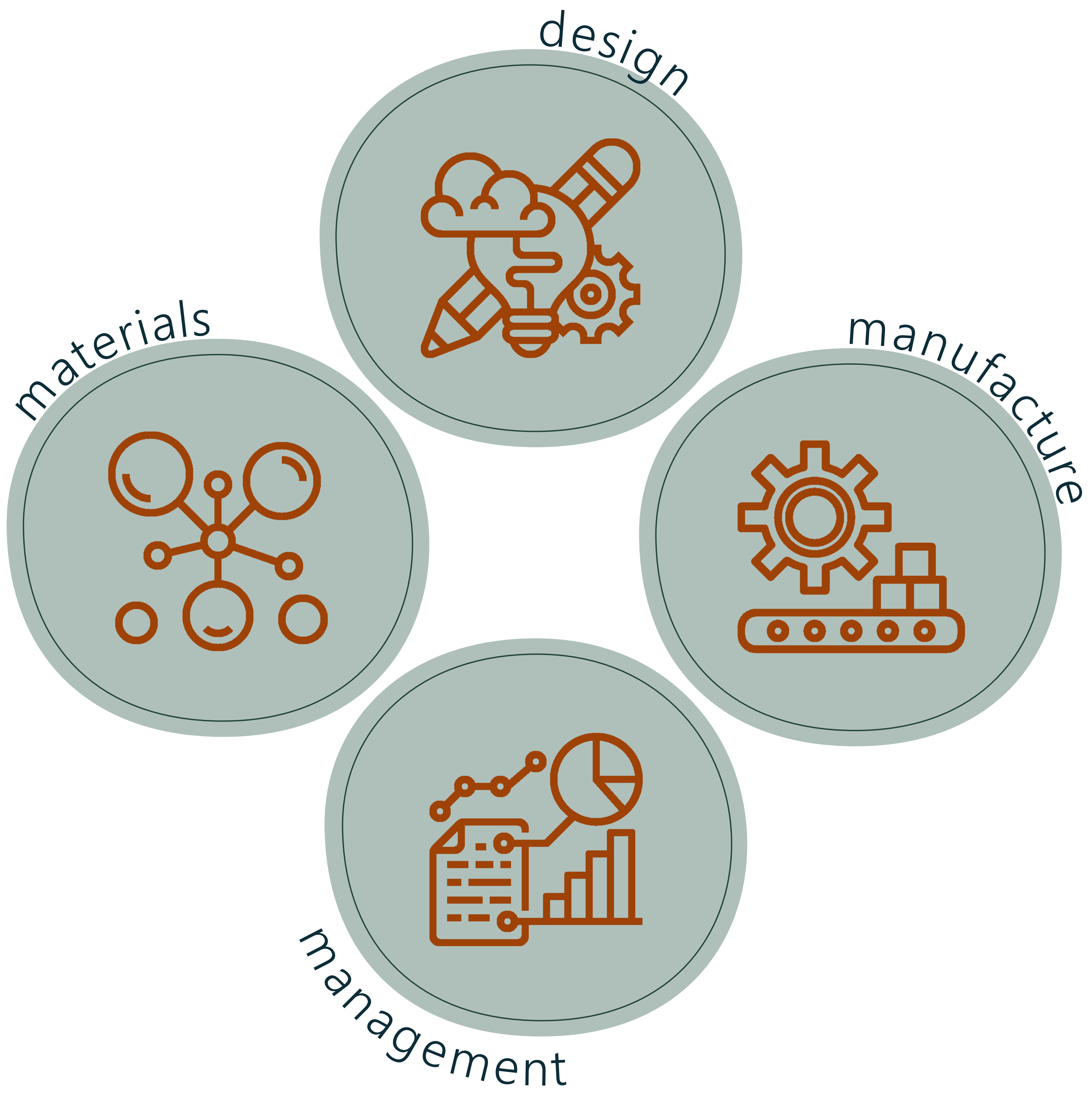
Circularity | R-Strategies

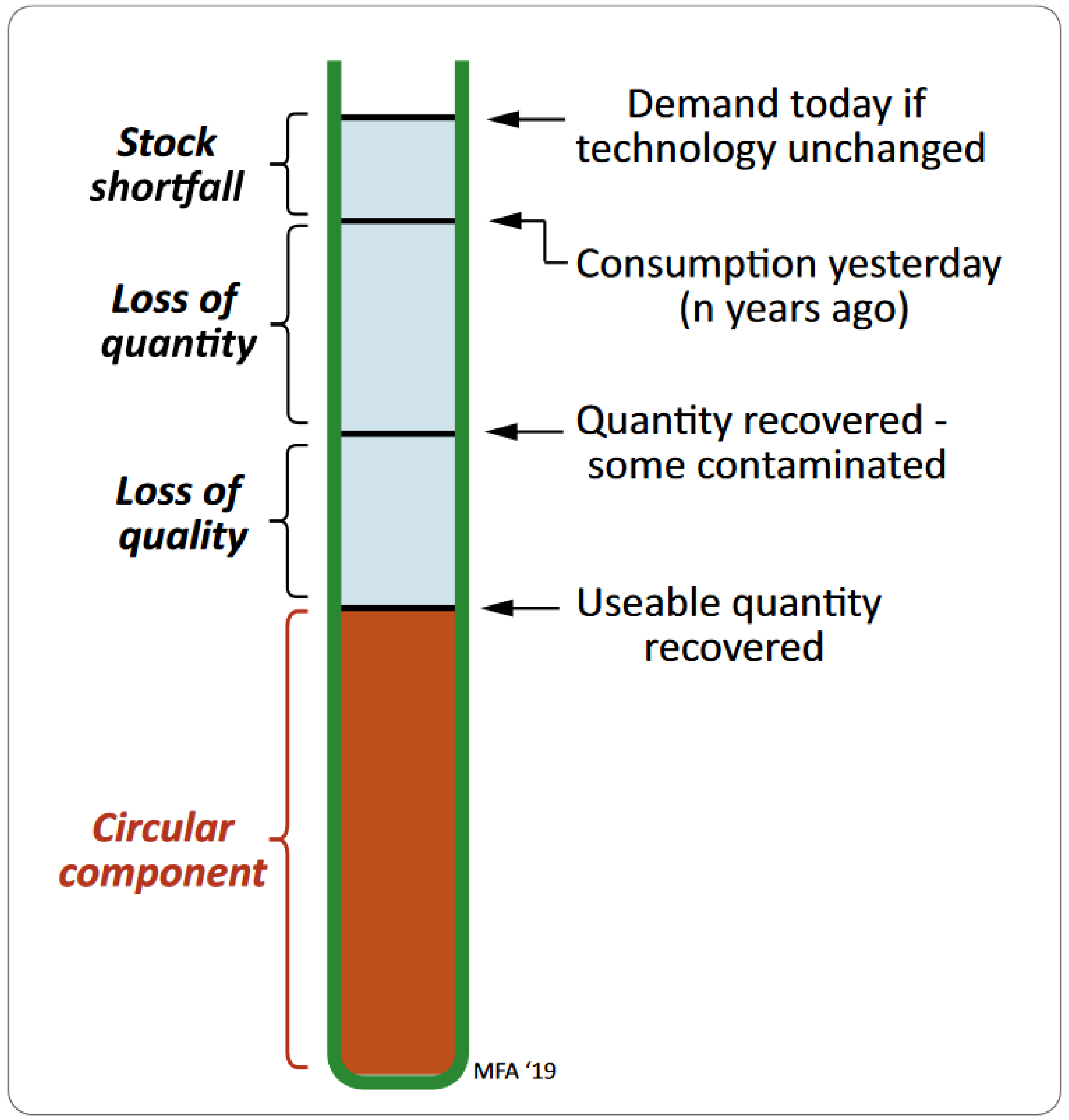
R strategies

smarter product use and manu-facture	R0	Refuse
	R1	Rethink
	R2	Reduce
extend lifespan of products and its parts	R3	Re-use
	R4	Repair
	R5	Refurbish
	R6	Remanufacture
	R7	Repurpose
useful application of materials	R8	Recycle
	R9	Recover

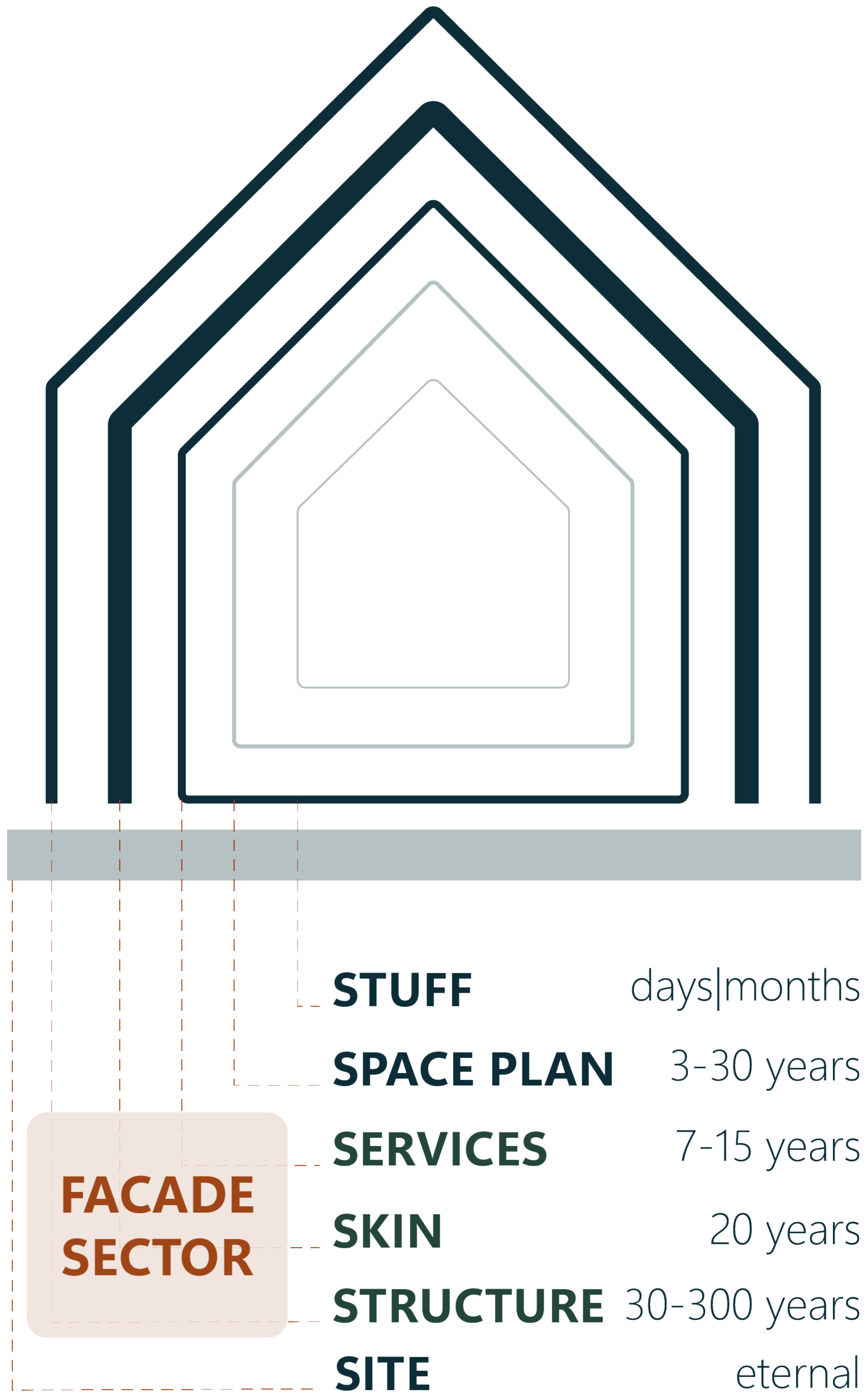
Adapted from PBL (2017)

Literature review
Circularity | domains



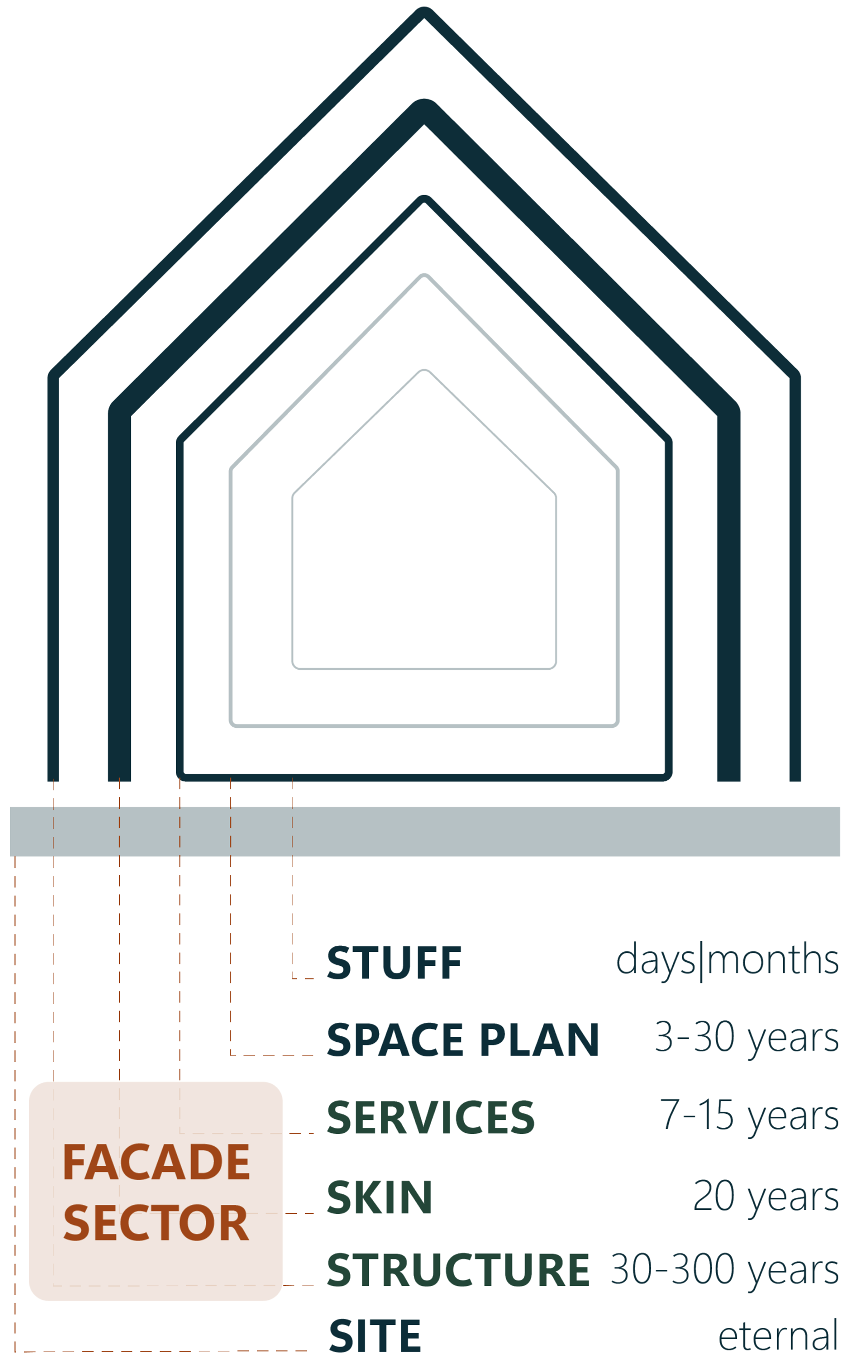


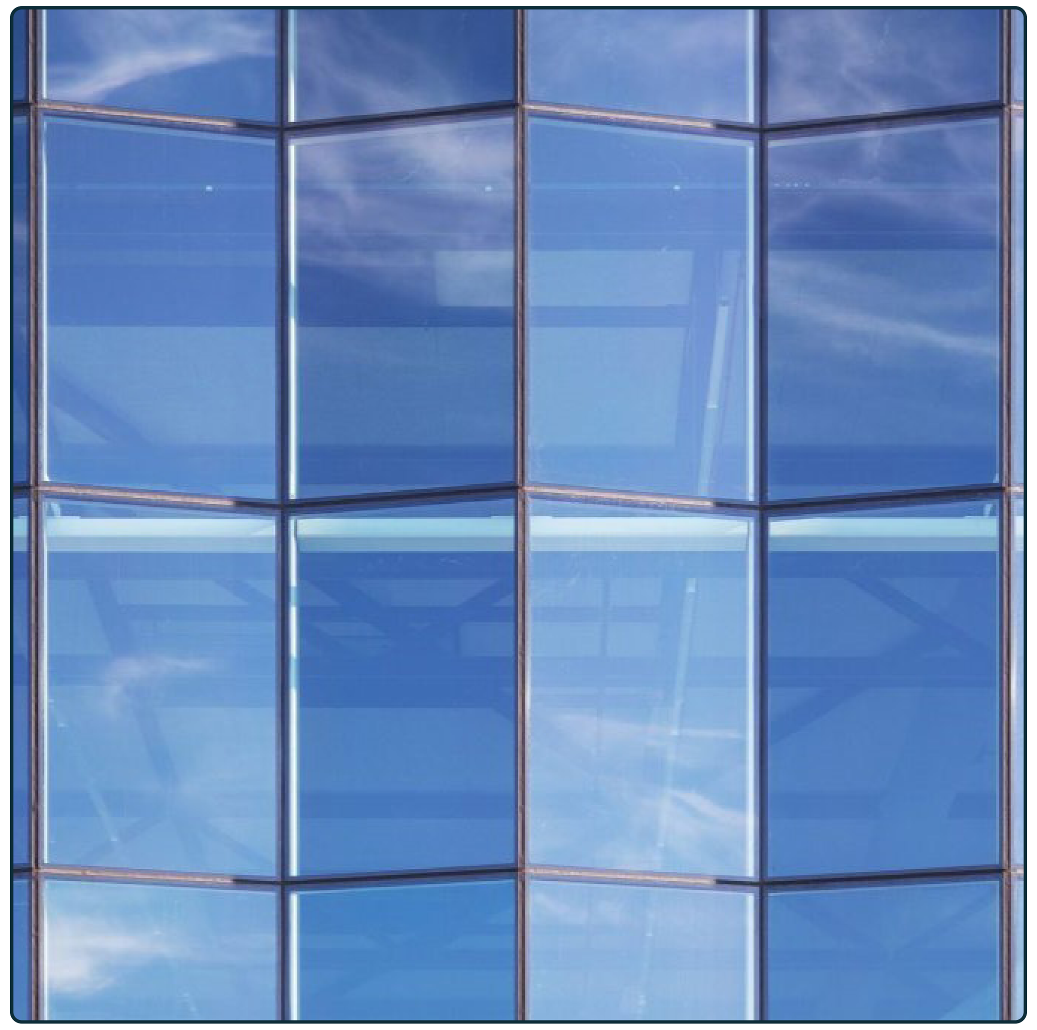
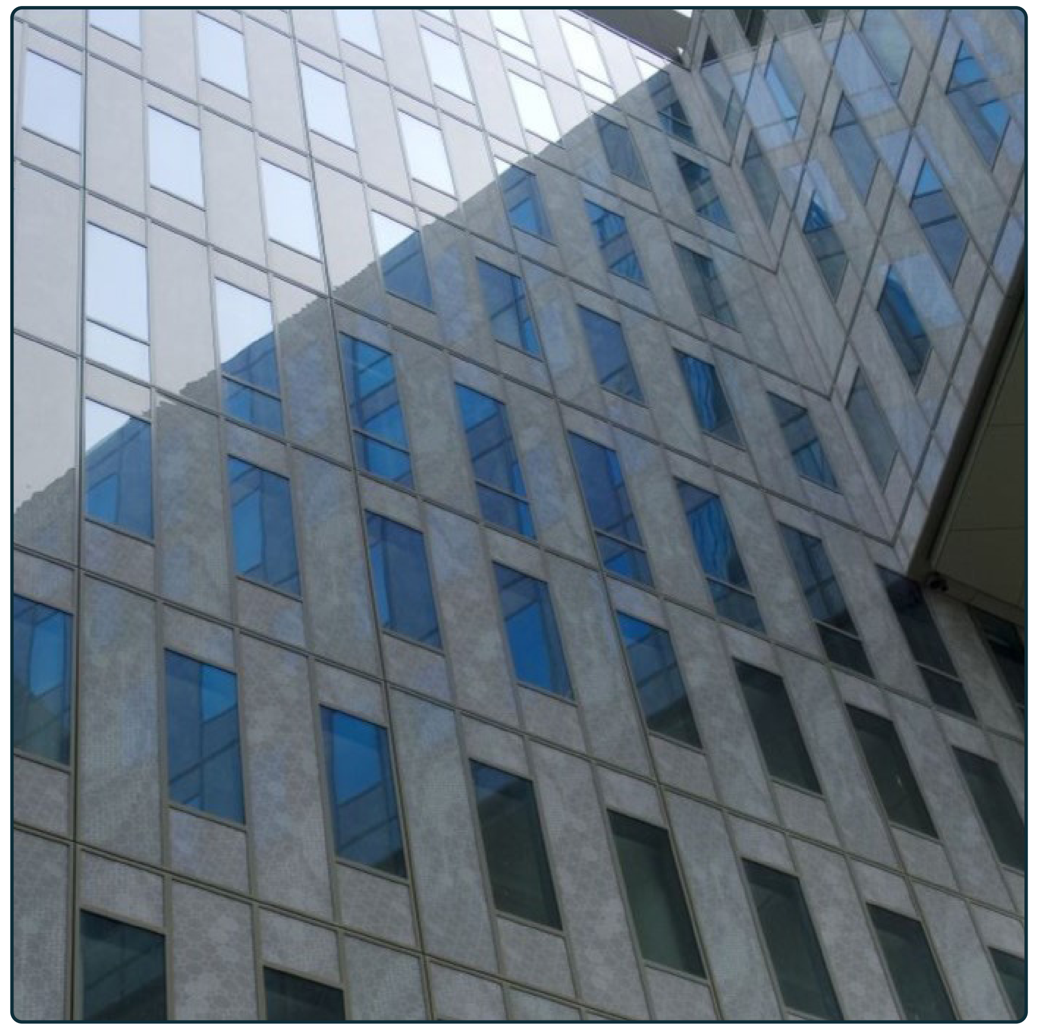
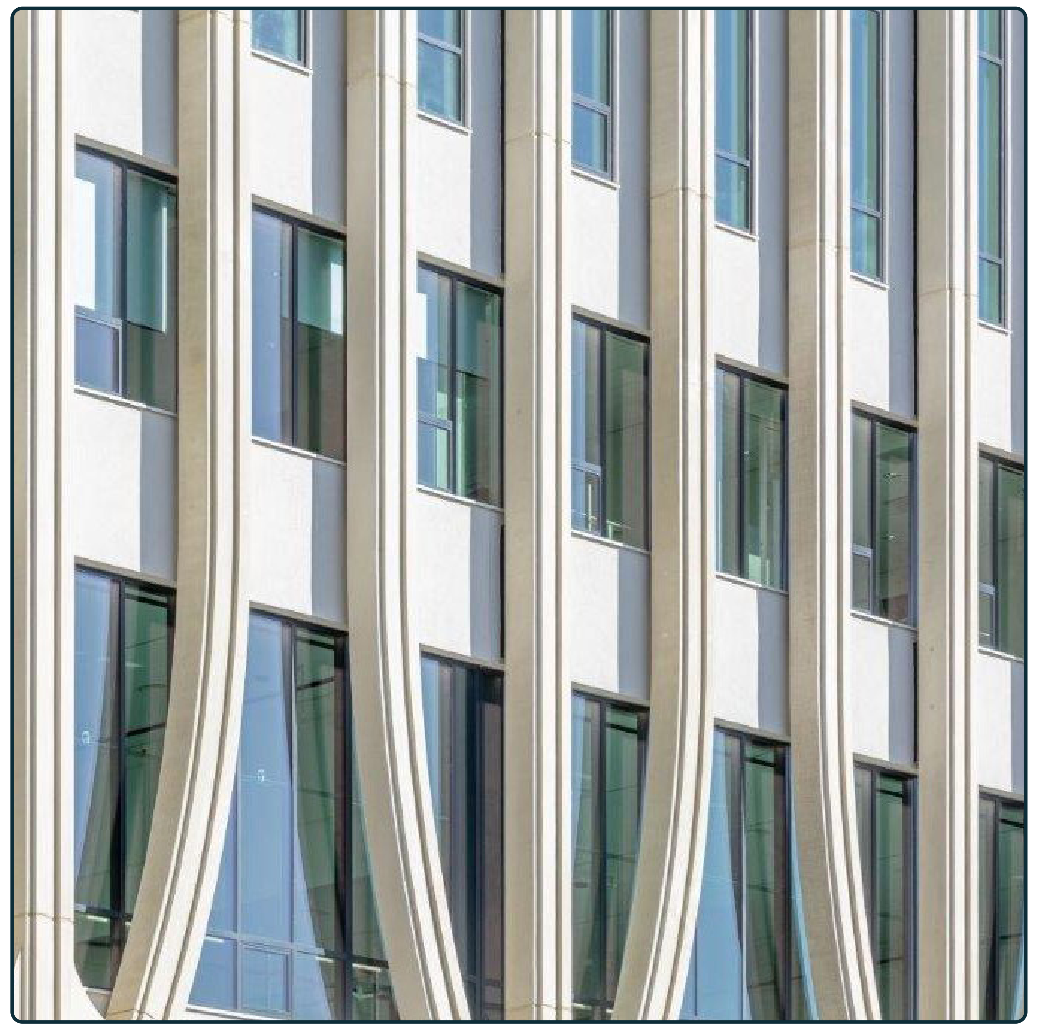
- rise in demand already means that we need more material input than we can get through recycling



Shearing layers | adapted from Brand (1994)

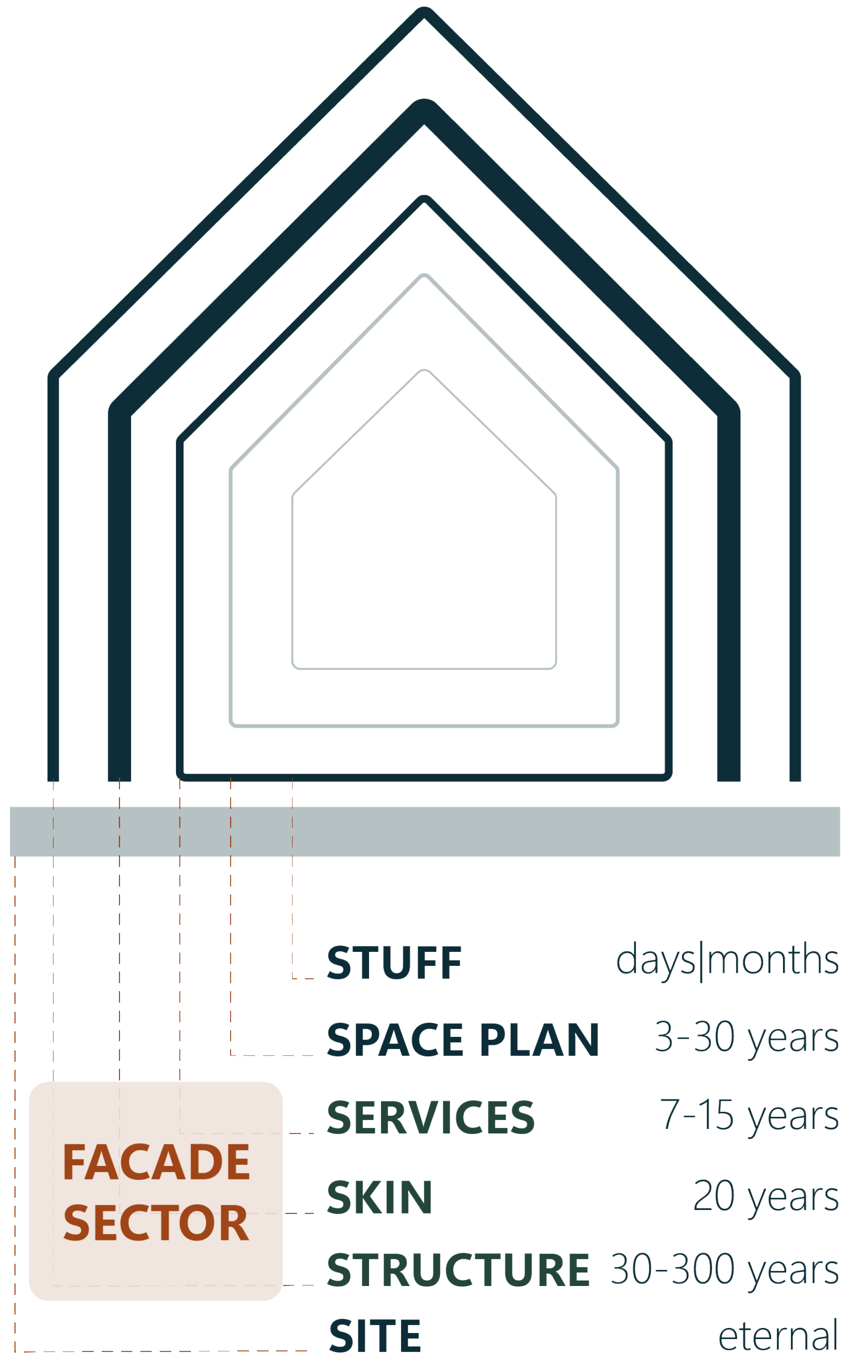
Literature review
Façades | curtain walls + shearing layers



Literature review

Façades | curtain walls + materials



materiality

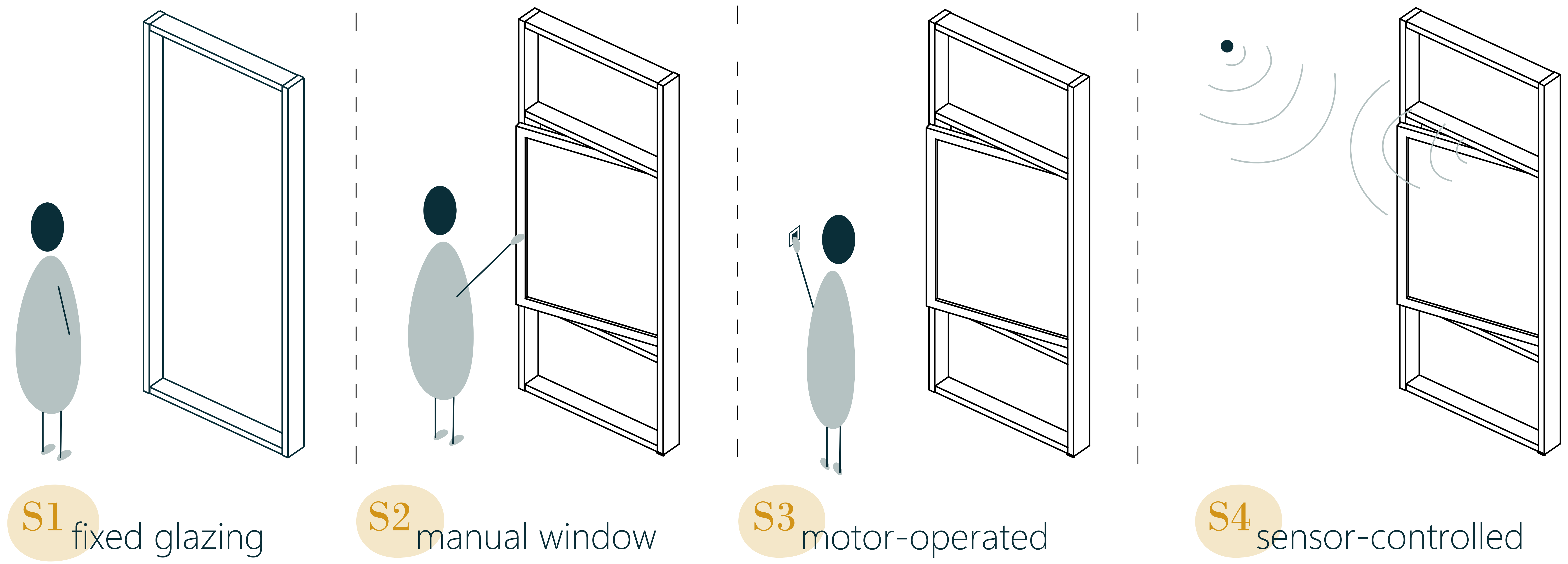
skin, structure: alloys
services: motors, sensors

façade analysis

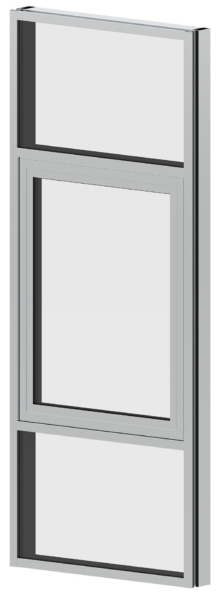
façade analysis

aluminium curtain wall analysis:

- *which CRMs*
- *how much of them*
- *where + why*

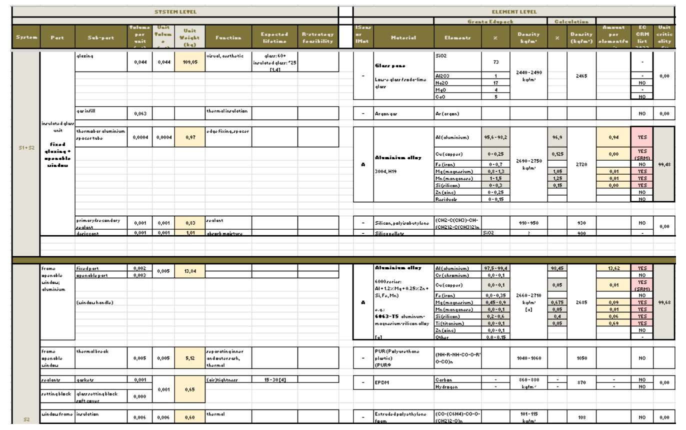

S1 fixed glazing
S2 manual window
S3 motor-operated
S4 sensor-controlled

Analysis
Analysis set-up



1. *define system*

[Rhino]

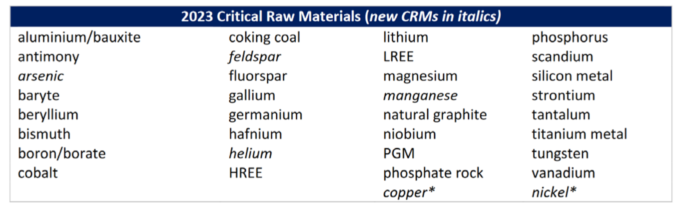


2. *list components and volumes*

[Excel]

3. *material composition*

[Granta EduPack]



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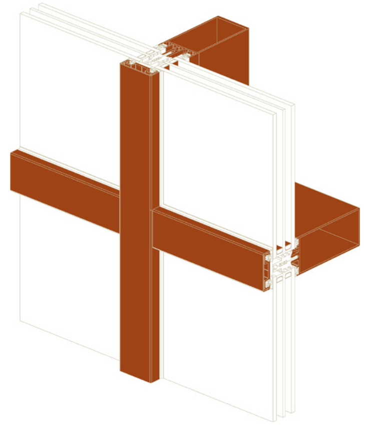
baryte	gallium	*manganese*	strontium
beryllium	germanium	natural graphite	tantalum
bismuth	hafnium	niobium	titanium metal
boron/borate	*helium*	PGM	tungsten
cobalt	HREE	phosphate rock	vanadium
		*copper**	*nickel**

4. *compare with CRM list*

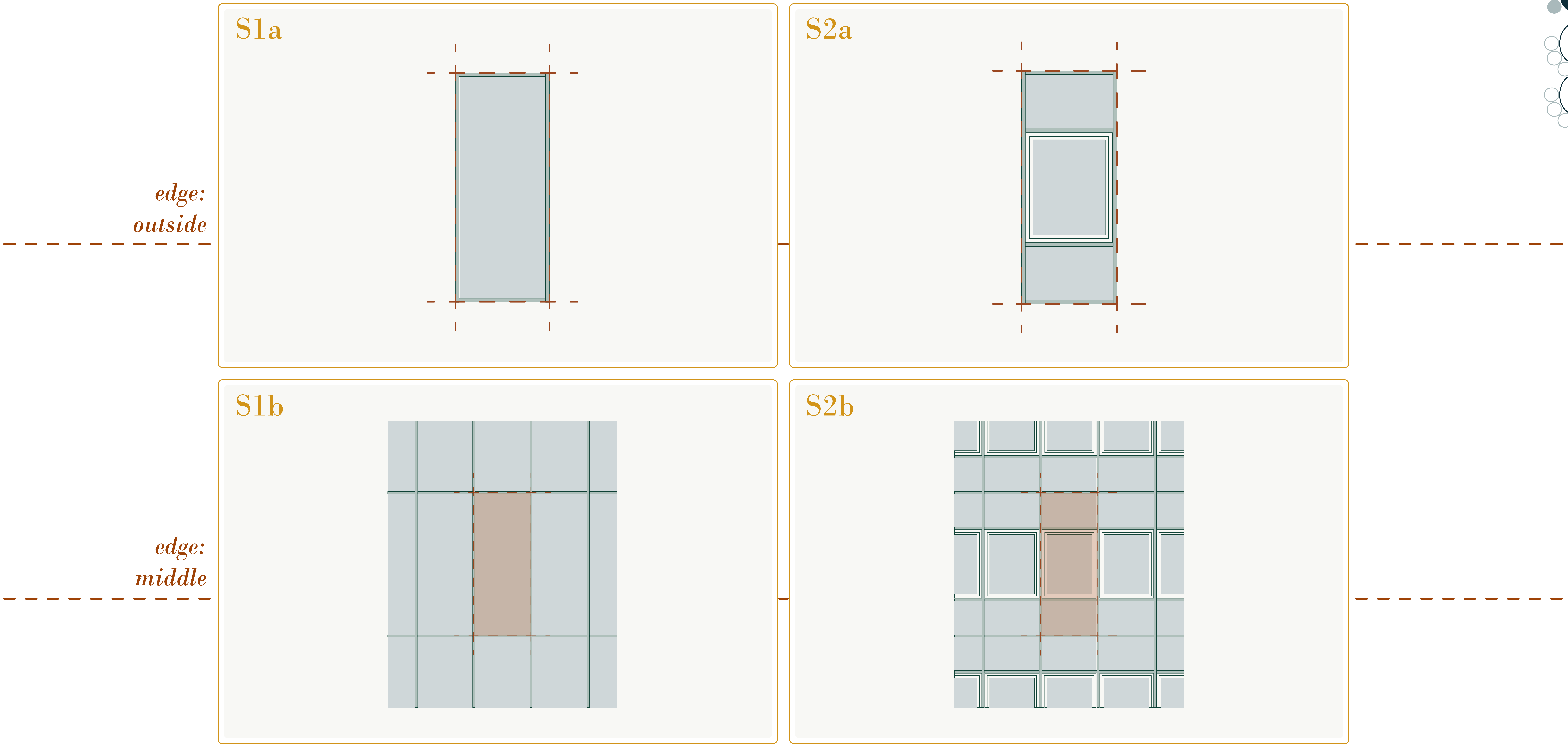
[European Commission]



5. *assess level of criticality*

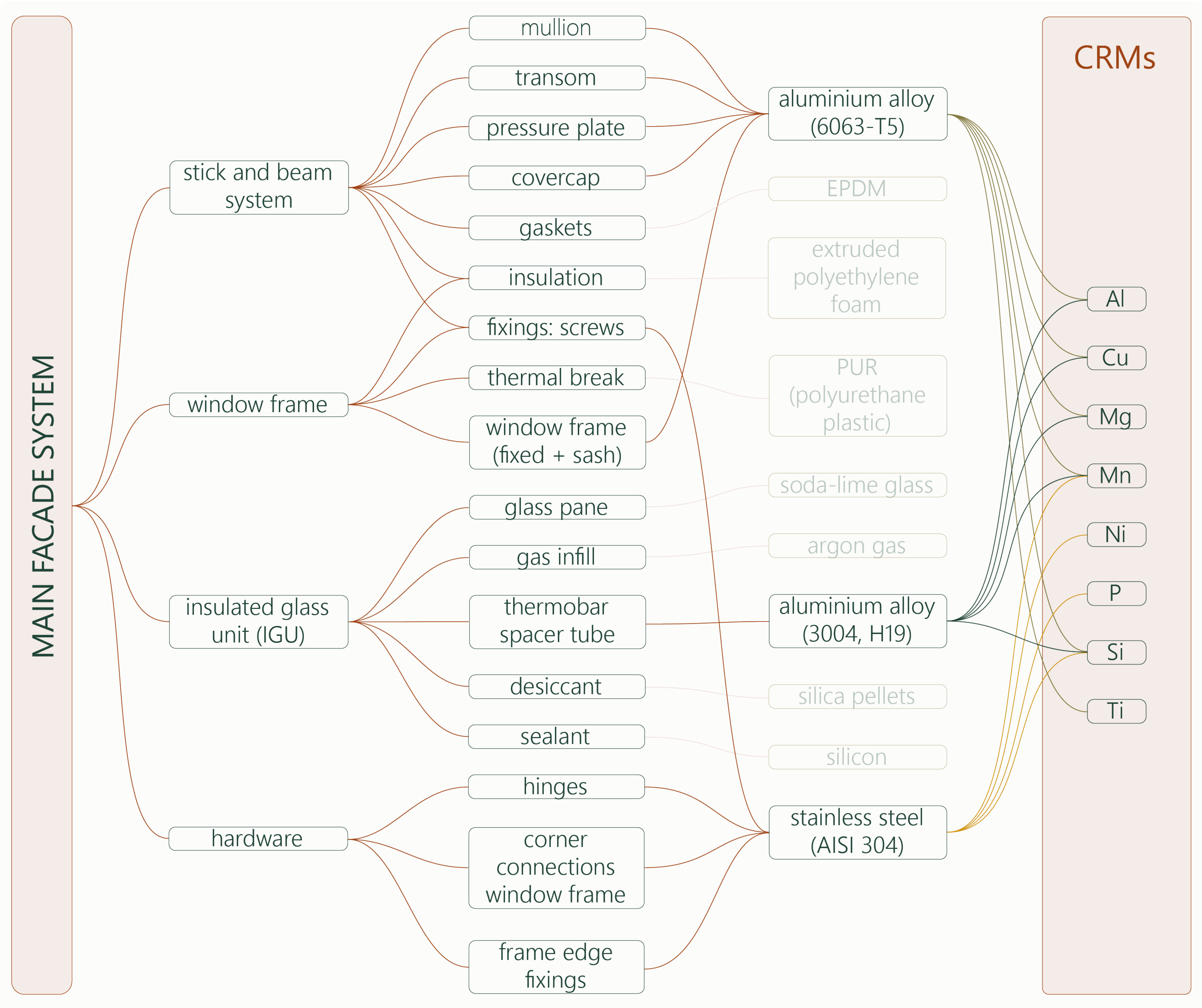
[Rhino, Excel, Adobe]

Analysis
Systems 1a,b + 2a,b



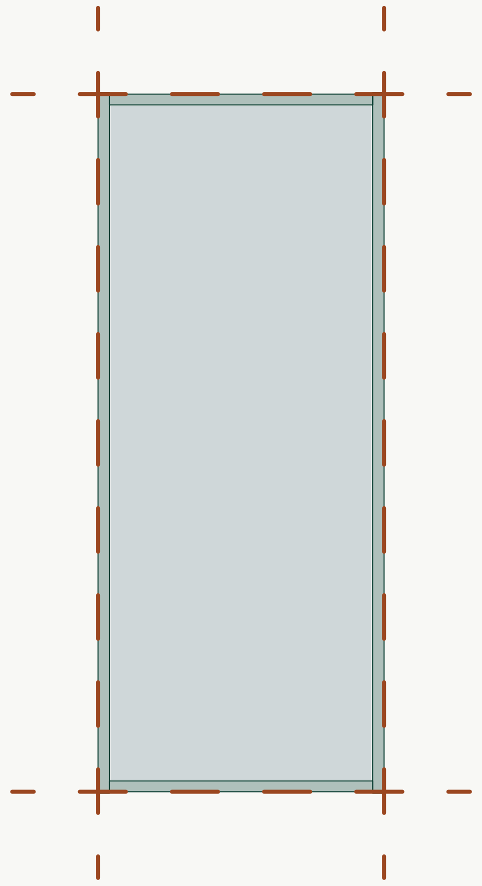
Analysis

Result | Material Composition S1+S2



Analysis
Results

S1a



fully fixed glazing

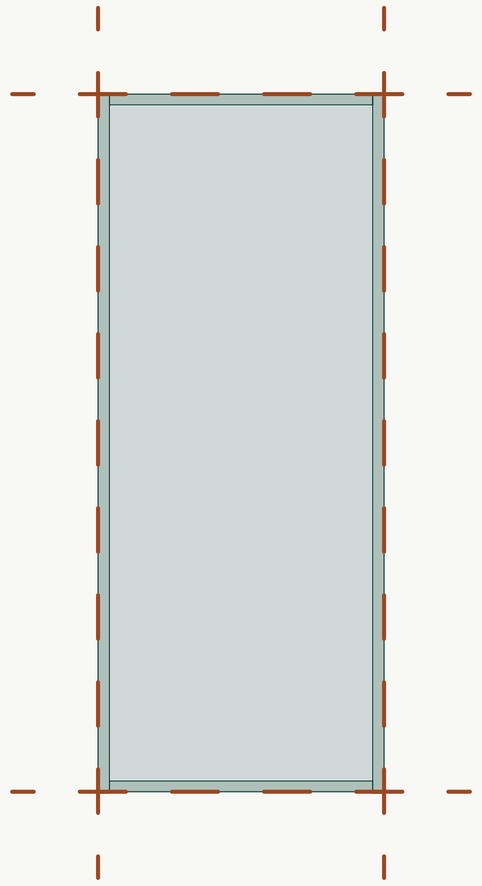
element size: 3.81 m²
glazing area: 3.4 m²

volume total: 0.07 m³
weight total: 163.85 kg
weight glass: 129.25 kg
weight CRMs: 28.48kg

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%**

Analysis
Results

S1a



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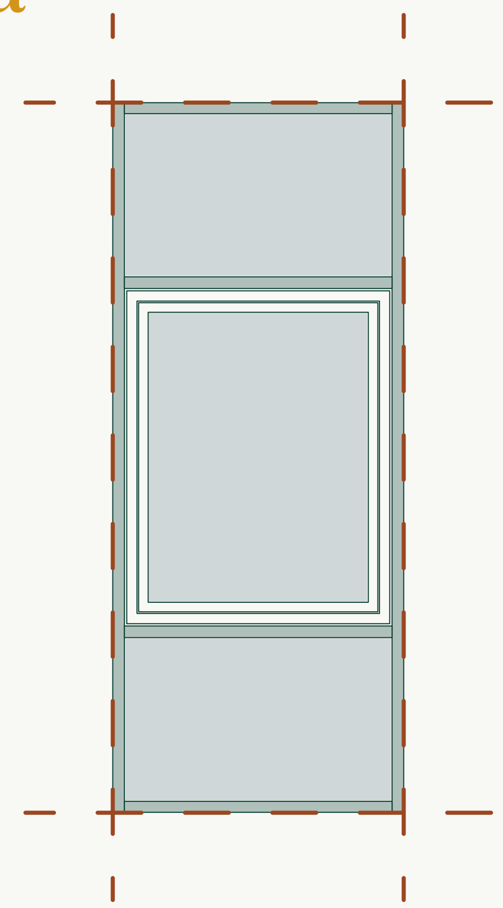
S2a

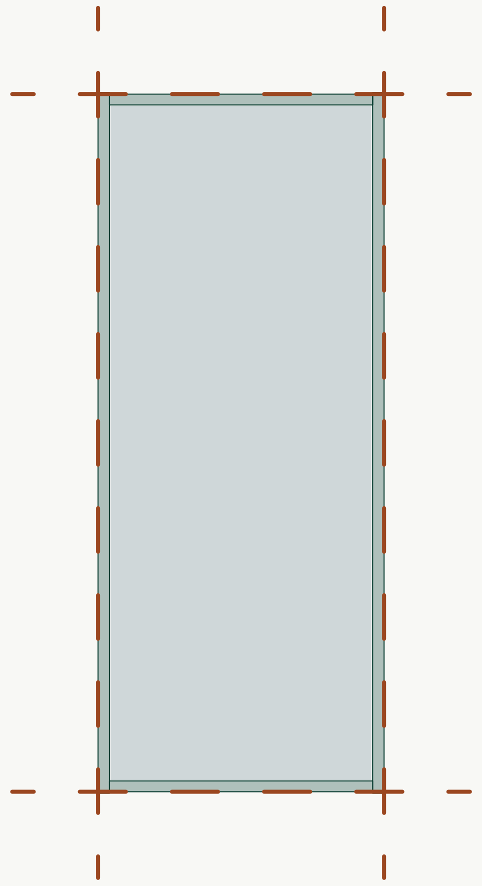


+ openable window

element size:	3.81 m²
glazing area:	2.8 m²
volume total:	0.09 m²
weight total:	**181.06 kg**
weight glass:	109.05 kg
weight CRMs:	50.60 kg

CRMs:	**kg**	**total %**
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%**

S1a



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volume total:	0.07 m^3
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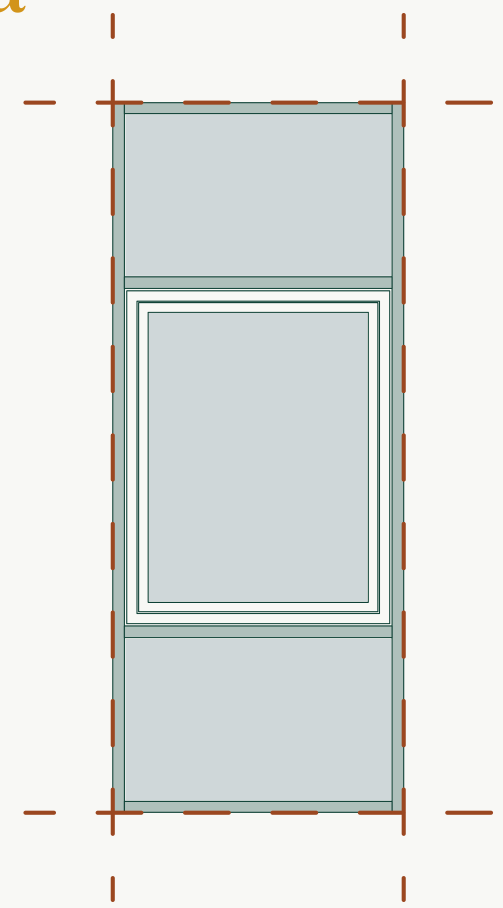
S2a



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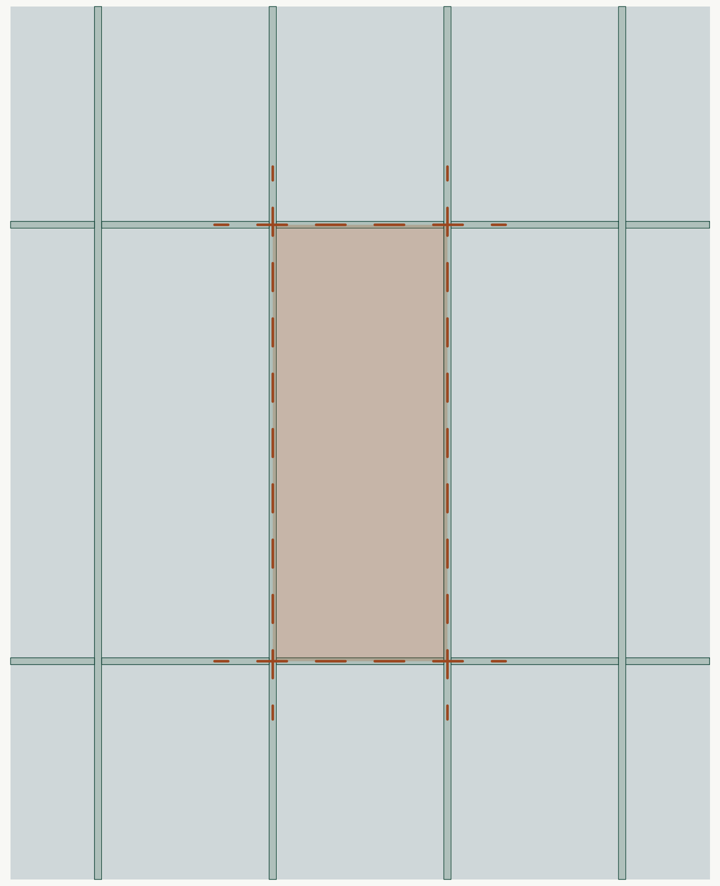
CRMs total:	**50.60**	**27.95%**

S1b

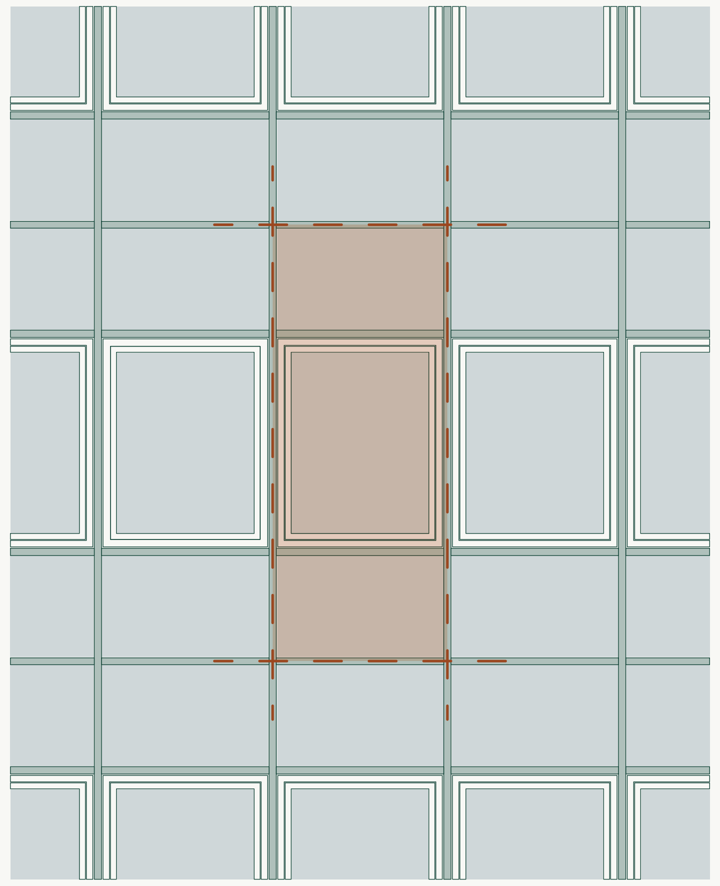


fully fixed glazing

element size:	3.6 m^2
glazing area:	3.4 m^2
volume total:	0,07 m^3
weight total:	**150 kg**
weight glass:	129.25 kg
weight CRMs:	14.7 kg

CRMs:	**kg**	**total %**
Al (aluminium):	14.28	9.52
Mg (magnesium):	0.1	0.067
Mn (manganese):	0.04	0.027
P (phosphorus):	0.0005	0.0003
Si (silicon metal):	0.06	0.04
Ti (titanium metal):	0.01	0.0067
Cu (copper):	0.01	0.0067
Ni (nickel):	0.21	0.14
CRMs total:	**14.70**	**9.8%**

S2b



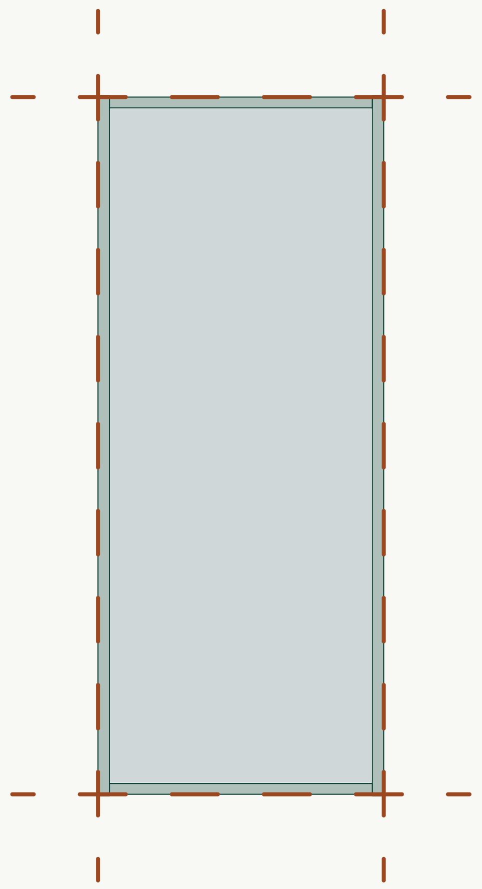
+ openable window

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%**

Analysis
Results

S1a



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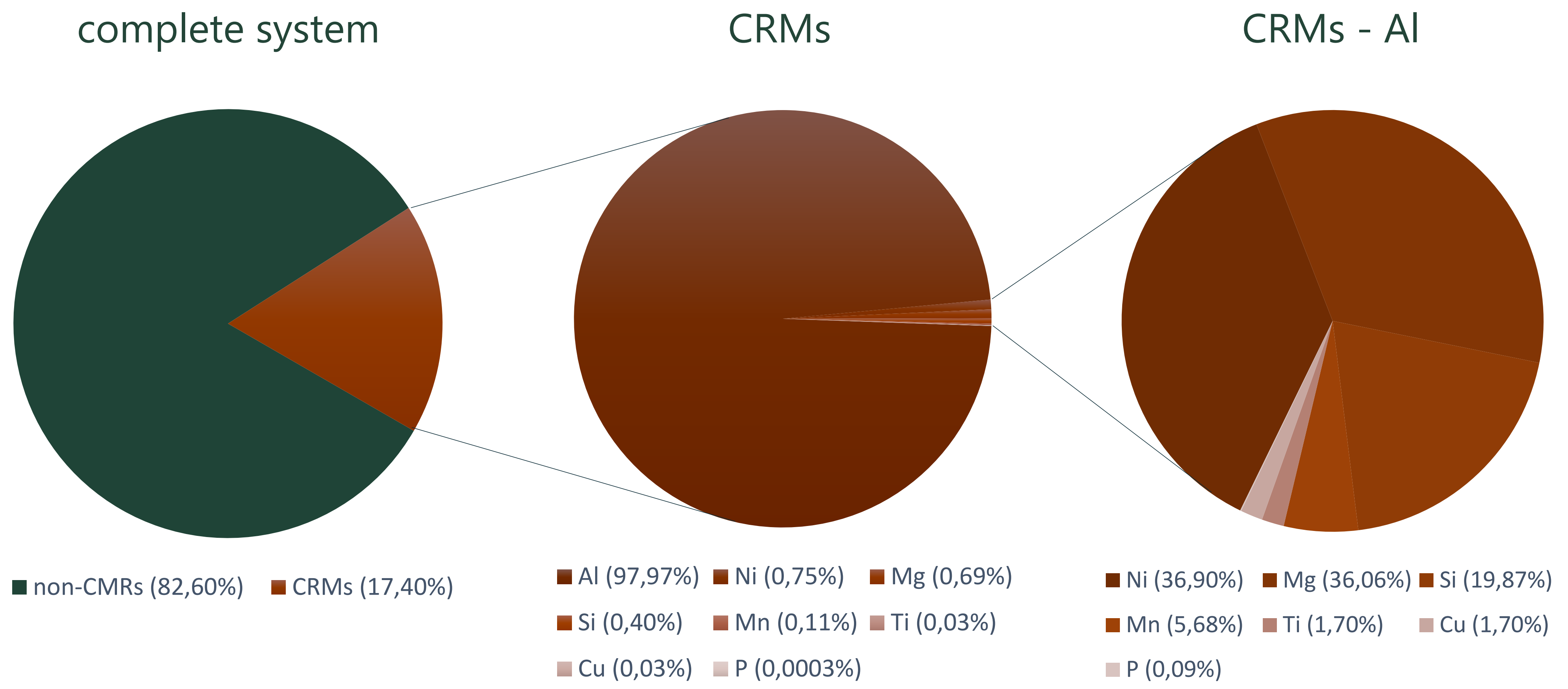
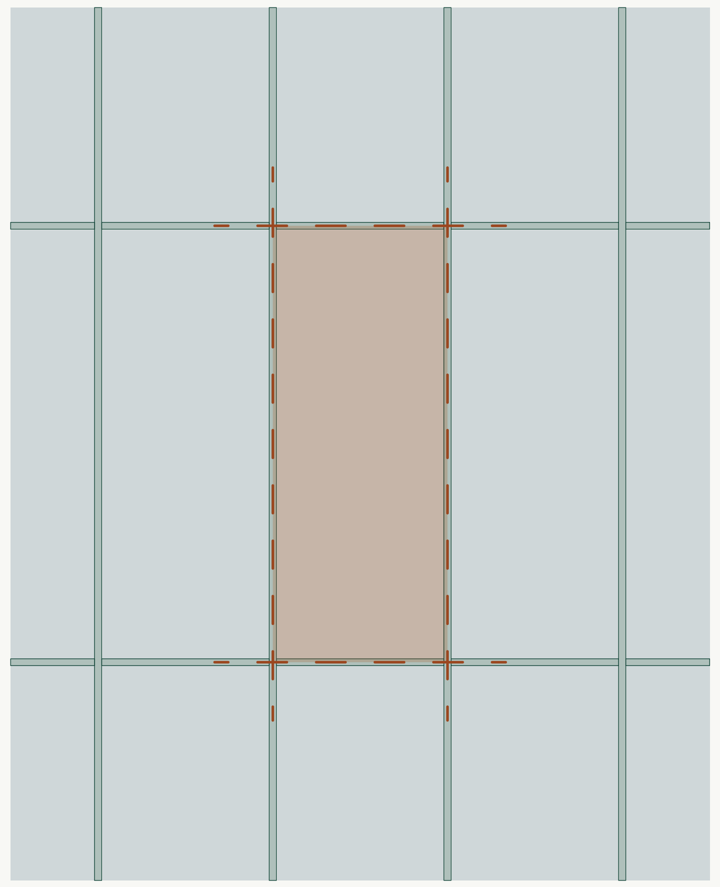
Al (aluminium):	27.92	17.04
Mg (magnesium):	0.19	0.12
Mn (manganese):	0.04	0.02
P (phosphorus):	0.0005	0.0003
Si (silicon metal):	0.11	0.07
Ti (titanium metal):	0.01	0.006
Cu (copper):	0.01	0.006
Ni (nickel):	0.21	0.13
CRMs total:	**28.48**	**17,4%**



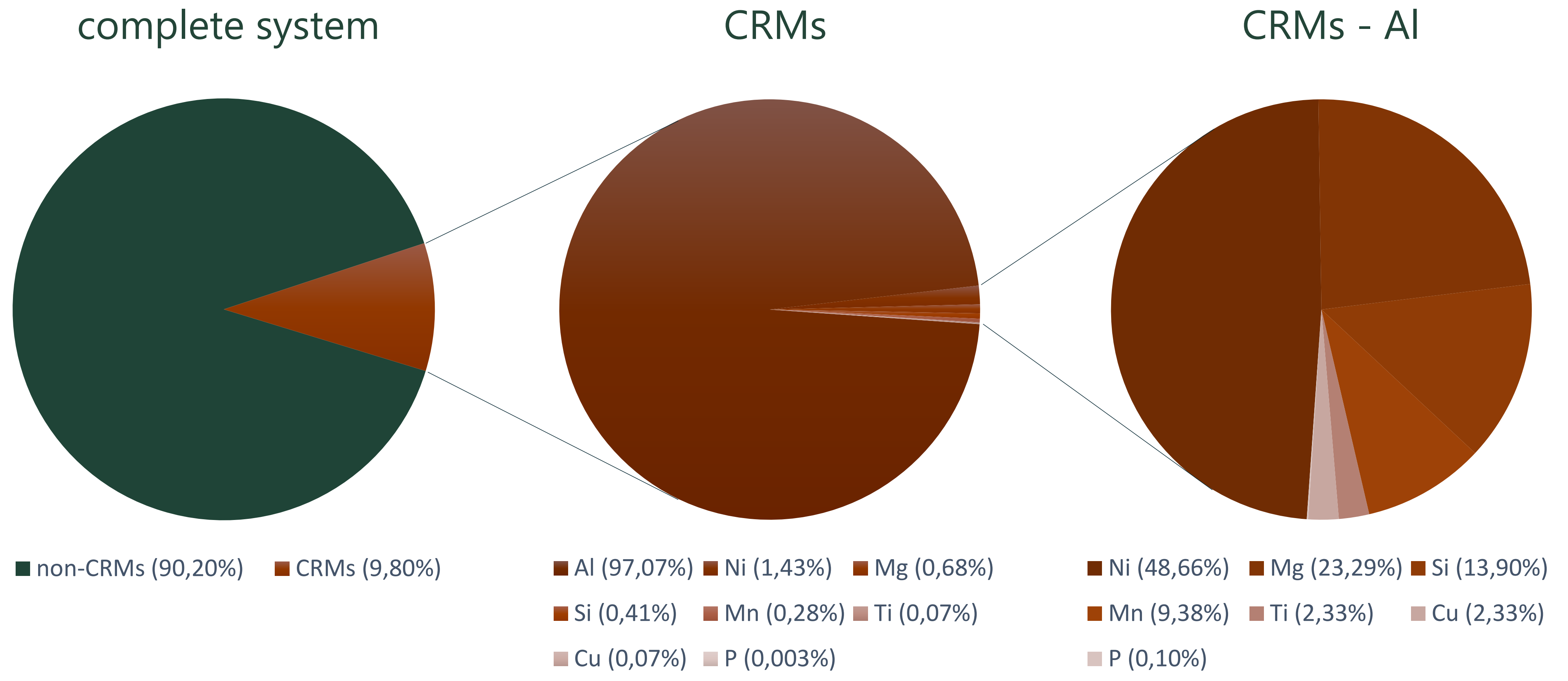
S1b



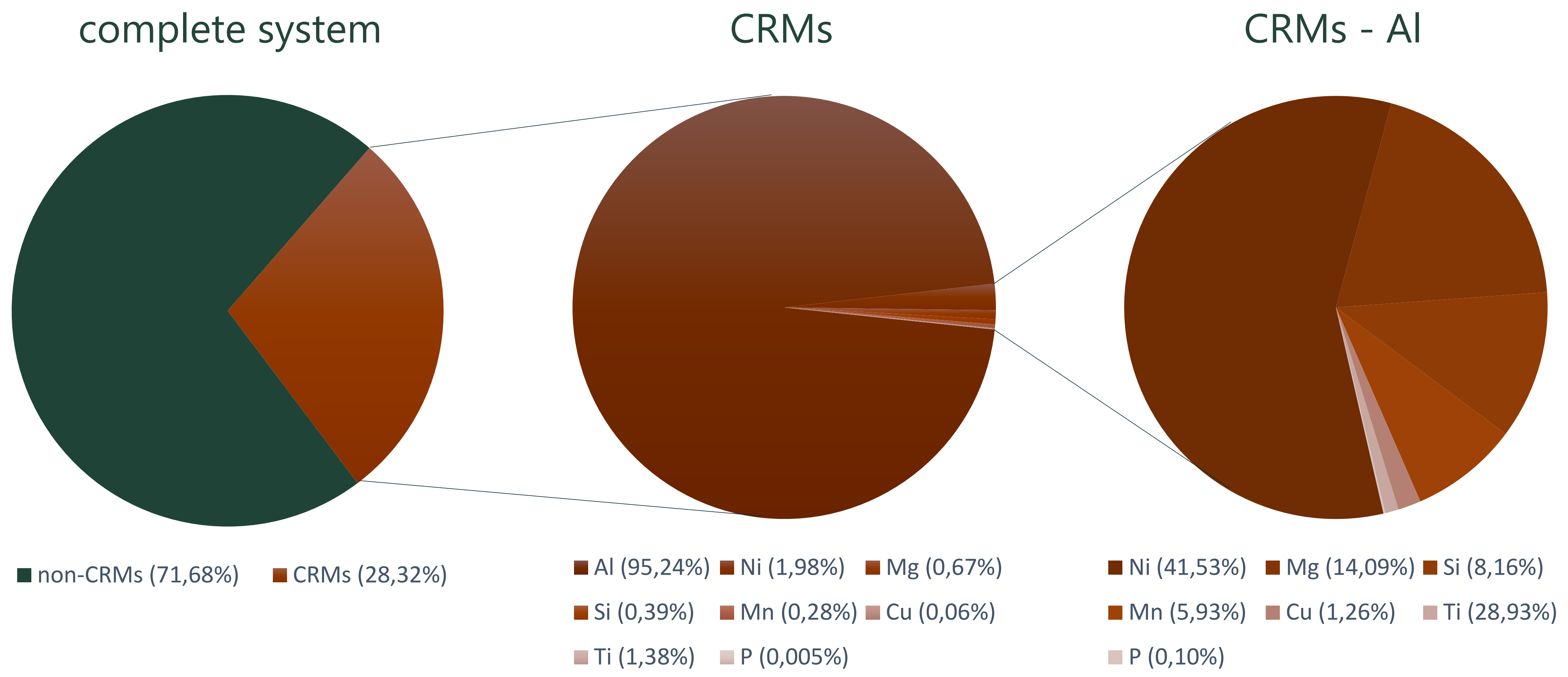
fully fixed glazing

element size:	3.6 m²
glazing area:	3.4 m²
volume total:	0,07 m³
weight total:	**150 kg**
weight glass:	129.25 kg
weight CRMs:	14.7 kg

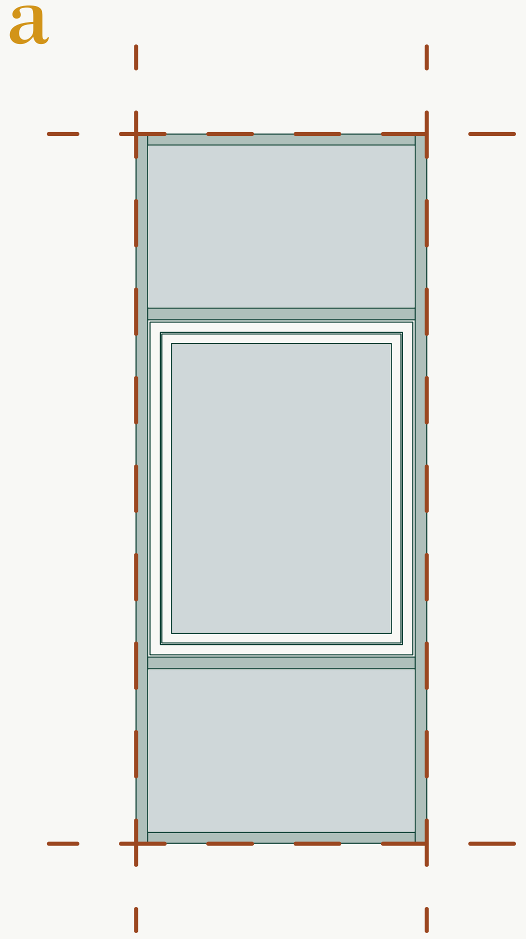
CRMs:	**kg**	**total %**
Al (aluminium):	14.28	9.52
Mg (magnesium):	0.1	0.067
Mn (manganese):	0.04	0.027
P (phosphorus):	0.0005	0.0003
Si (silicon metal):	0.06	0.04
Ti (titanium metal):	0.01	0.0067
Cu (copper):	0.01	0.0067
Ni (nickel):	0.21	0.14
CRMs total:	**14.70**	**9.8%**



Analysis
Results



S2a

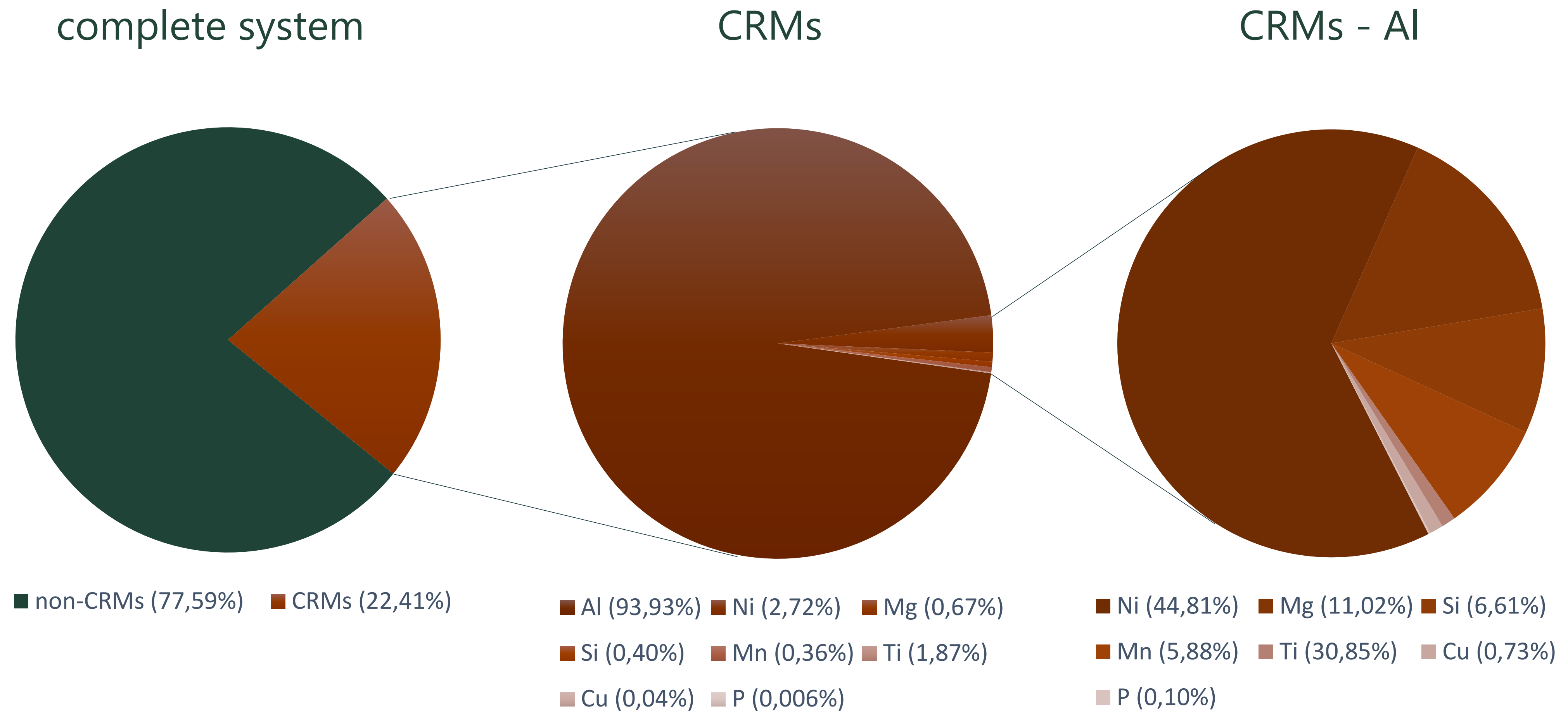


+ openable window

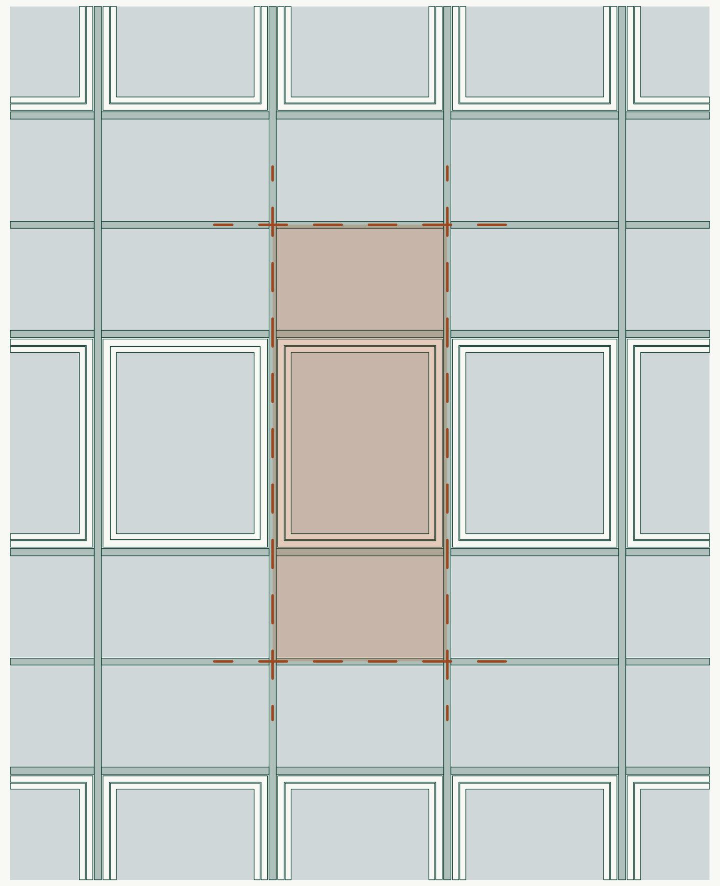
element size: 3.81 m²
glazing area: 2.8 m²

volume total: 0.09 m²
weight total: 181.06 kg
weight glass: 109.05 kg
weight CRMs: 50.60 kg

CRMs:	**kg**	**total %**
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%**



S2b



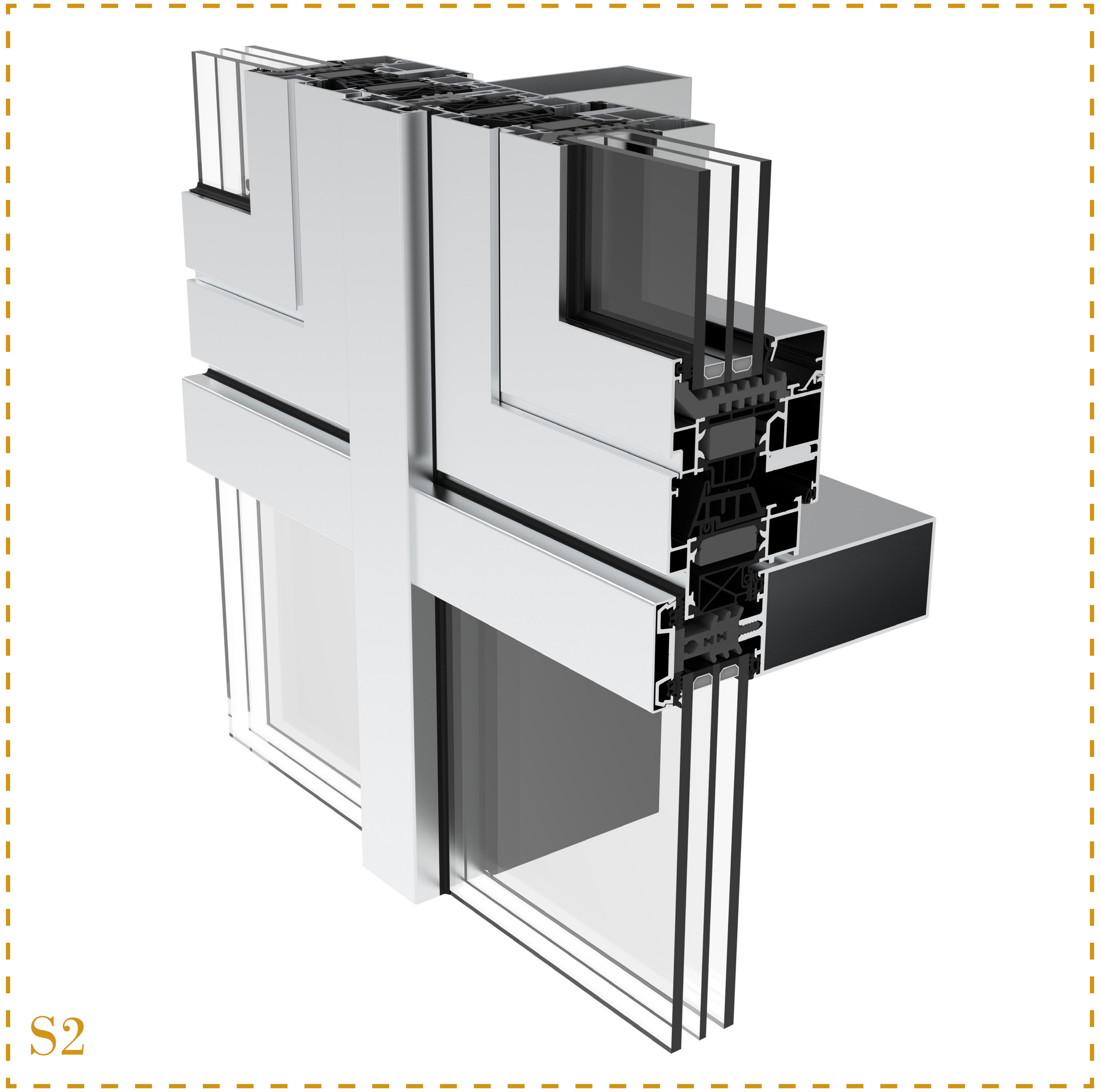
+ openable window

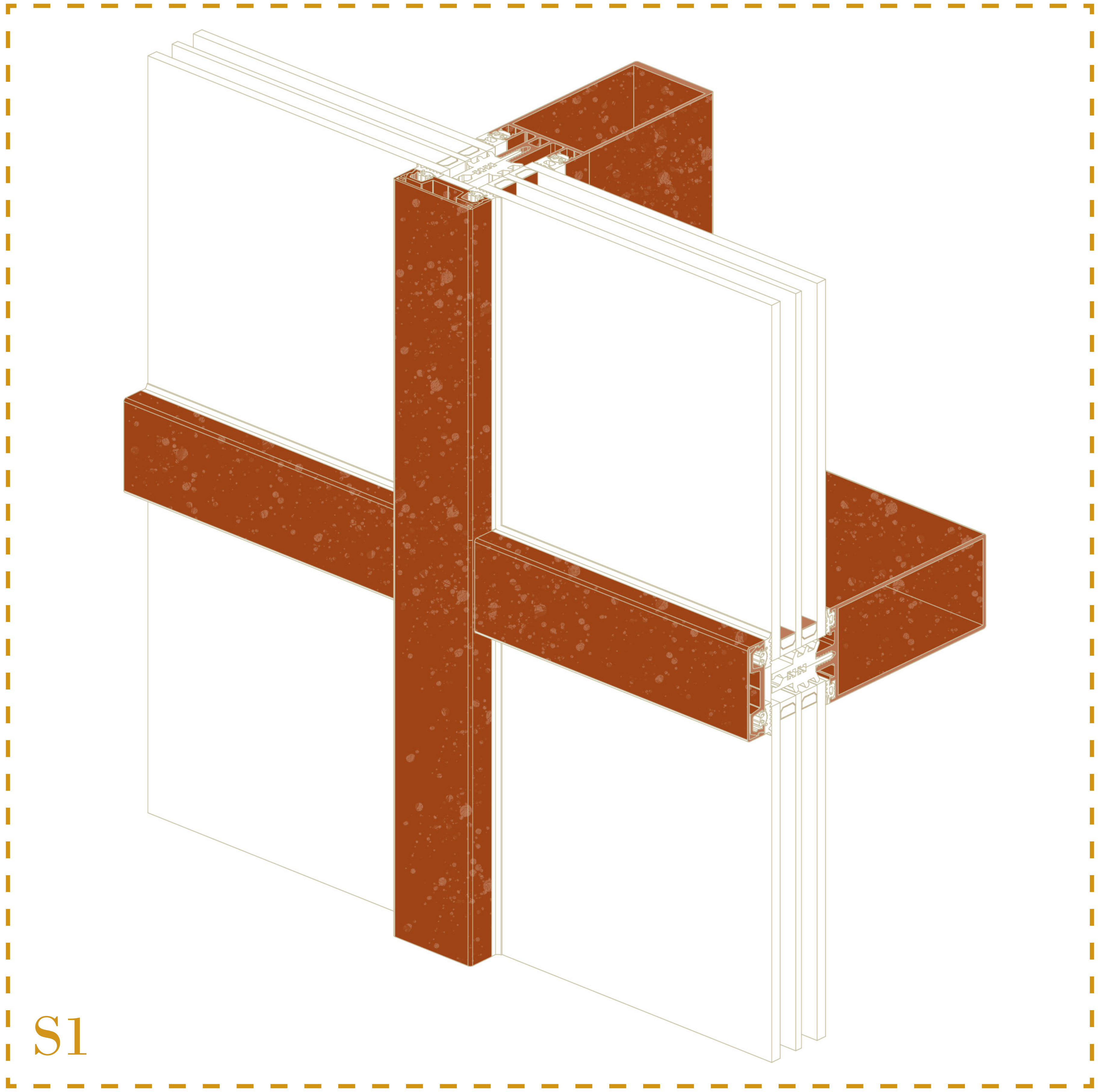
element size: 3.6 m²
glazing area: 2.8 m²

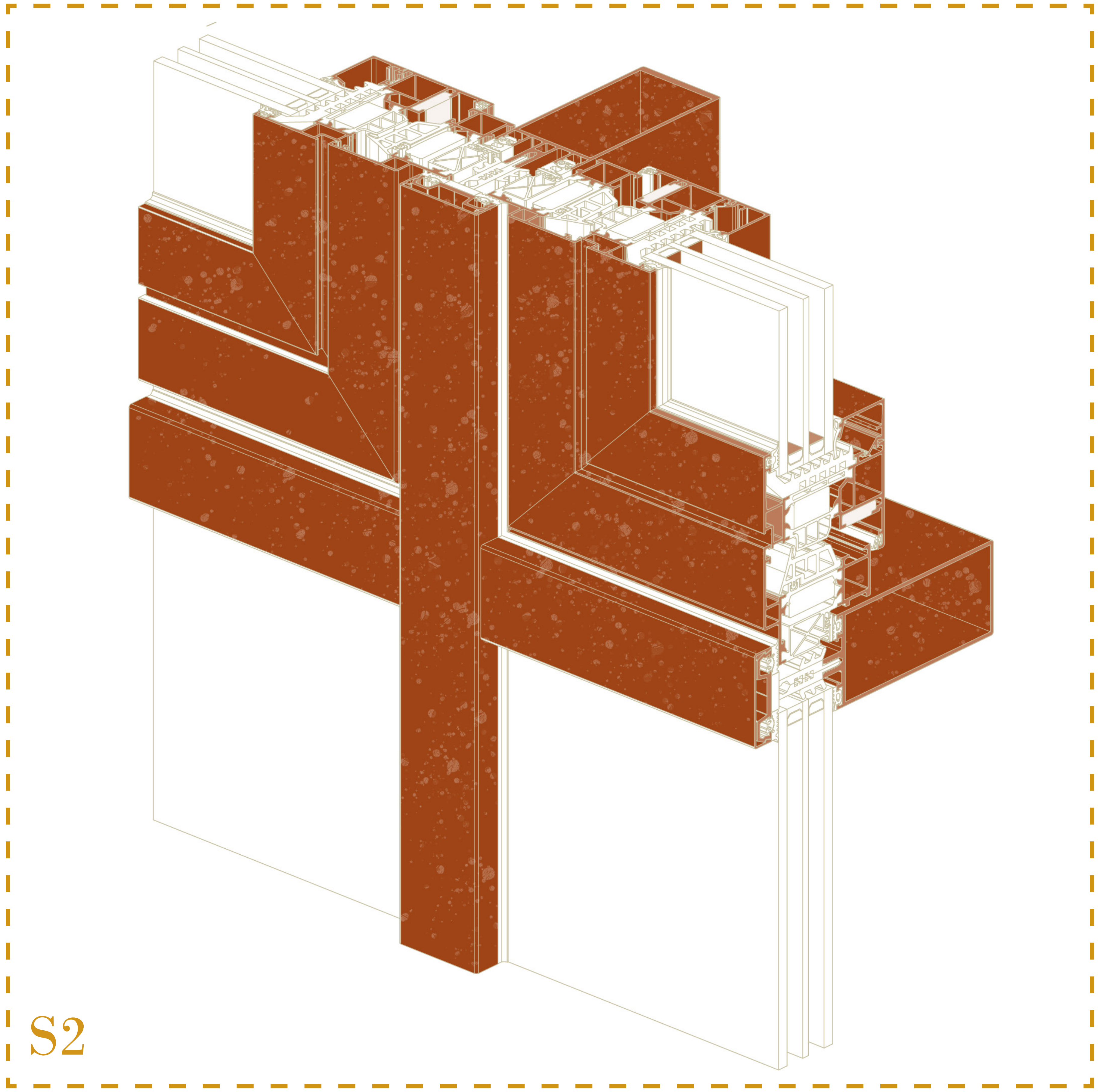
volume total: 0,08 m³
weight total: 167.21 kg
weight glass: 109.05 kg
weight CRMs: 36.79 kg

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%**

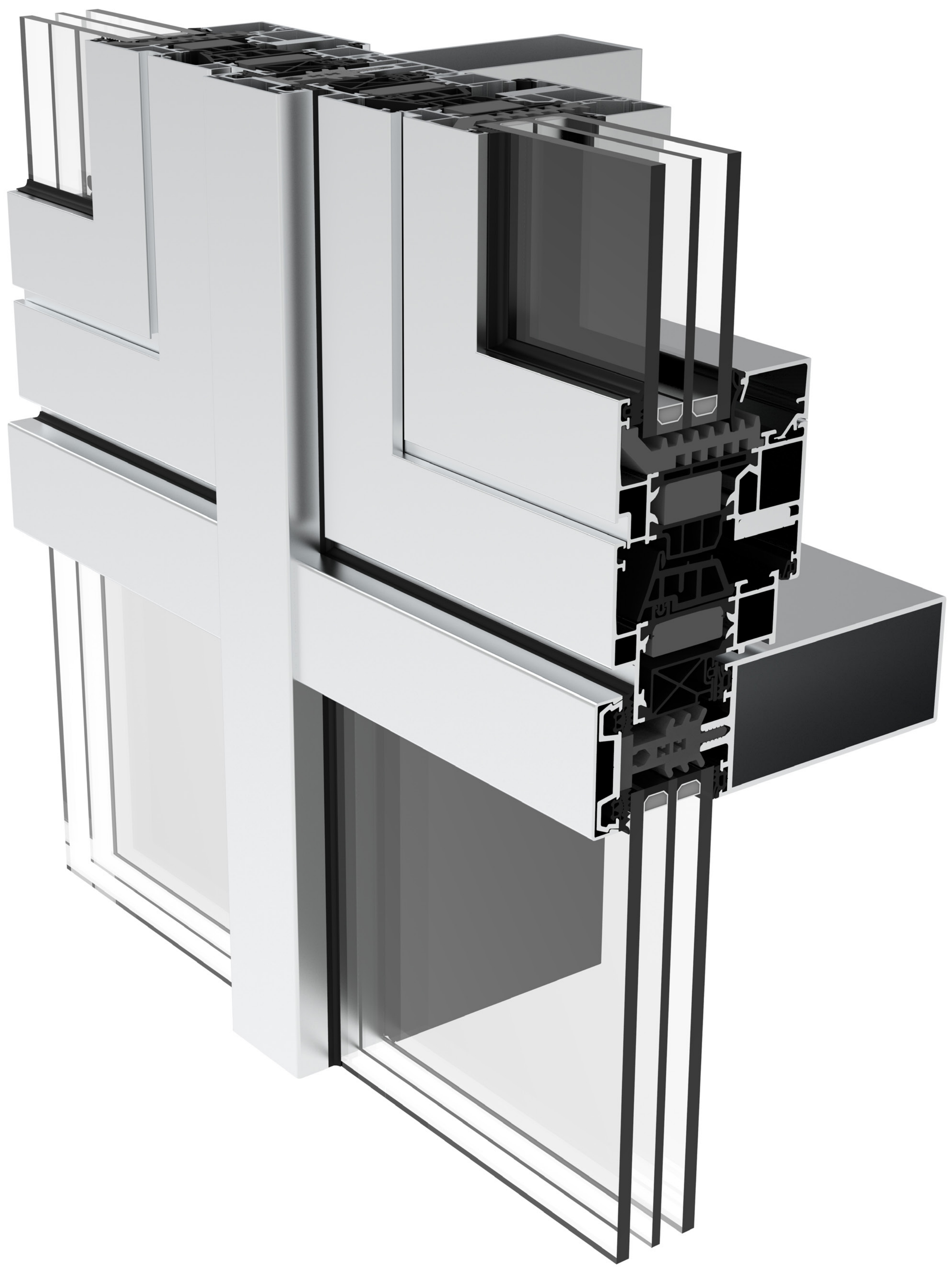
Analysis
Results



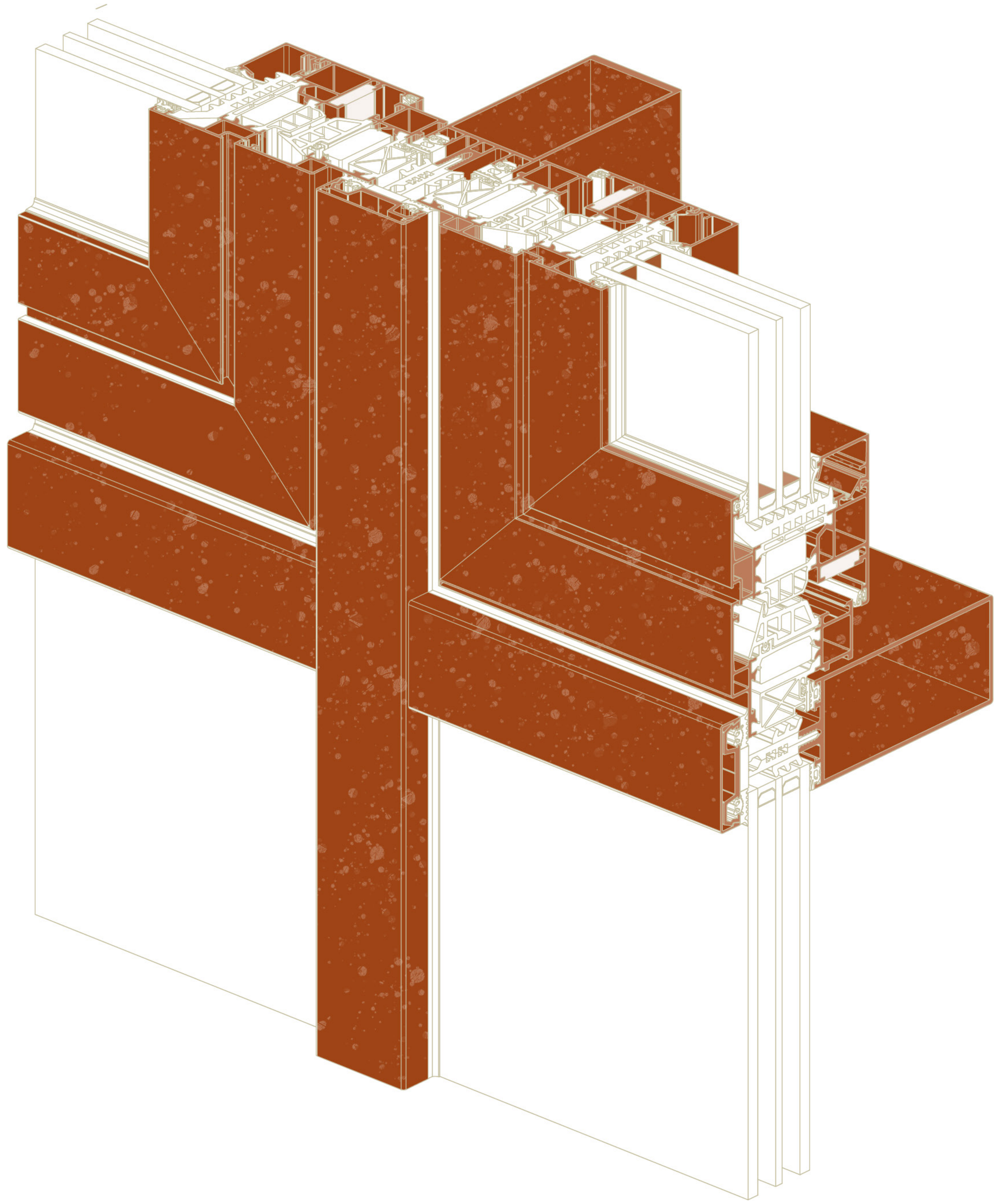

S1


S2

Analysis
Results



S2



S2

Analysis
Results

Aluminium	*series*	*alloy elements*	*characteristics*	*system*	*strengths*	*limitations*	*uses*	*effect of composition*
Cast	1xx.x	Pure Al		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
	2xx.x	Cu-alloyed						
	3xx.x	Si, Cu, Mg-alloyed						
	4xx.x	Si-alloyed						
	5xx.x	Mg-alloyed	- best combination of strength and toughness - most difficult to cast					
	7xx.x	Zn-alloyed	- excellent surface appearance and machinability - most susceptible to stress corrosion cracking					
Wrought	1000	Pure Al	- inferior machineablility to other wrought alloys - lowest strength	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		aerospace, aircraft applications, domestic electrical appliances, weapons industry, transport applications, forged missile and aircraft fittings, pistons	increasing alloying additions reduces corrosion resistance
	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					

Analysis
Results

Aluminium Alloy
6063-T5

Element	Effect
Mg	Increased strength and hardness
Si	Increased castability + strength + resistance to abrasive wear
Fe	Increased strength Decreased ductility - mostly undesirable in Al-alloys
Mn	Improves low cycle fatigue resistance + corrosion resistance.
Cu	Increased tensile strength, fatigue strength and hardness Decreases the ductility of the alloys + corrosion resistance
Ti	Refined grains of primary aluminum
Zn	Increased strengtht through precipitation hardening heat treatment Increased susceptibility to stress corrosion cracking
Cr	Improved ductility and toughness Reduced susceptibility to stress corrosion cracking

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		

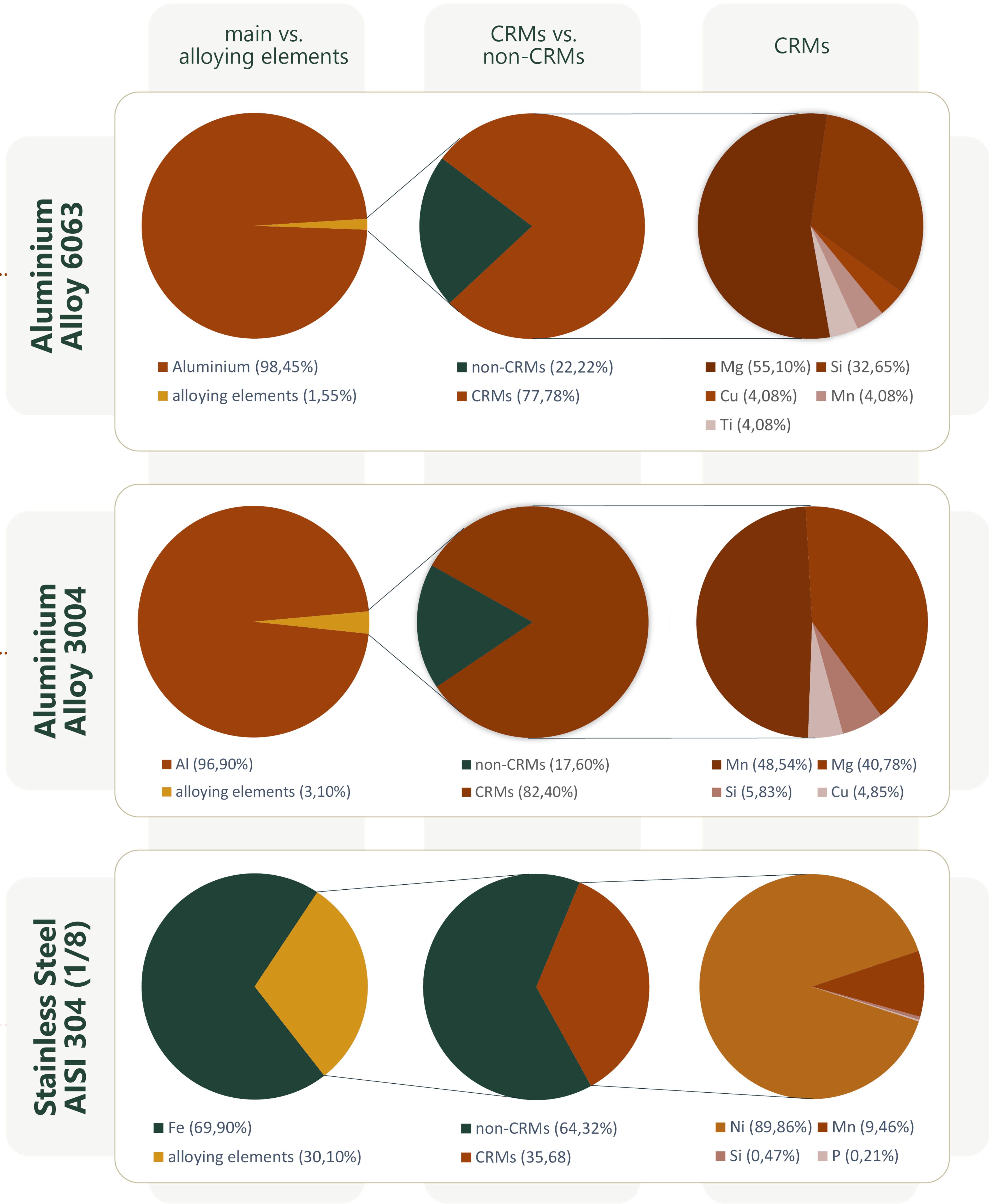
crm 2023 list

Analysis
Results

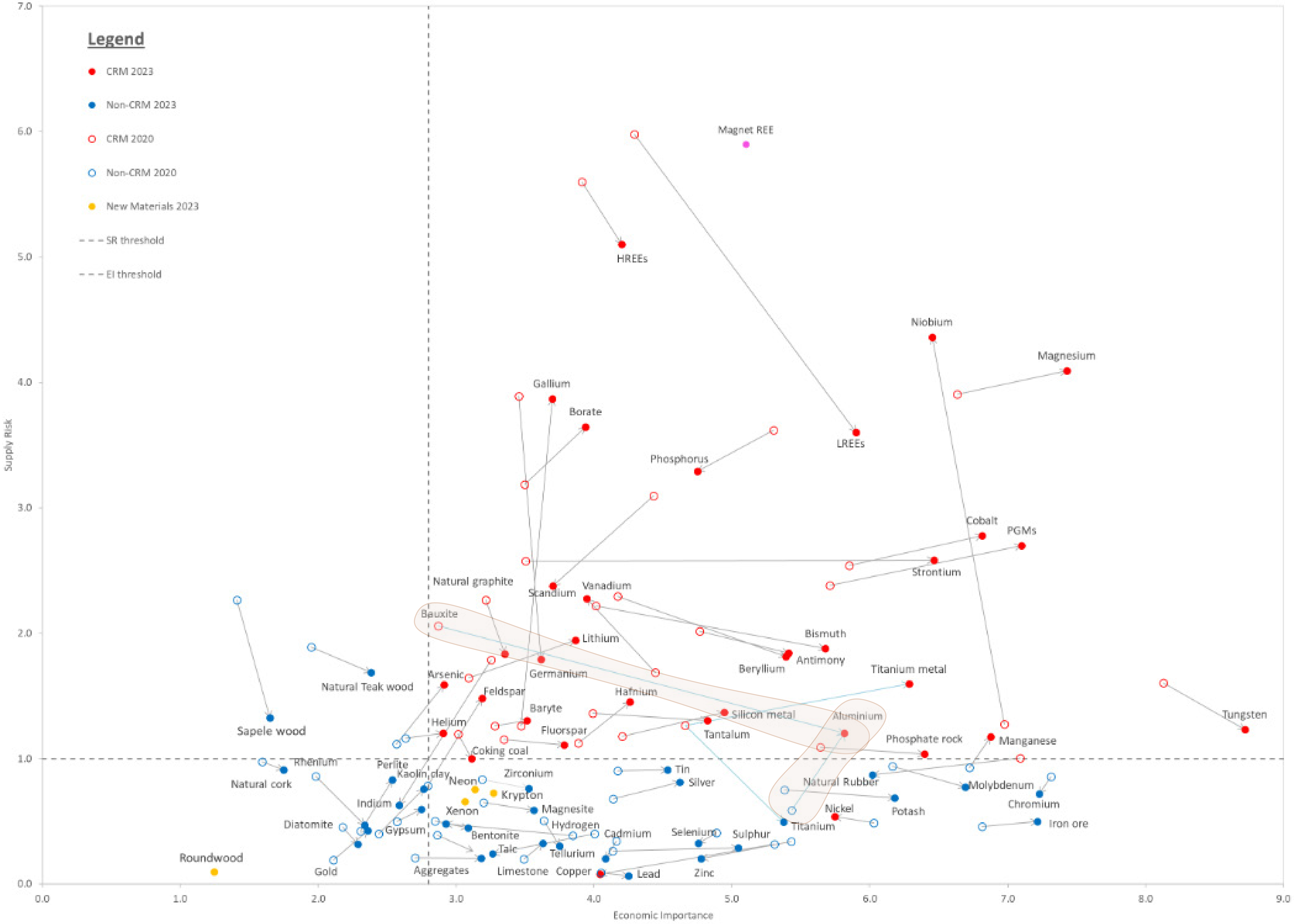
99.68%
CRMs

99.48%
CRMs

10.57%
CRMs

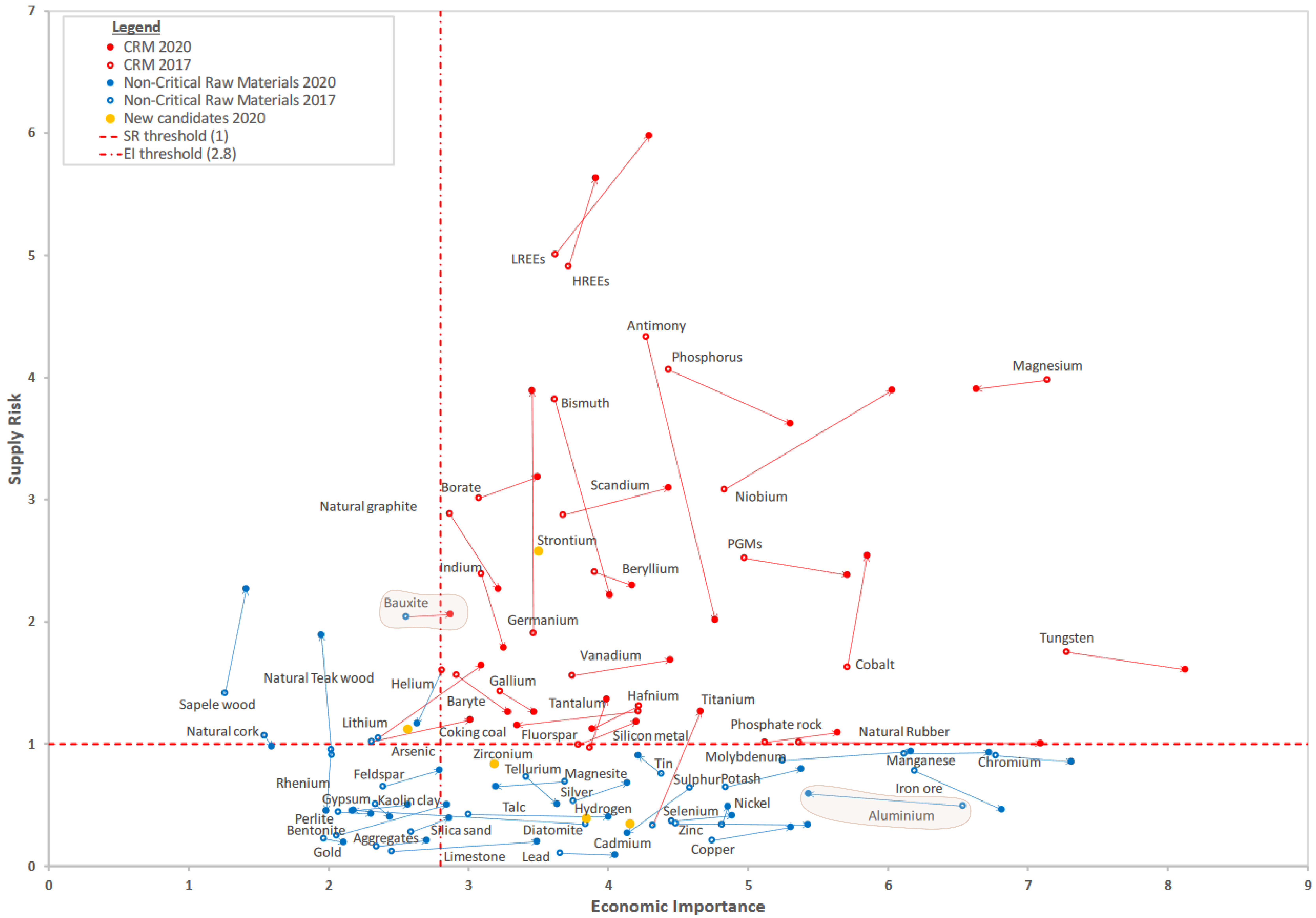


Analysis
EC CRM list | changes from 2020 to 2023



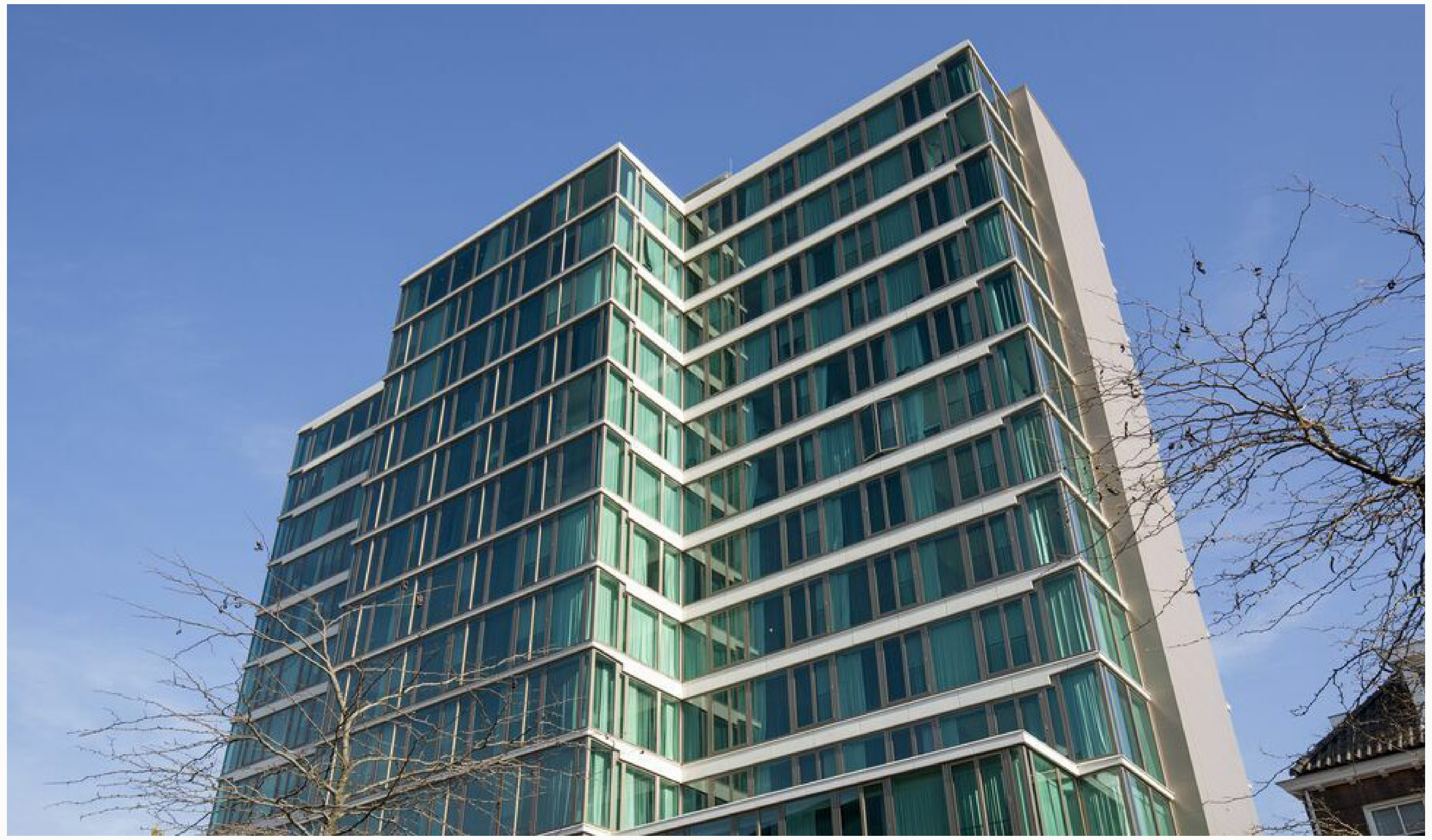
Analysis

EC CRM list | changes from 2017 to 2020

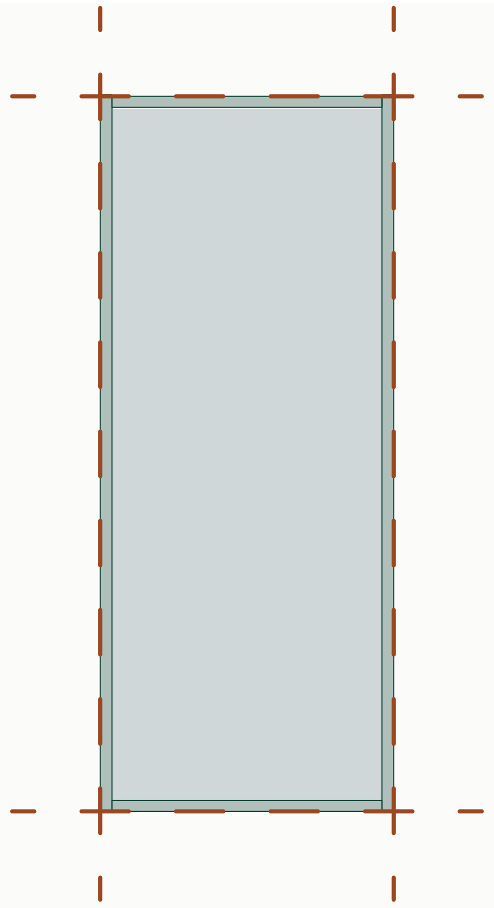


example scale-up

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

original facade total area:

5.100m²

(aluminium curtain wall)

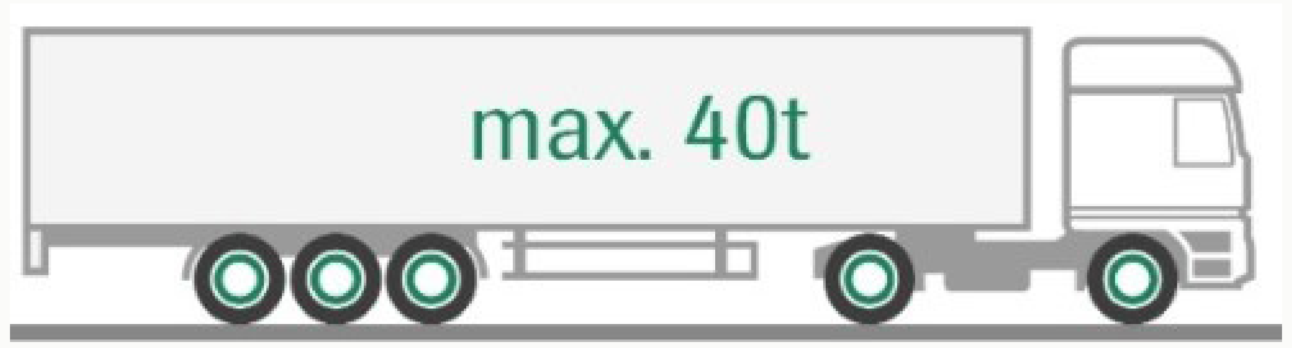
Al	37373,2	kg
Mg	254,33	kg
Mn	53,54	kg
P	0,67	kg
Si	147,24	kg
Ti	13,39	kg
Cu	13,39	kg
Ni	281,10	kg

total CRMs: **38.136,9 kg**

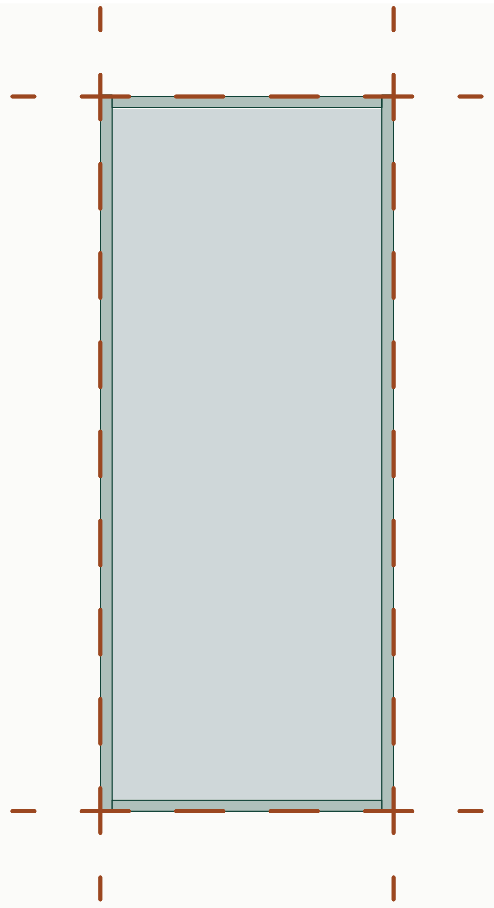
photo, m²: https://www.reynaers.com/inspiration/aluminium-project-references/sliding-folding-doors-groene-toren-eindhoven-eindhoven

example scale-up

GROENE TOREN,
EINDHOVEN



if built with: *S1.a*



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

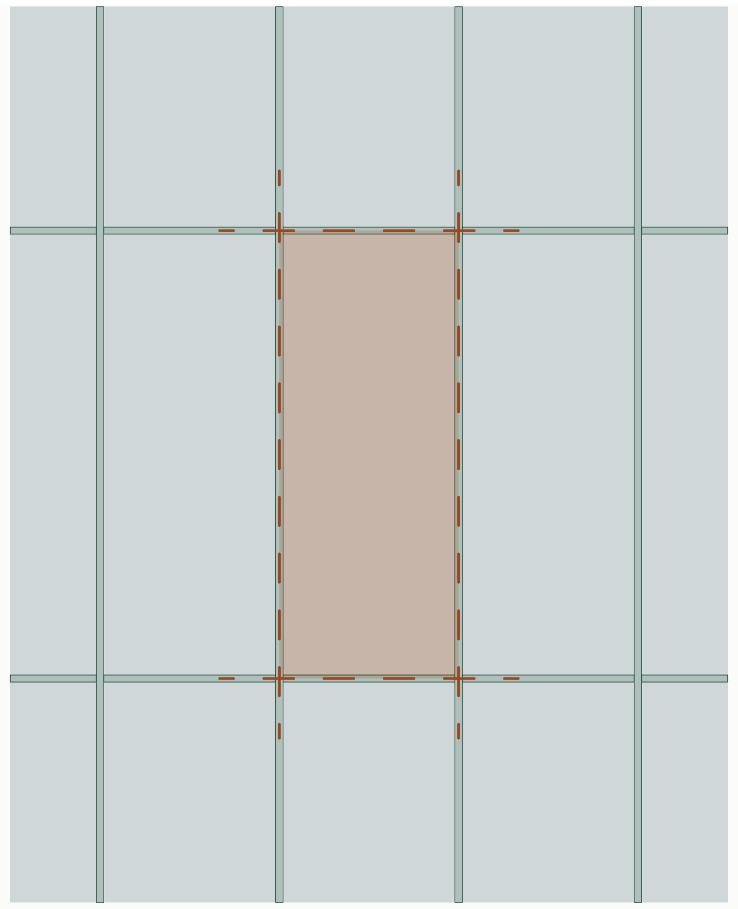
Analysis

Assumption scale-up

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**

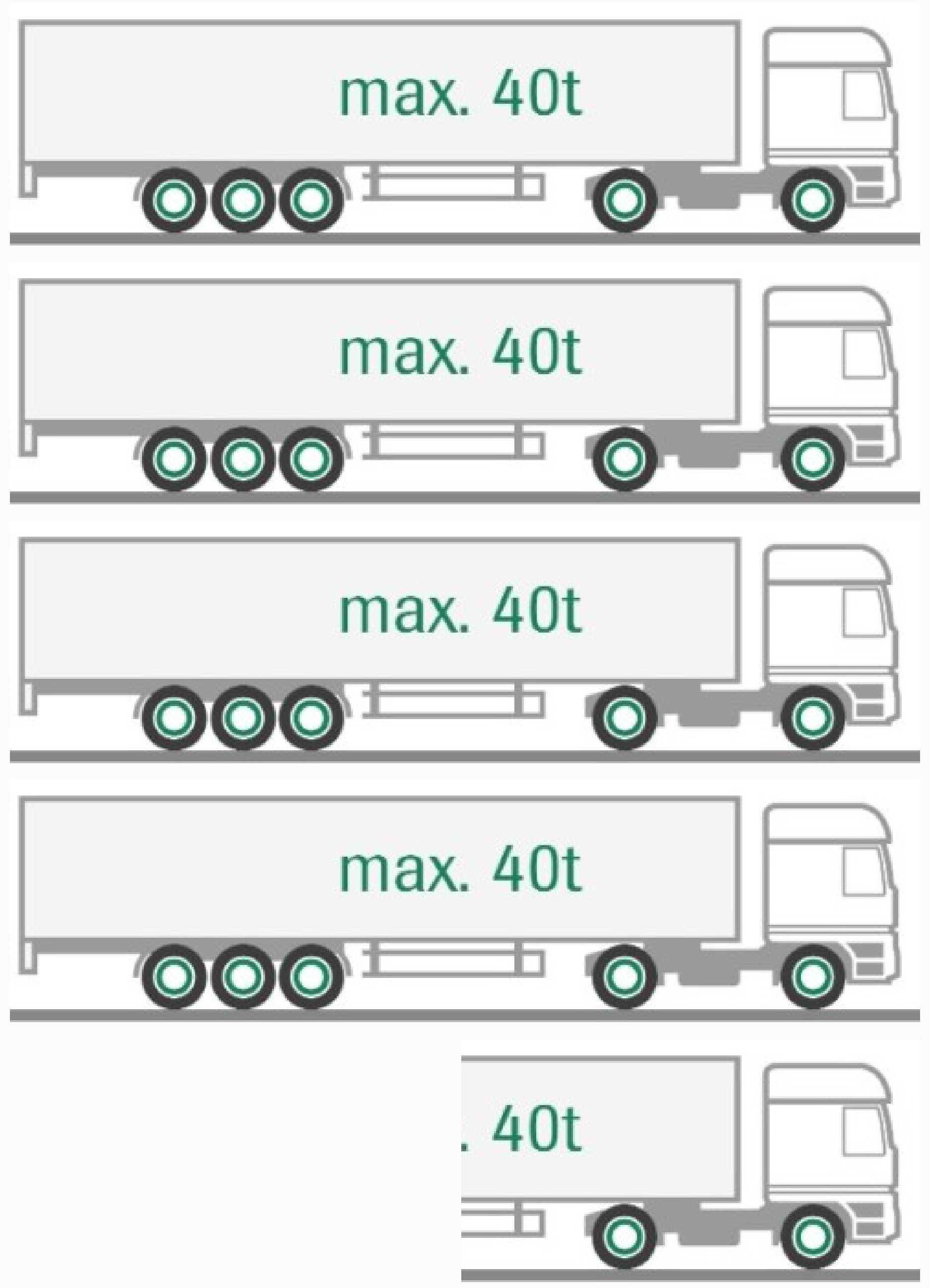
m²: https://www.permasteelisagroup.com/project-detail?project=1895, photo: https://www.cityrotterdam.com/attracties/architectuur-rotterdam/de-rotterdam-gebouw/

Analysis

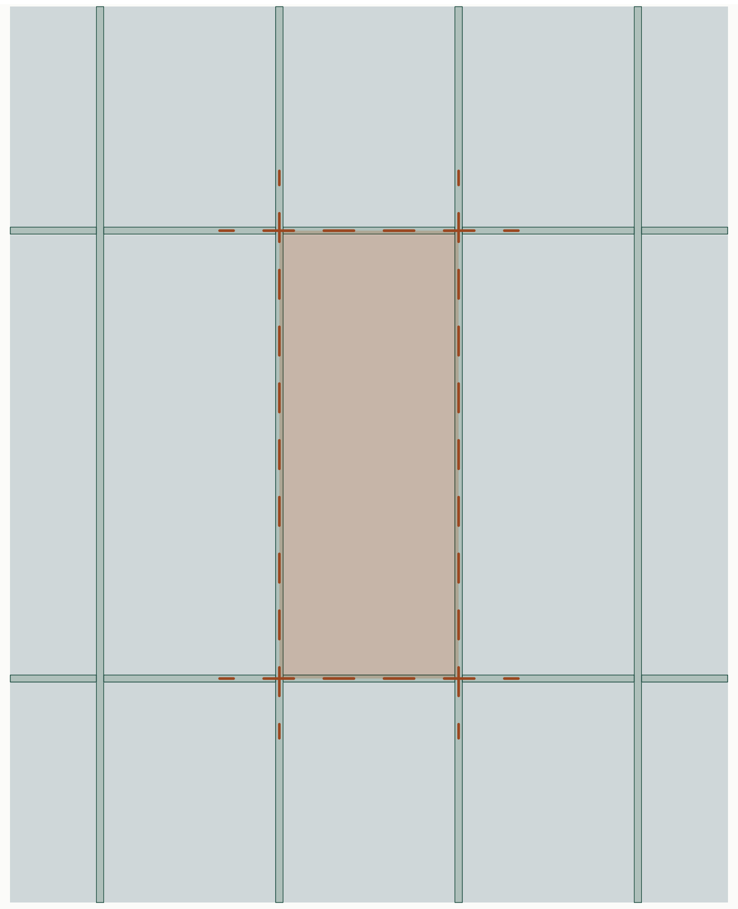
Assumption scale-up

example scale-up

DE ROTTERDAM,
ROTTERDAM



if built with: S1.b



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Ni	0,21	0,06
	14,71	4,09

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original facade total area:

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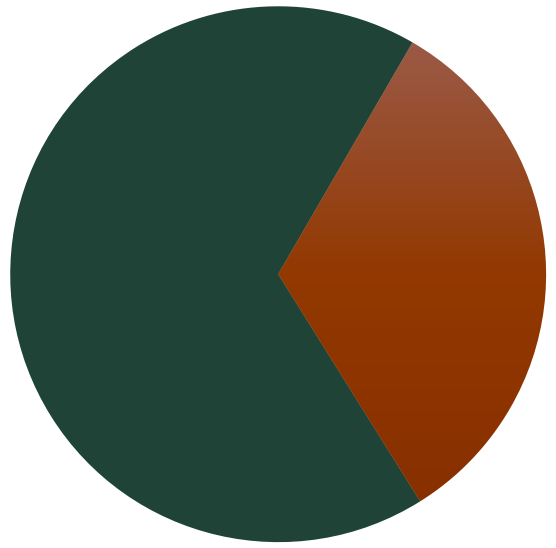
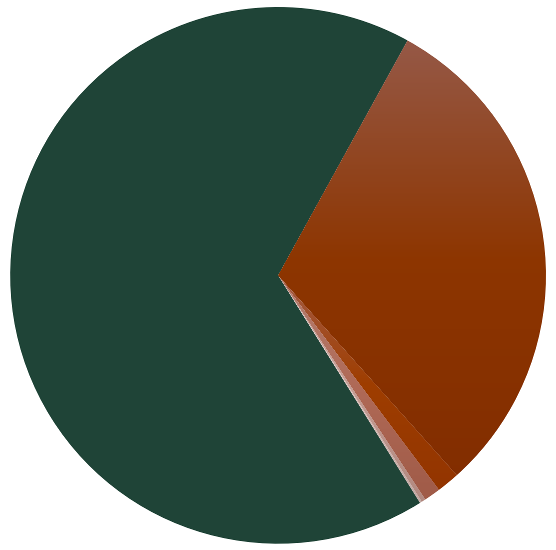
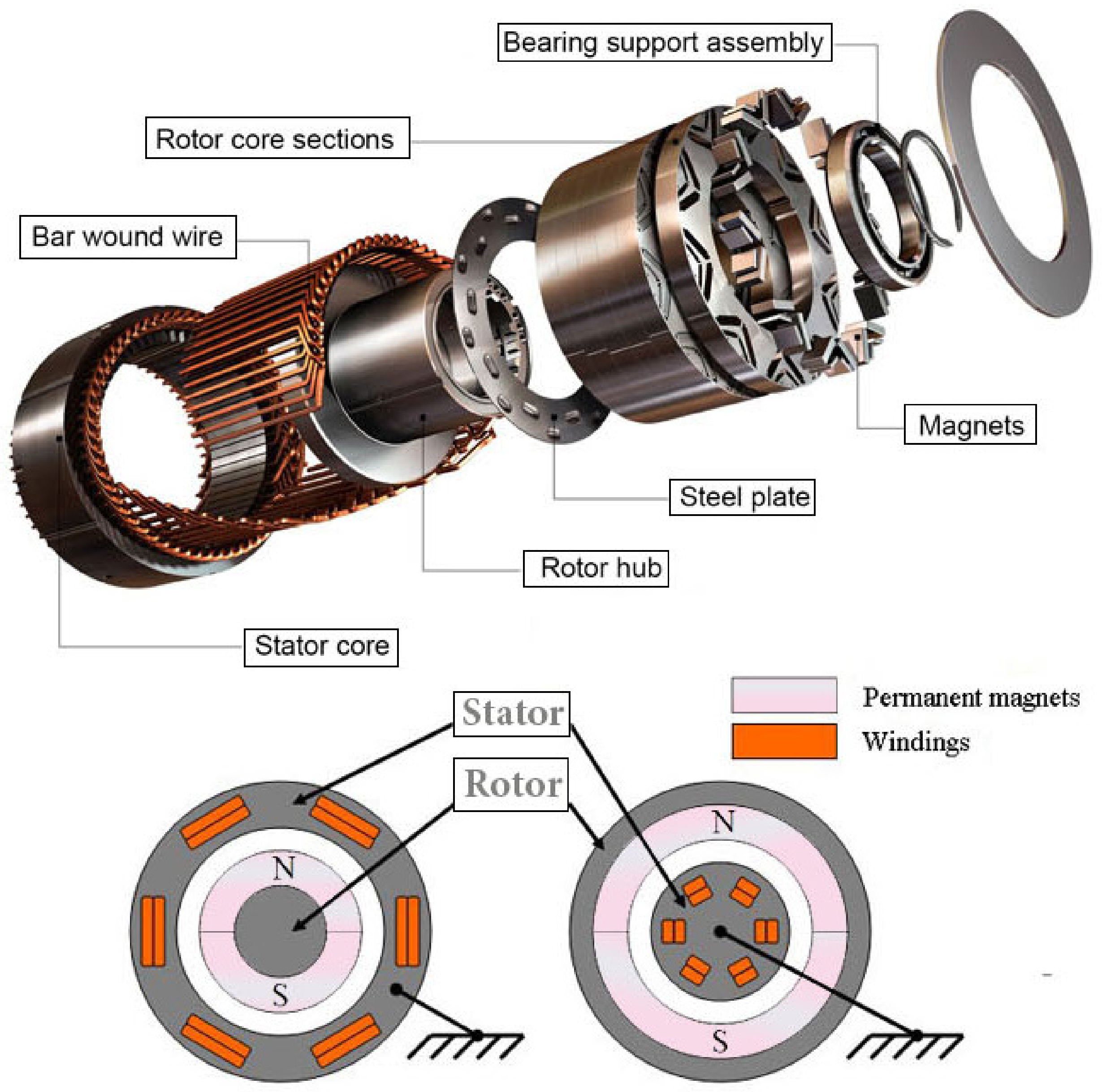
m²: https://www.permasteelisagroup.com/project-detail?project=1895, photo: https://www.cityrotterdam.com/attracties/architectuur-rotterdam/de-rotterdam-gebouw/

Analysis
Motors, magnets

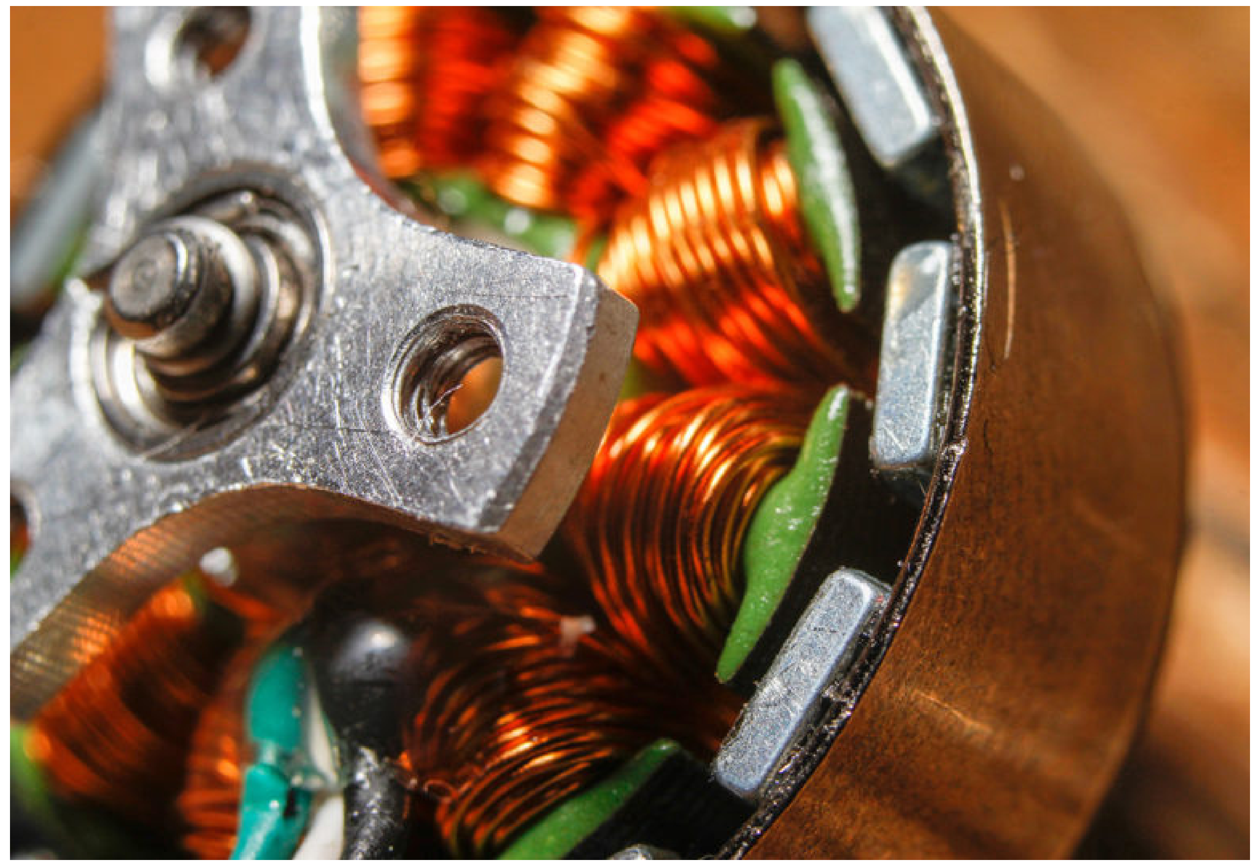
Material	Elements	%	Density kg/m³
Neodymium iron boron (NdFeB) magnets (used for e.g. brushless DC motors, sensors, switches,…) e.g.: neodymium magnet N42	B (boron)	1	7400-7500 kg/m³
	Co (cobalt)	0,25-2,5	
	Dy (dysprosium)	0-0,25	
	Fe (iron)	65,5-69	
	Nd (neodymium)	30,5	
	Tb (terbium)	0,25	







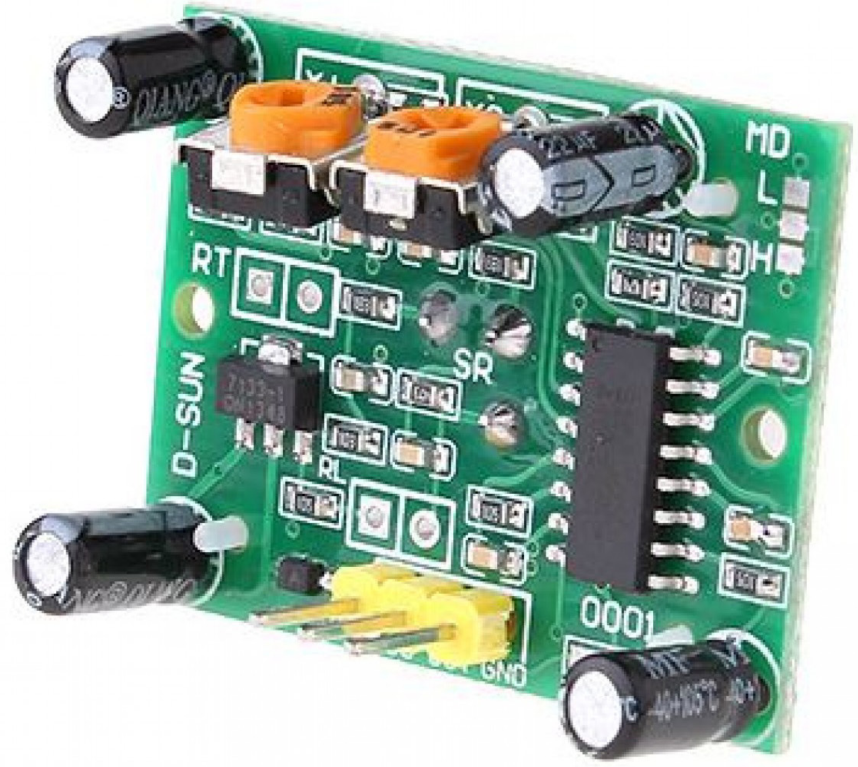
https://www.newkidscar.com/electric-car/permanent-magnet-synchronous-motor-construction/



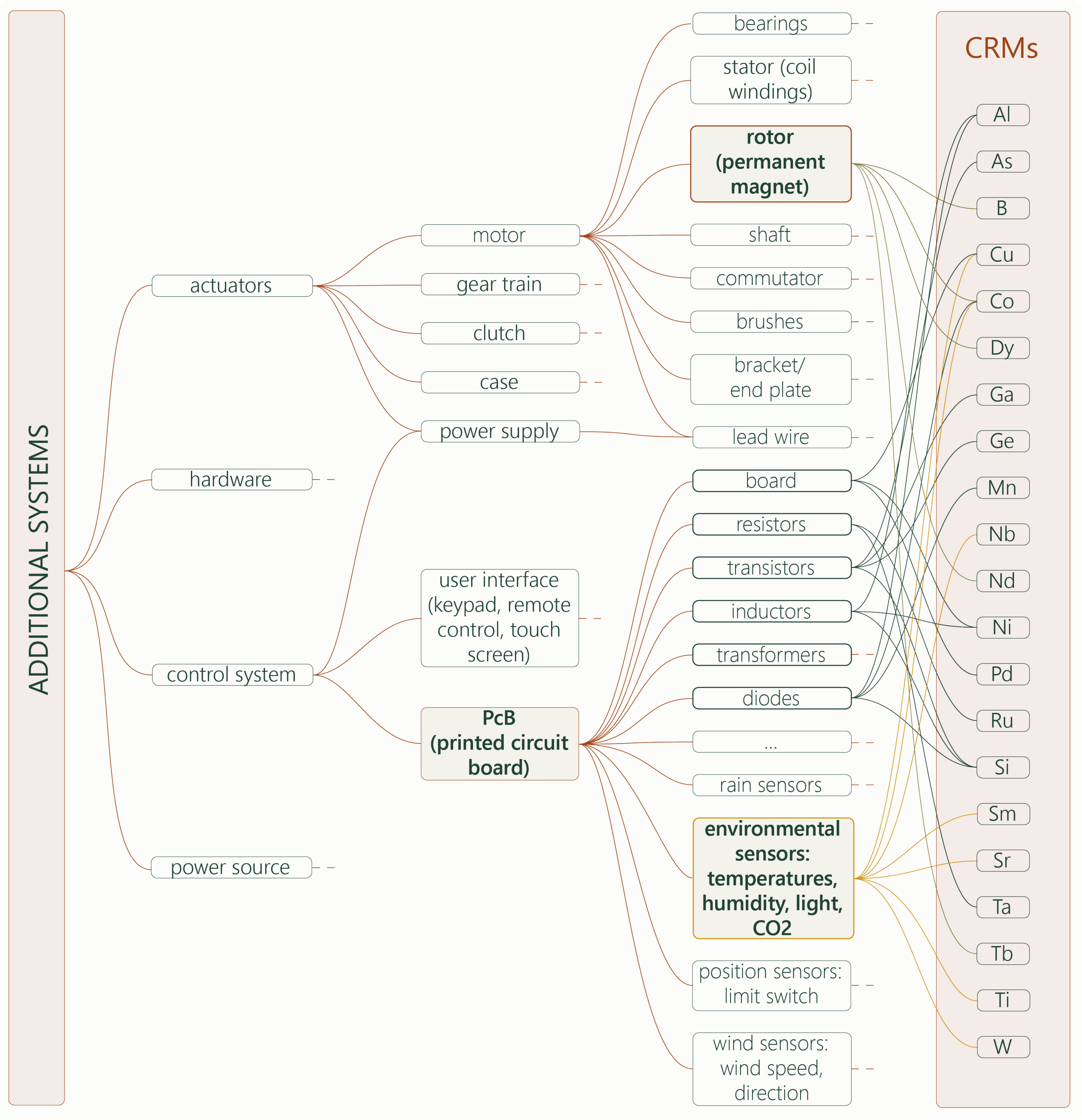
https://www.pivotint.com/blog/7-esc-and-brushless-motor-applications/

https://www.electricaltechnology.org/2021/01/types-of-electric-motors.html

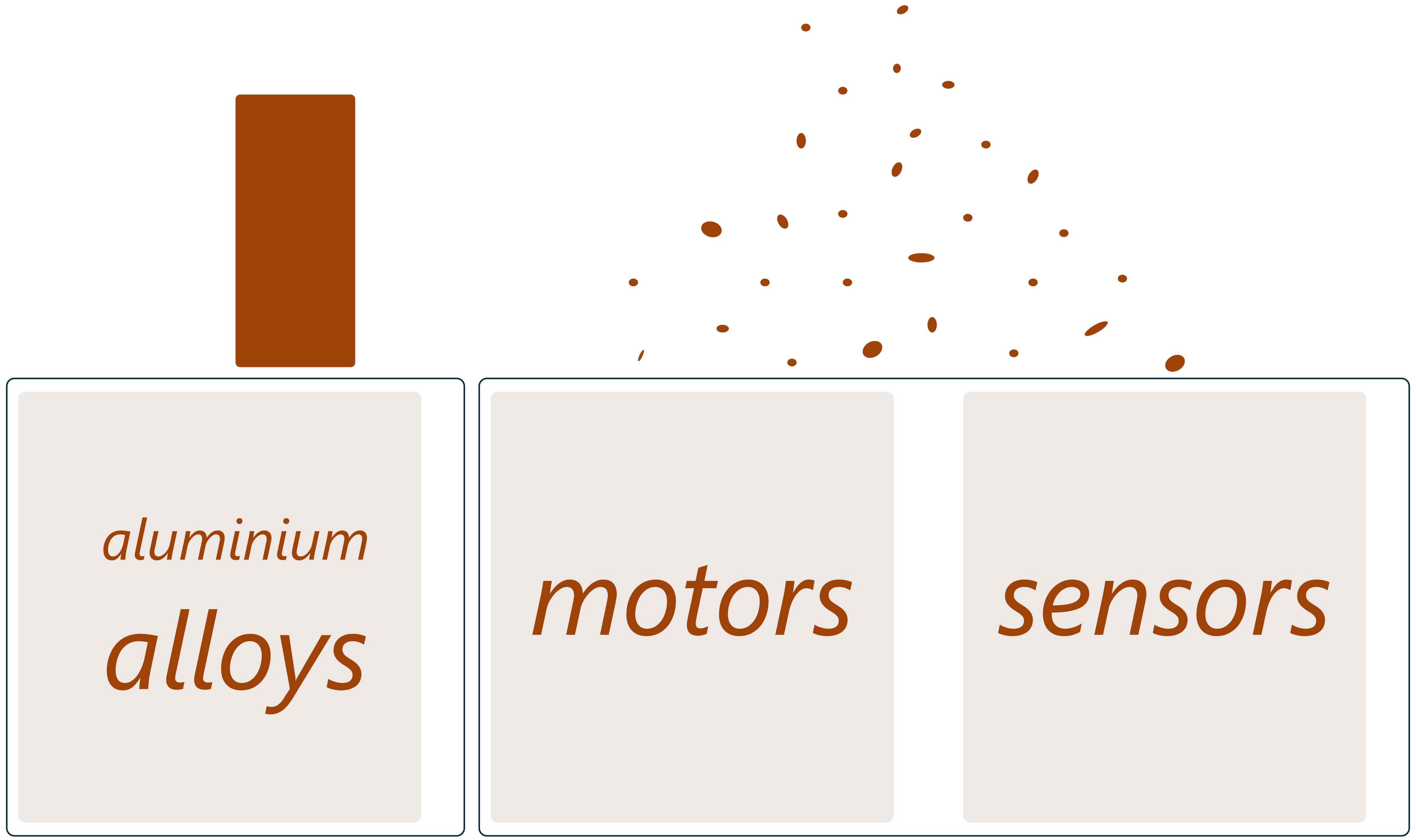
Analysis
Sensors



Analysis
CRMs in magnet + sensor



motor components: https://www.nidec.com
PcB components: https://www.ablcircuits.co.uk
PcB components: (Meyer, 2018)



- can quantify them but
- use a lot of them as big elements / systems

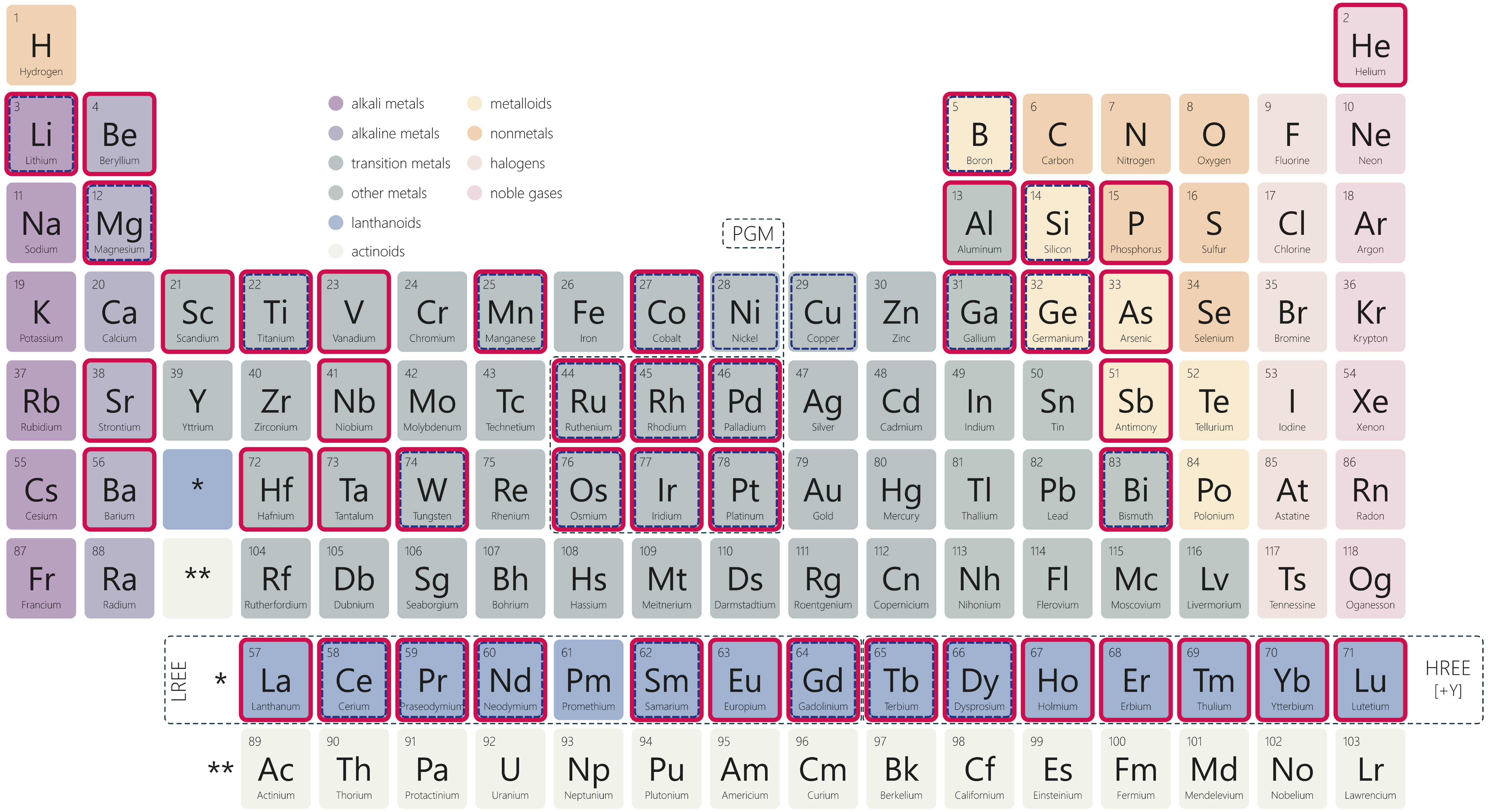
- not enough information to quantify
- used in very small amounts, makes it difficult to trace or recycle them

PERIODIC TABLE OF THE ELEMENTS

EC CRM+SRM list 2023

periodic table

total: 118



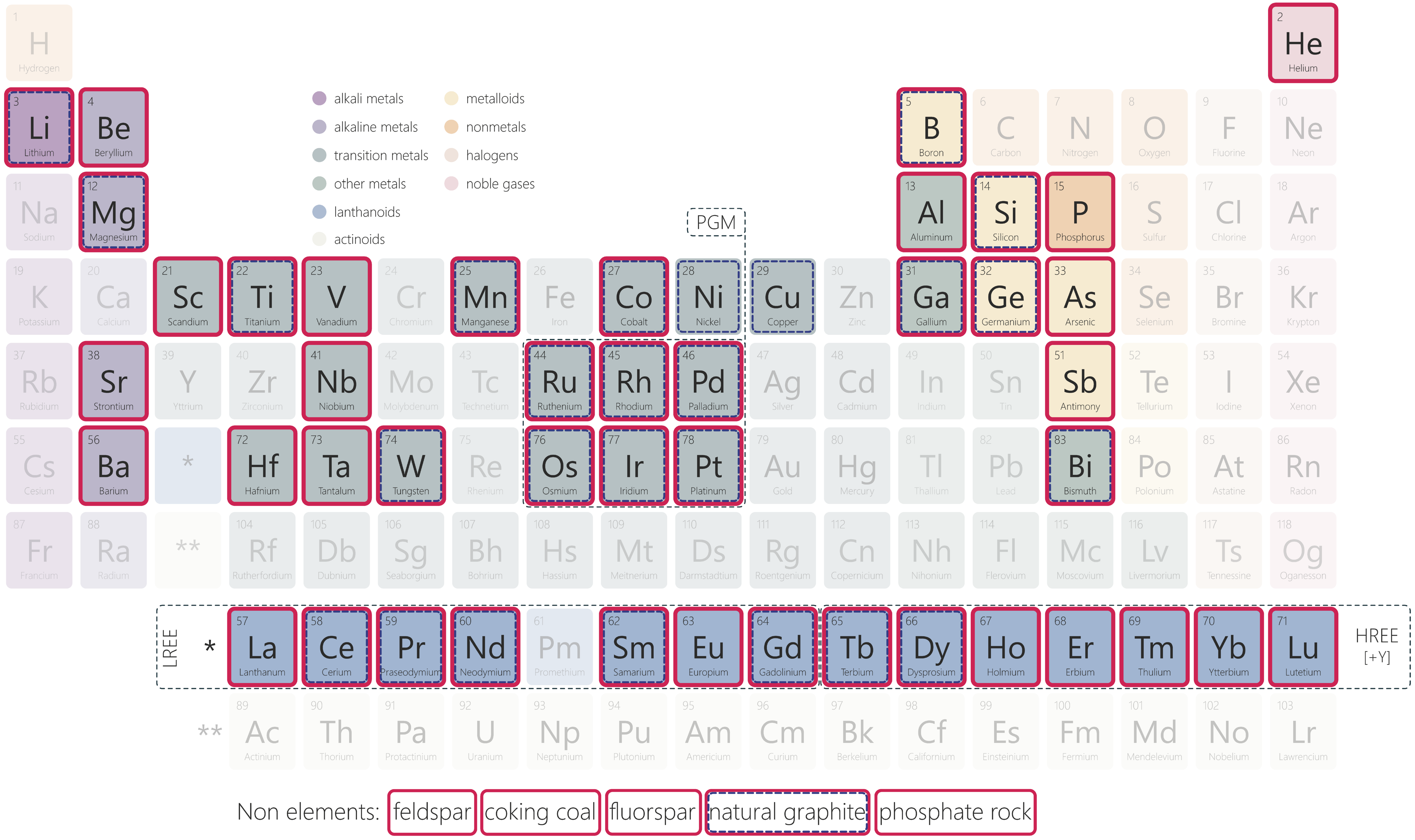
Non elements: feldspar coking coal fluorspar natural graphite phosphate rock

PERIODIC TABLE OF THE ELEMENTS

EC CRM+SRM list 2023

CRMs on the periodic table

total: 118
CRM list: 49+2

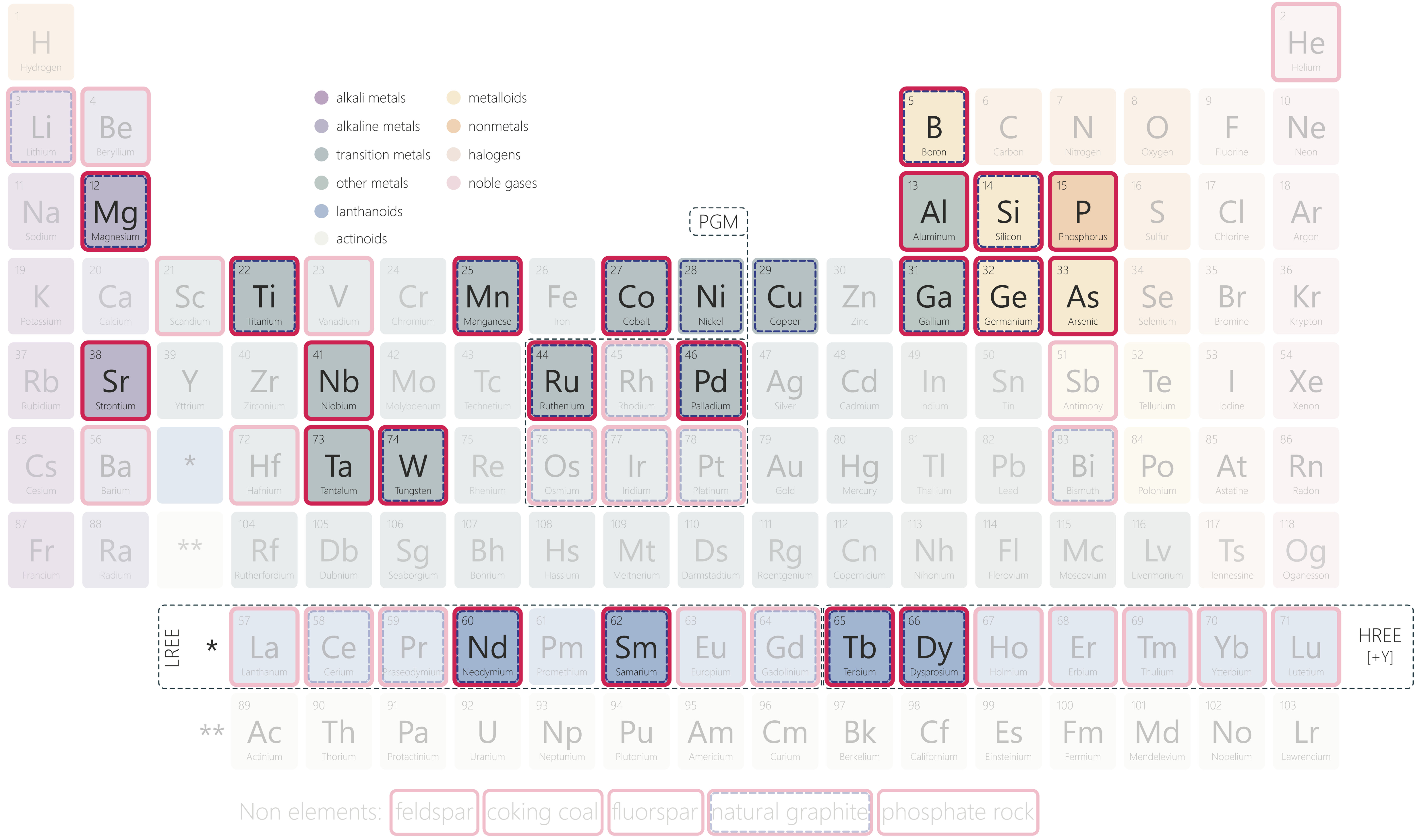


PERIODIC TABLE OF THE ELEMENTS

EC CRM+SRM list 2023

CRMs present in the analysis

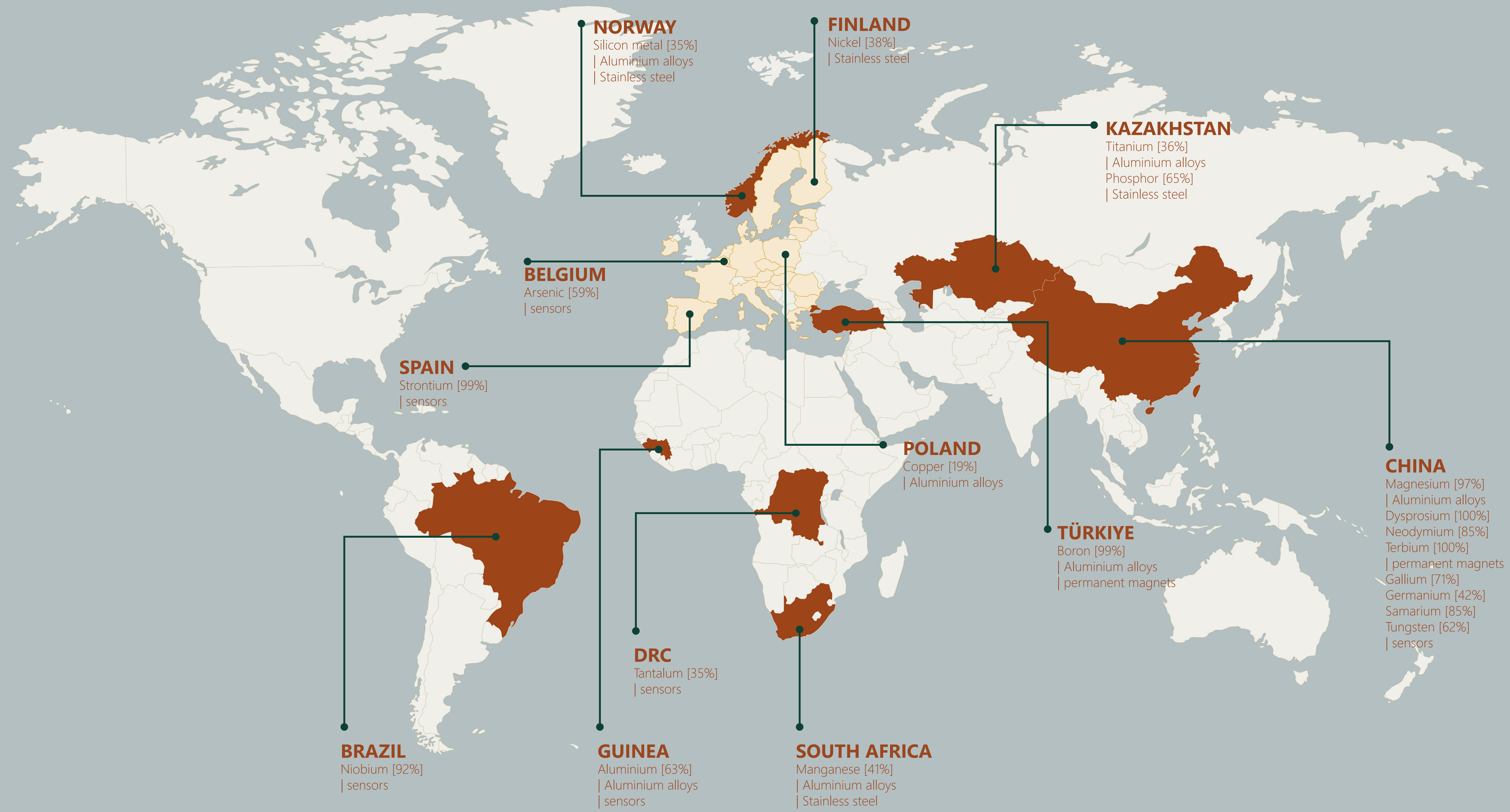
total: 118
CRM list: 49+2
included: 21+2



Policy
Import Dependency

	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)	•		•

Main EU supply countries of CRMs related to curtain wall systems



[%] = refers to import rate of the EU, not global production of country | numbers from EC publication on CRMs list 2023

CRMA

Critical Raw Materials Act

10% ...of annual consumption extracted by the EU

40% ...of processing done within the EU

15% ...of materials provided through recycling capacity

not more than... **65%** ...supplied by one single third country

material policy

policymaking

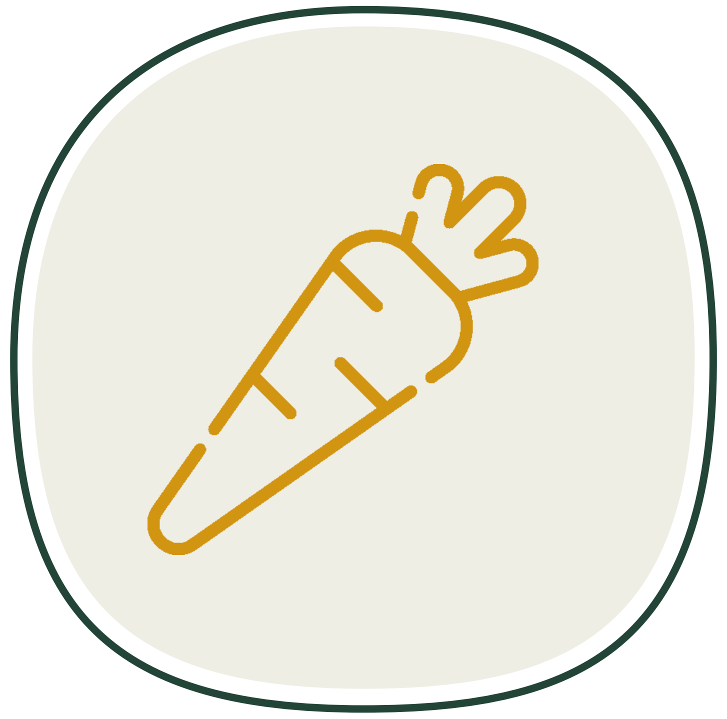
WHY – address (...) challenges

WHO – civil servants, politicians, technocrats (law, policy, trade, procedure), stakeholders from different sectors

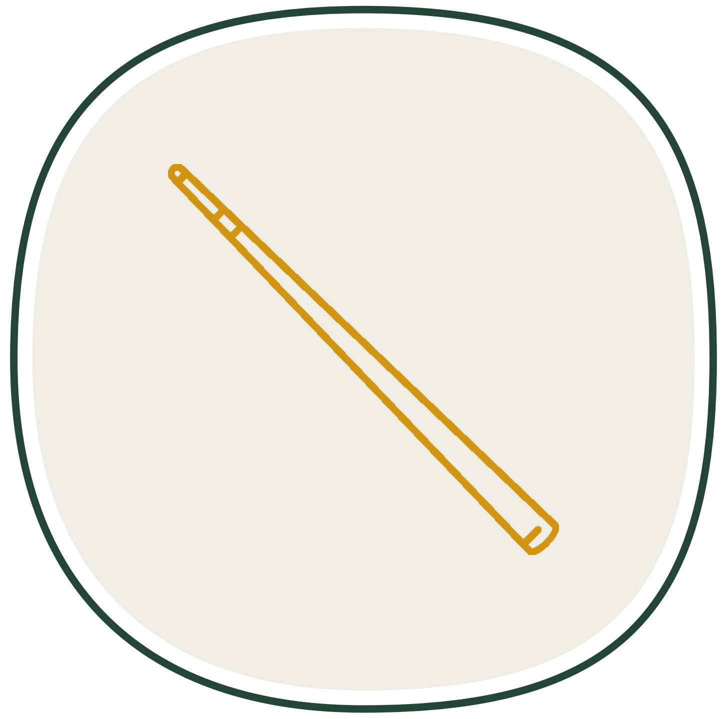
WHAT – dynamic process; always takes place in a specific context - reflection of social and economic developments – social, economic, political and environmental fields

HOW – policy instruments

Policy
Policy instruments



economic
instruments

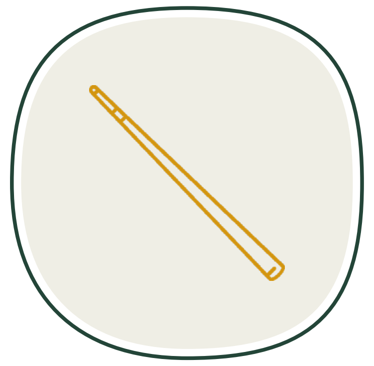


regulatory
instruments

informative
instruments

Policy

Instruments towards a sustainable built environment



policy instruments	
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Information tools	Public information campaign Technological information diffusion programs Environmental labeling schemes
Voluntary tools	Unilateral commitment or declaration Negotiated agreement or commitment Selective regulation or public voluntary program
Research + development	Research and development tools

Vedung, 1998

Kibert, C.J. (2002)

Policy
Landmark publications

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

focus on ecology

set the foundation for following 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 connection 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"

first introduction of "sustainability"

Ashby, M. F. (2021). Materials and the Environment. Eco-InformedMaterial Choice. Elsevier.

Policy
Directives

1985	The Product Liability Directive
1999	The Landfill Directive
2000	The Volantile Organic Compound (VOC) Directive
2000	End-of-Life Vehicles (ELV) Directive
2002	**Waste Electrical and Electronic Equipment (WEEE)**
2002	Restriction of Hazardous Substances (RoHS) Directive
2006	Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)
2006	The Battery Directive
2008	Waste Framework Directive (2008)
2009	**The Energy-Using Products (EuP) and Energy Related Products Directive**

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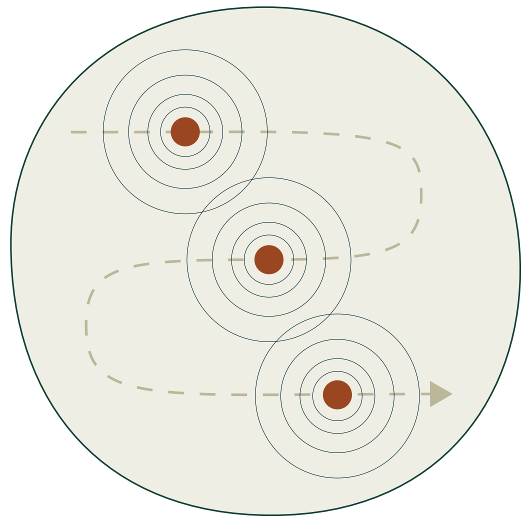
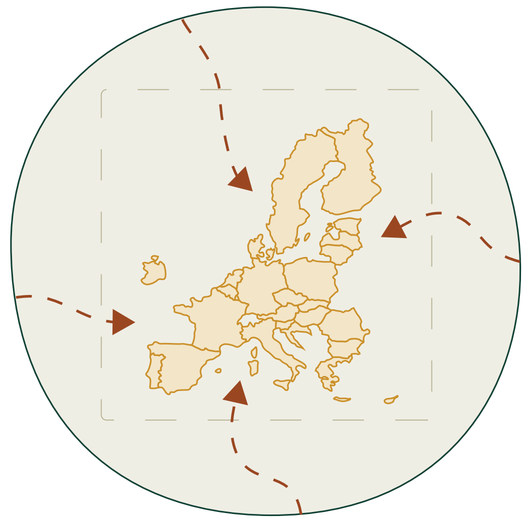
Policy

newest EU developments

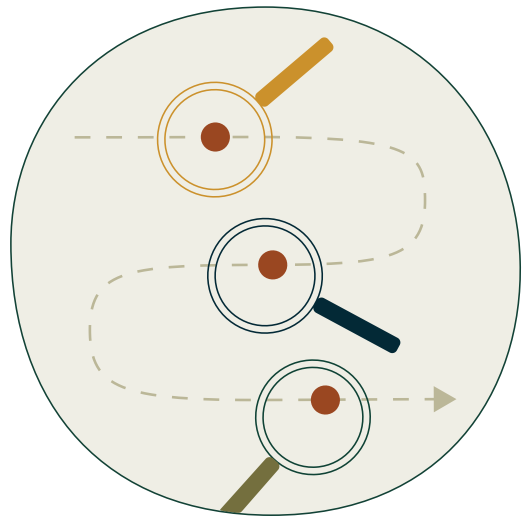
CRMA
Critical Raw Materials Act



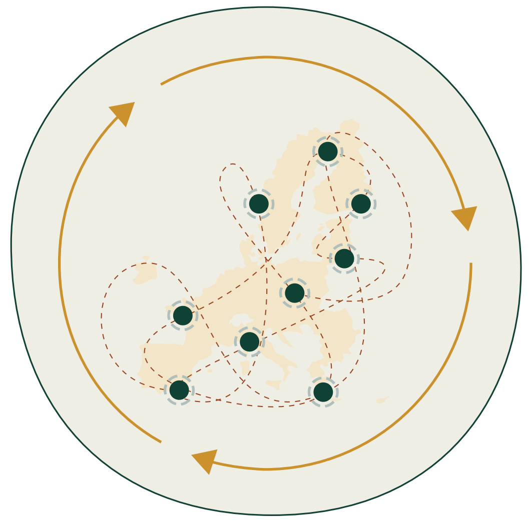
"to **strengthen** the different stages of the European critical raw materials **value chain**"



"to **diversify the EU's imports** of critical raw materials to reduce strategic dependencies"



"to improve the EU capacity to **monitor and mitigate** current and future risks of **disruptions to the supply** of critical raw materials"



"to **ensure the free movement** of critical raw materials on the single market while ensuring a high level of environmental protection, by improving their **circularity and sustainability**"

NZIA
Net-Zero Industry Act

The net-zero technology global market is worth about **€600 billion per year by 2030**

3x key mass-manufactured net-zero technologies expected by 2030

The EU net-zero ecosystem **doubled in value from 2020 to 2021**, reaching €100 billion

Deployment of renewables will **nearly quadruple by 2050**

Deployment of heat pumps will increase **6-fold by 2050**

Global production of electric vehicles will increase **15-fold by 2050**

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 process for net-zero strategic projects should have priority status

Eco-Design

aims to **help achieve a circular economy**

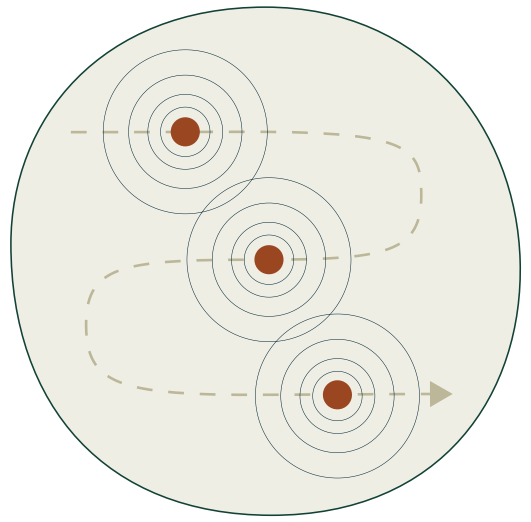
objective: **reduce energy consumption** along with other environmental impacts throughout the whole life cycle of a product

does not specifically mention building products

refers to revises 'construction products regulation', which **neither mentions circular strategies nor critical materials**

Policy
newest EU developments

CRMA
Critical Raw Materials Act



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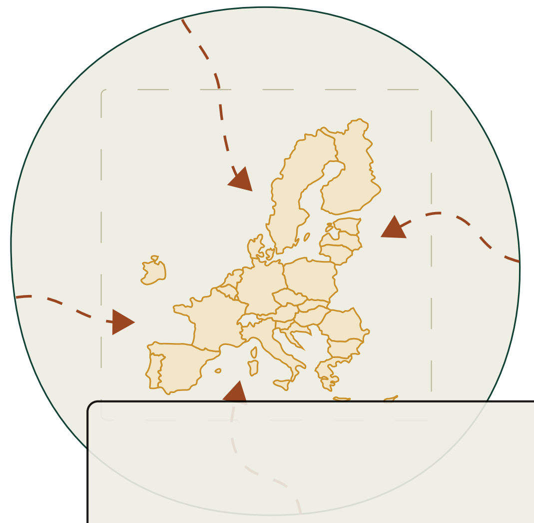

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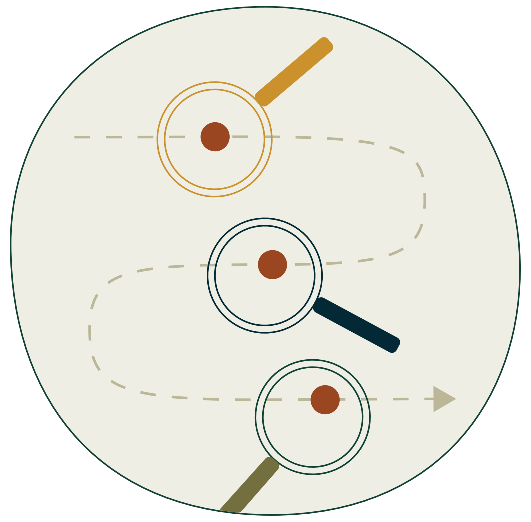

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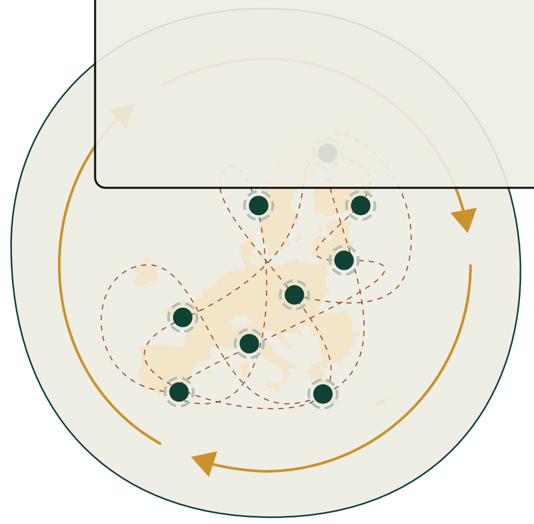

"to **ensure the free movement** of critical raw materials on the single market while ensuring a high level of environmental protection, by improving their **circularity and sustainability**"

NZIA
Net-Zero Industry Act

clear targets

no clear path

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 process for net-zero strategic projects should have priority status

Eco-Design

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recommendations

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 of circular strategies
- 100% circular economy will never be possible
- curtain wall façades: toolbox of components, environmental control, smart systems
- CRMs in façades not discussed as of yet

chapter conclusions

Analysis: 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

ANALYSIS | LITERATURE
CONCLUSION

complexity of the related challenges: industry will not solve them on itself

1.
have to reduce use of critical raw materials in façade products

2.
have to keep CRMs and products with CRMs in the loop

Recommendations

Topics

documentation on CRM content

Recommendation 1

WHAT materials and quanity

WHY functionality and purpose in product

WHEN how long in use and when available for recovery

HOW manufacturing process and is material recovery feasible

WHERE location within product

WHO is responsible for which information/ at different stages of a product's life

limitation of CRM contents

Recommendation 2

option1: LIMIT
- set limits on different levels;
• per components
• per system (balance)

- threshold % can be different per differernt critical material/group of material

option 2: RANGES
define %-% ranges, which can then be linked to different mitigation strategies or policy instruments

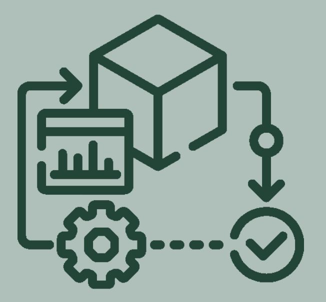
design + circular strategies

Recommendation 3

awareness for CRMs concerns at the beginning of the design process

• impact of design decision need to be further investigation (e.g. in regard to curtain wall facades: optimisation of frame-to-glass ratio impacts level of criticality per element)

• define circular strategies applicable at EoL from the beginning



circular business models

Recommendation 4

• alternative ownership models, products leasing programmes, take-back strategies

• different domains (material, design, manufacture, management)

• different scales of businesses

geo-political considerations

Recommendation 5

• supply diversification

• resource dependencies

• limited resources = conflicts (access and control of CRMs)

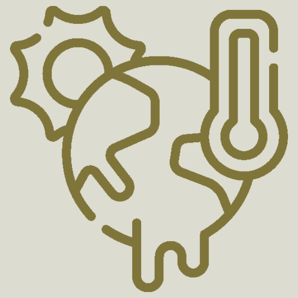
ethical considerations

Recommendation 6

• responsibility for a sustainable and just world for everybody

• resource use and its impacts (e.g. mining + local communities)

• local working conditions



environmental considerations

Recommendation 7

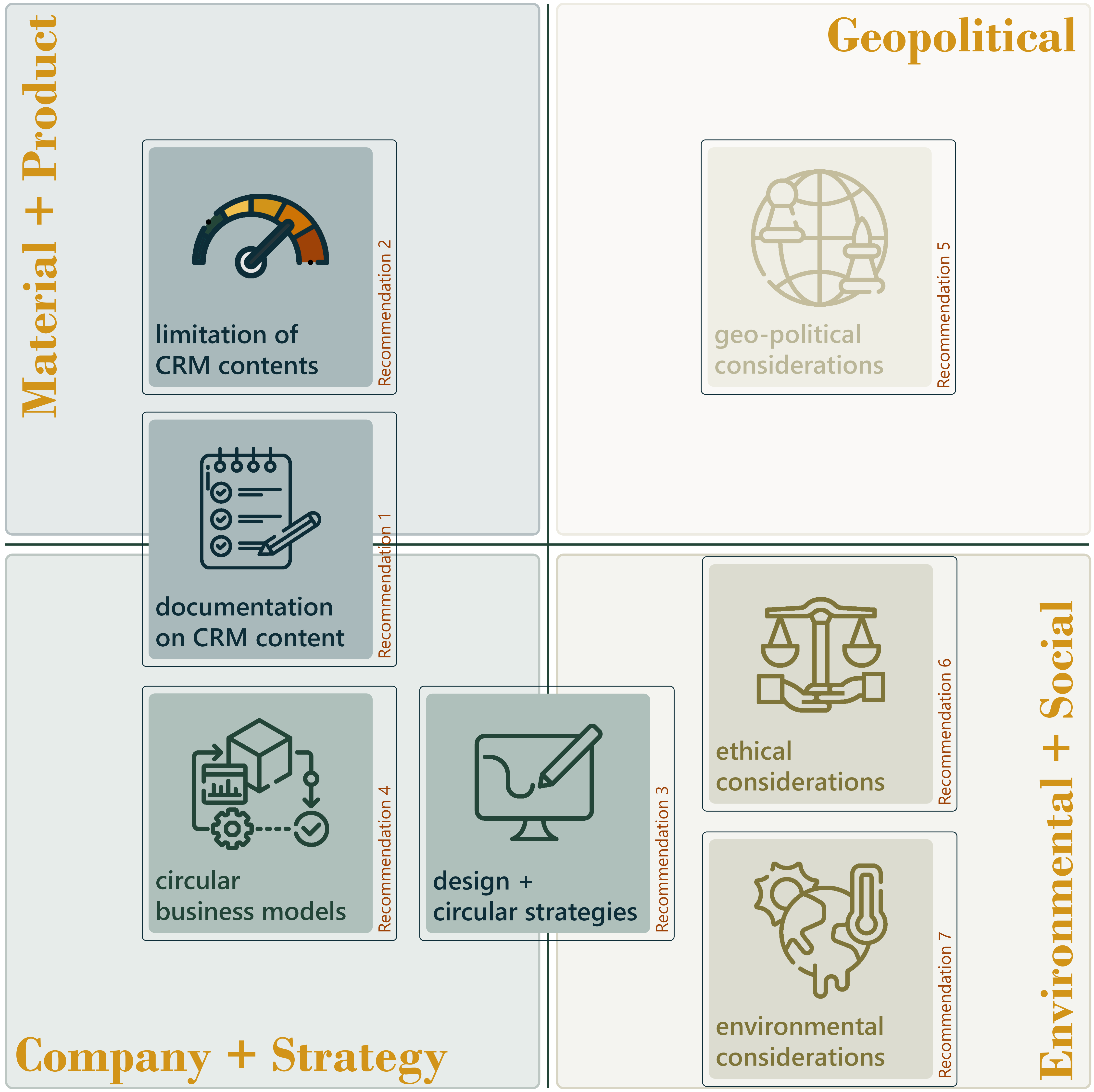
• mining + environment

• material processing

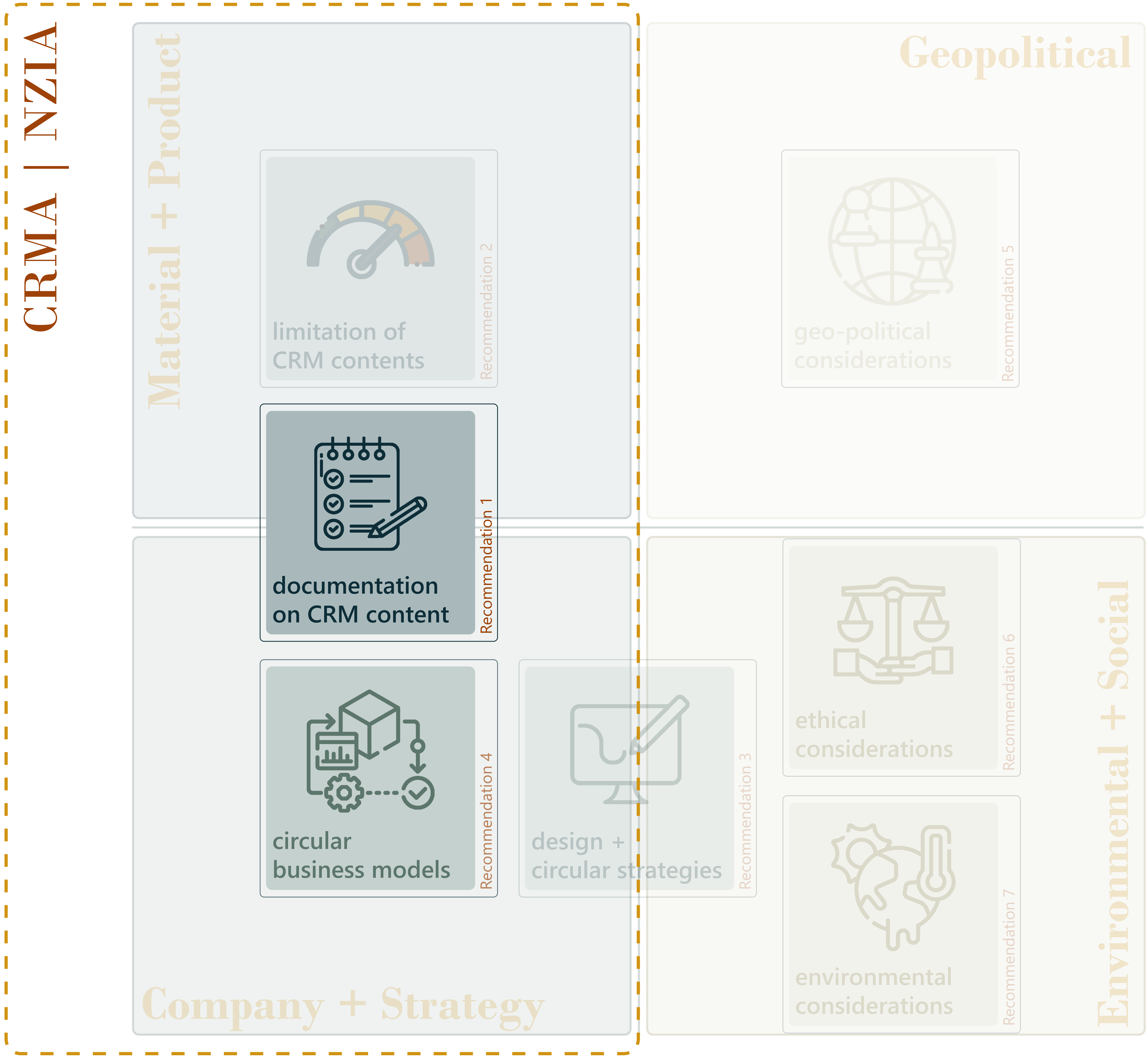
• supply chain

Recommendations

Recommendations



Recommendations
Current coverage



Recommendations

Cross-checking policy instruments

Policy instruments	
Regulatory instruments	Technology-based standards Performance-based standards
Economic instruments	Emission charges and taxes Product charges and taxes User charges Marketable (tradable, transferable) permits Deposit-refund systems Non-compliance fees Performance bonds Liability payments Environmental subsidies
Information tools	Public information campaign Technological information diffusion programs Environmental labeling schemes
Voluntary tools	Unilateral commitment or declaration Negotiated agreement or commitment Selective regulation or public voluntary program
Research + development	Research and development tools

documentation on CRM content

Recommendation 1

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

limitation of CRM contents

Recommendation 2

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

circular business models

Recommendation 4

Recommendation 3: design + circular strategies

smarter product use and manufacture

R0 Refuse	R1 Rethink	R2 Reduce

extend lifespan of product and its parts

R3 Re-use	R4 Repair	R5 Refurbish	R6 Remanufacture	R7 Repurpose

useful application of materials

R8 Recycle	R9 Recover

design + circular strategies

Recommendation 3

Recommendation 4 : circular business models

design solutions

circular supply: development of new materials	product and process design: strategic plan through the value chain

use solutions

lifetime extension (engineering solutions,...)	product-as-a-service	sell and buy back	tracking of materials, components or parts	sharing platforms	tracking facility

recovery solutions

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

Recommendations

Recommendations + policy instruments

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)

Recommendations

Policy instruments

documentation on CRM content

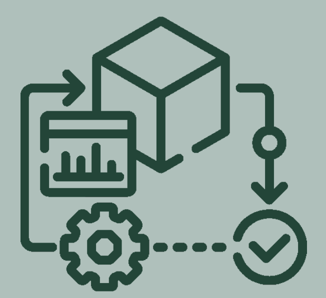
Recommendation 1

limitation of CRM contents

Recommendation 2

design + circular strategies

Recommendation 3



circular business models

Recommendation 4

documentation on CRM content (Recommendation 1)	limitation of CRM contents (Recommendation 2)	design + circular strategies (Recommendation 3)	circular business models (Recommendation 4)
REGULATORY INSTRUMENTS generally applicable, probably needs ADDITIONAL type to technology-/ performance-based standards	**REGULATORY INSTRUMENTS** standards/norms applicable in theory, problem here is how to define the %/ limitations	**REGULATORY INSTRUMENTS** differences for specific R-strategies, not feasible for R0-R2 (not measureable/ ADDITIONAL?), applicable for R3-R9	**REGULATORY INSTRUMENTS** important: standards/ norms regarding new material development, product design, reuse/remanufacture possibilities etc.
ECONOMIC INSTRUMENTS to address lack of documentation (charges, non-compliance fees)	**ECONOMIC INSTRUMENTS** can addres by charges, non-compliance fees, taxes/tax reductions	**ECONOMIC INSTRUMENTS** can be combined with regulatory, e.g. taxes/ tax exemptions, non-compliance fees	**ECONOMIC INSTRUMENTS** incentivise new business models to lower risk factors, reducing financial barriers

INFORMATION TOOLS
generally applicable (information campaigns, awareness campaigns)

VOLUNTARY POLICY TOOLS
generally applicable (commitments, agreements)

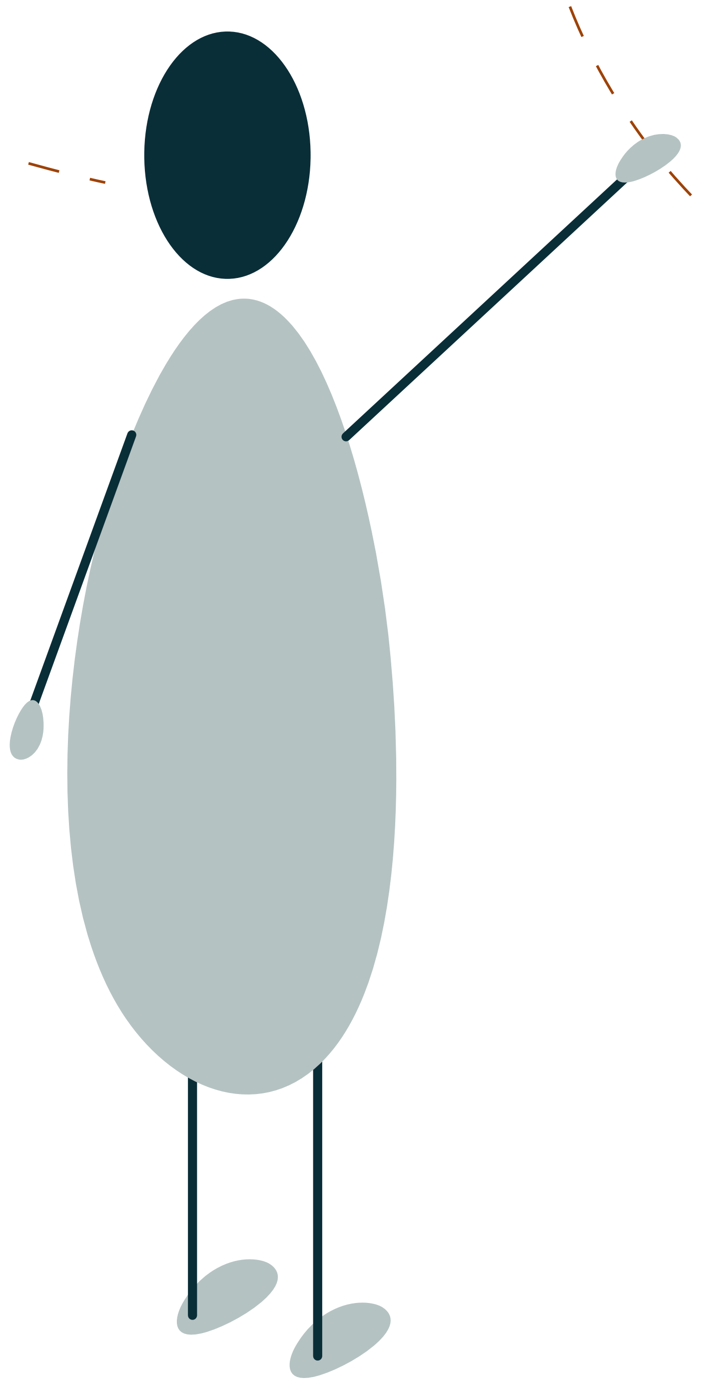
RESEARCH + DEVELOPMENT
generally applicable

Conclusion

we don't know enough about CRMs in façades

there is a lack of policies related to the topic

the combination of CRMs/BE/CE is too complex to not have any guidelines to follow



if we don't find a way or strategy to mitigate CRMs concerns in the building sector, we will run into major problems

this research demonstrates that there is indeed a need to increase awareness, knowledge and information (= further research) for CRMs concerns in the façade and building sector

Conclusion

1.

have to reduce use of critical raw materials in façade products

2.

have to keep CRMs and products with CRMs in the loop

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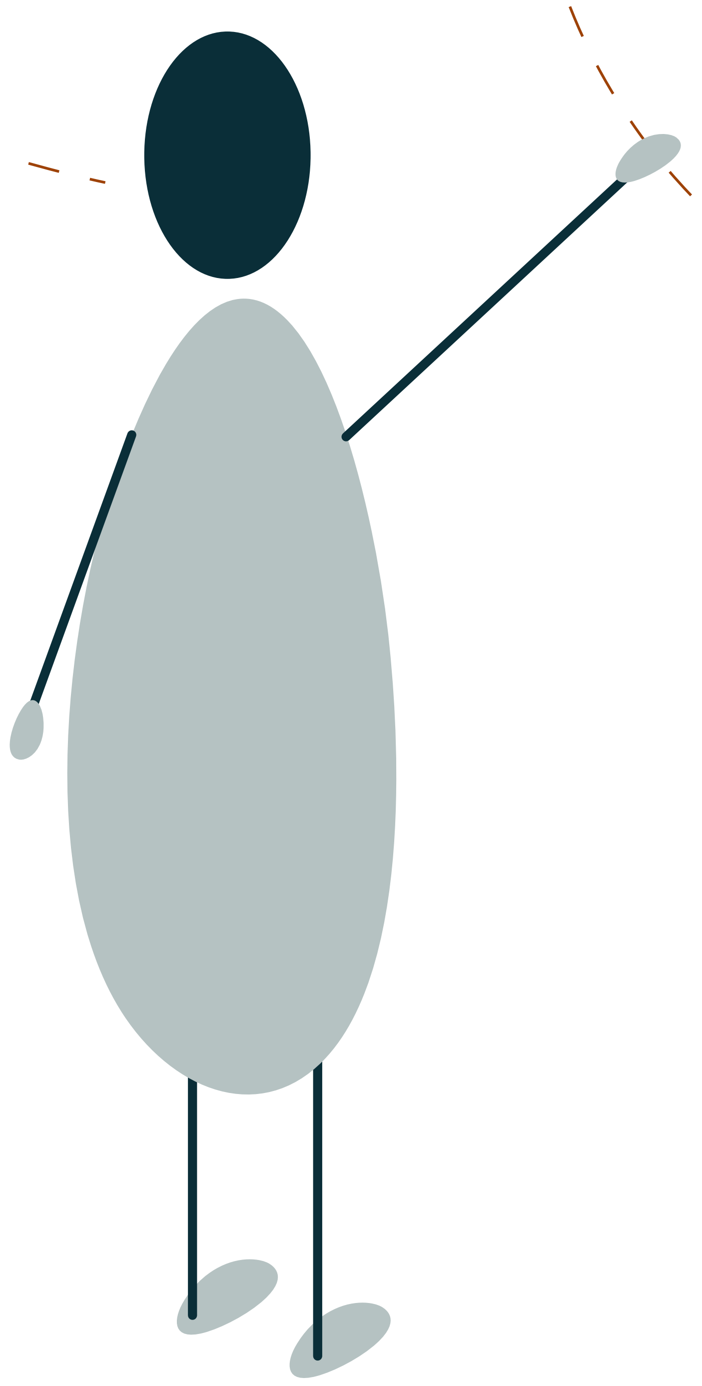

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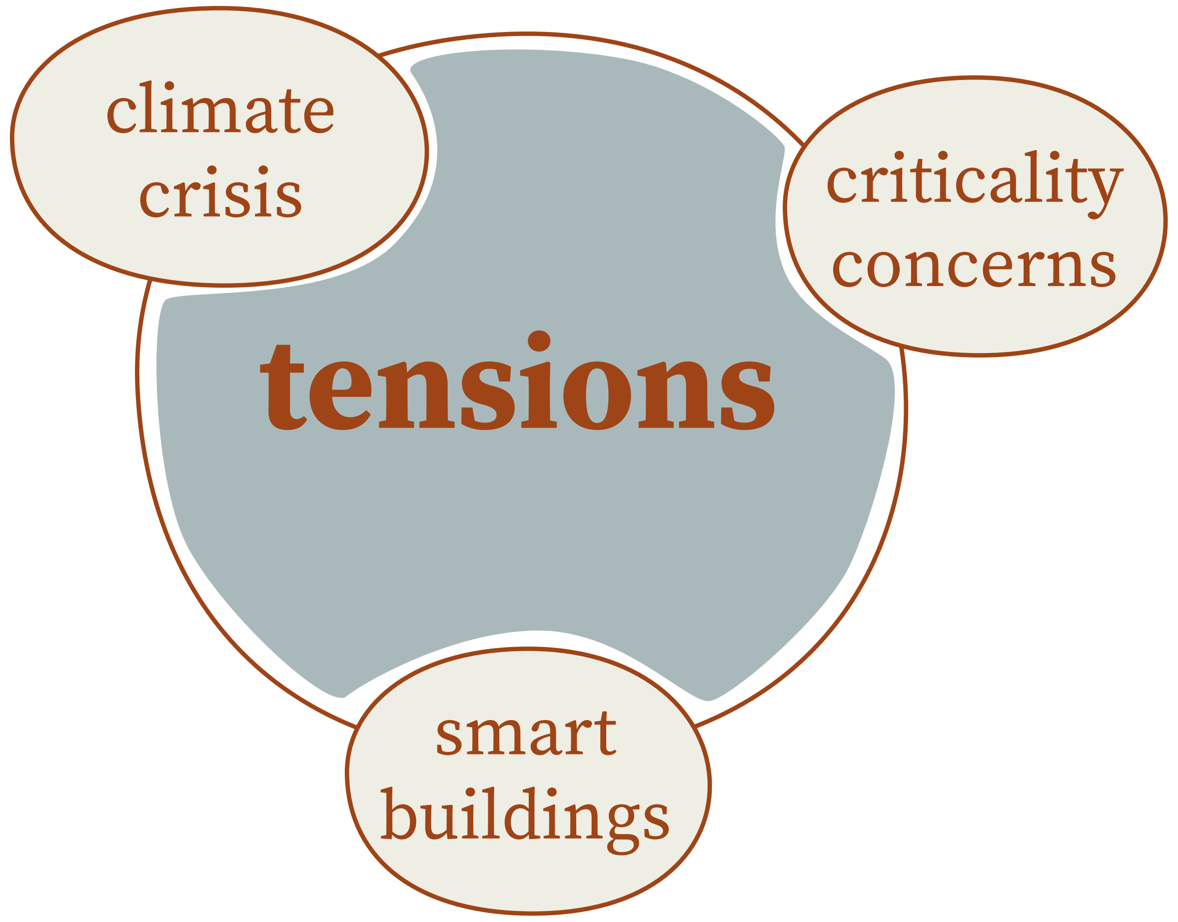
complexity of the related challenges: industry will not solve them on itself

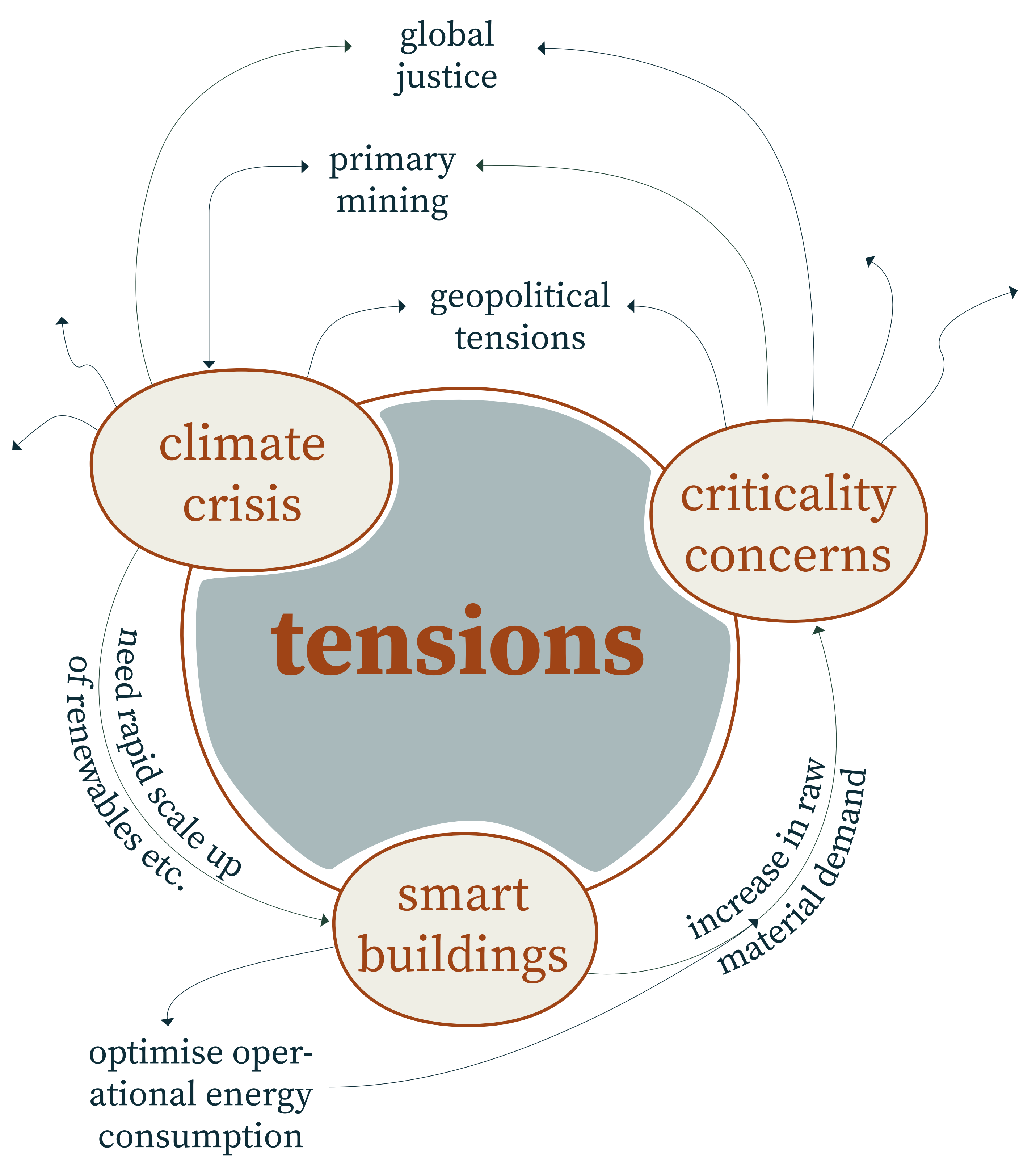
Discussion

Tension | Smart buildings + climate crisis



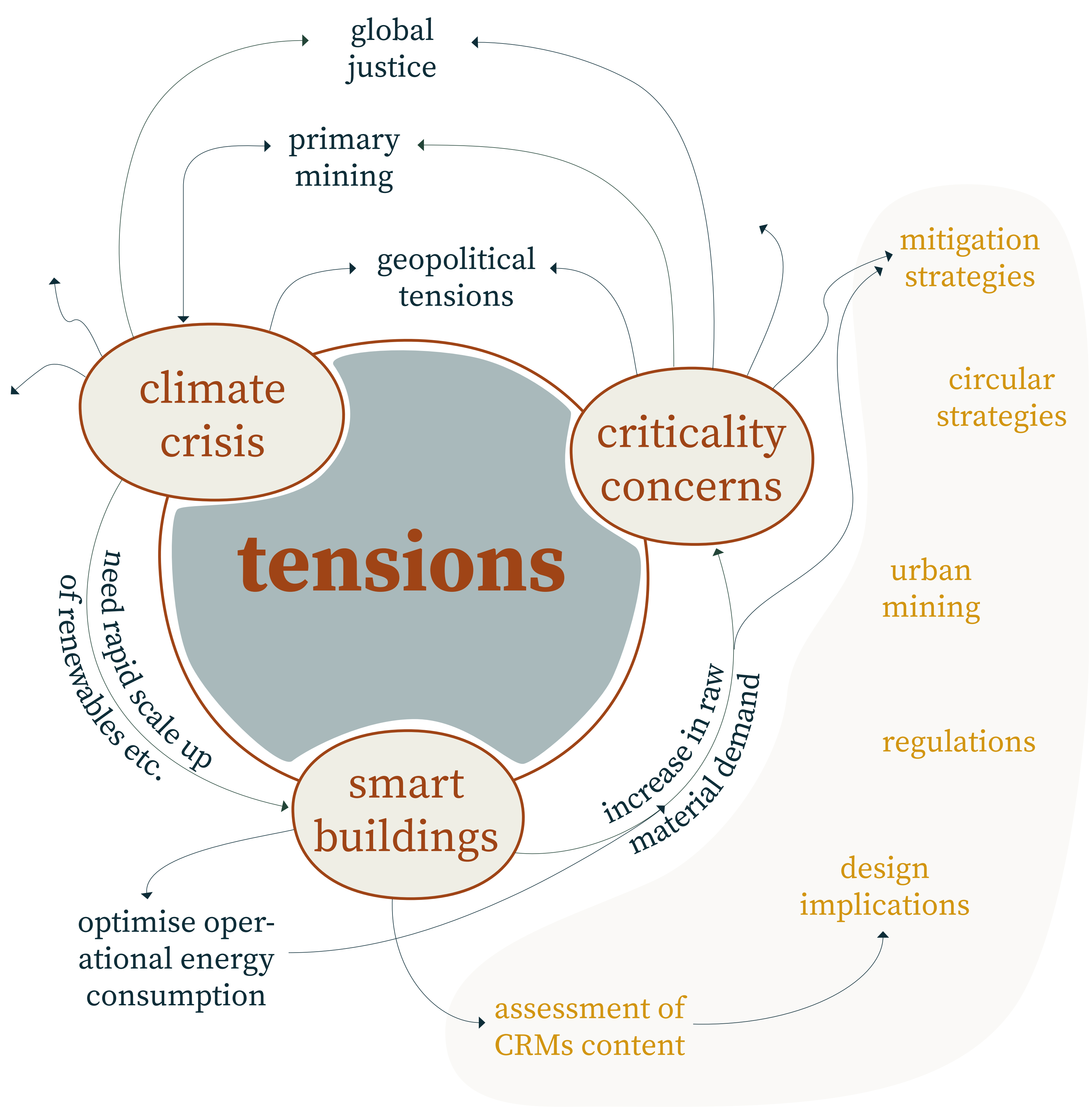
Discussion

Tension | Smart buildings + climate crisis



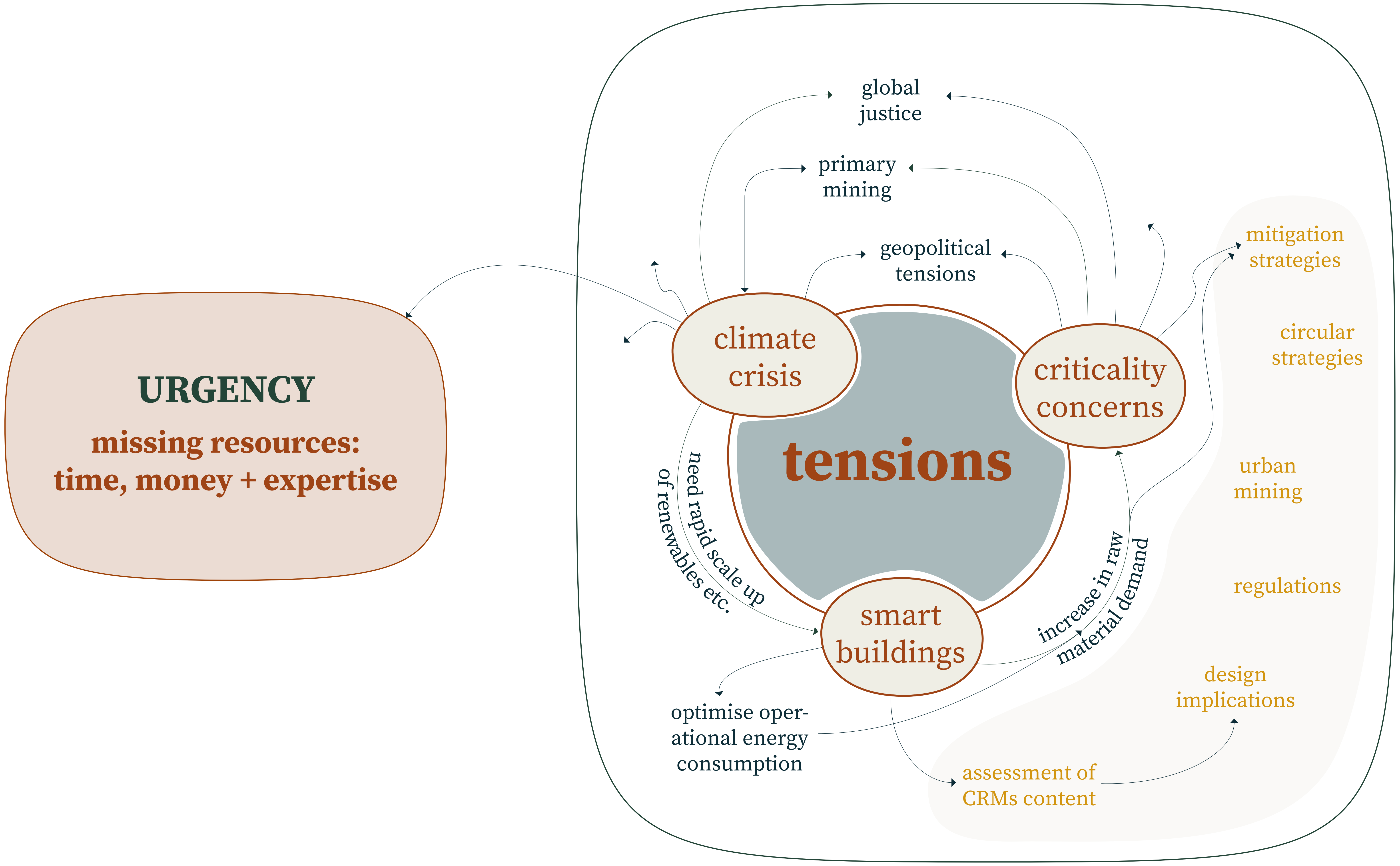
Discussion

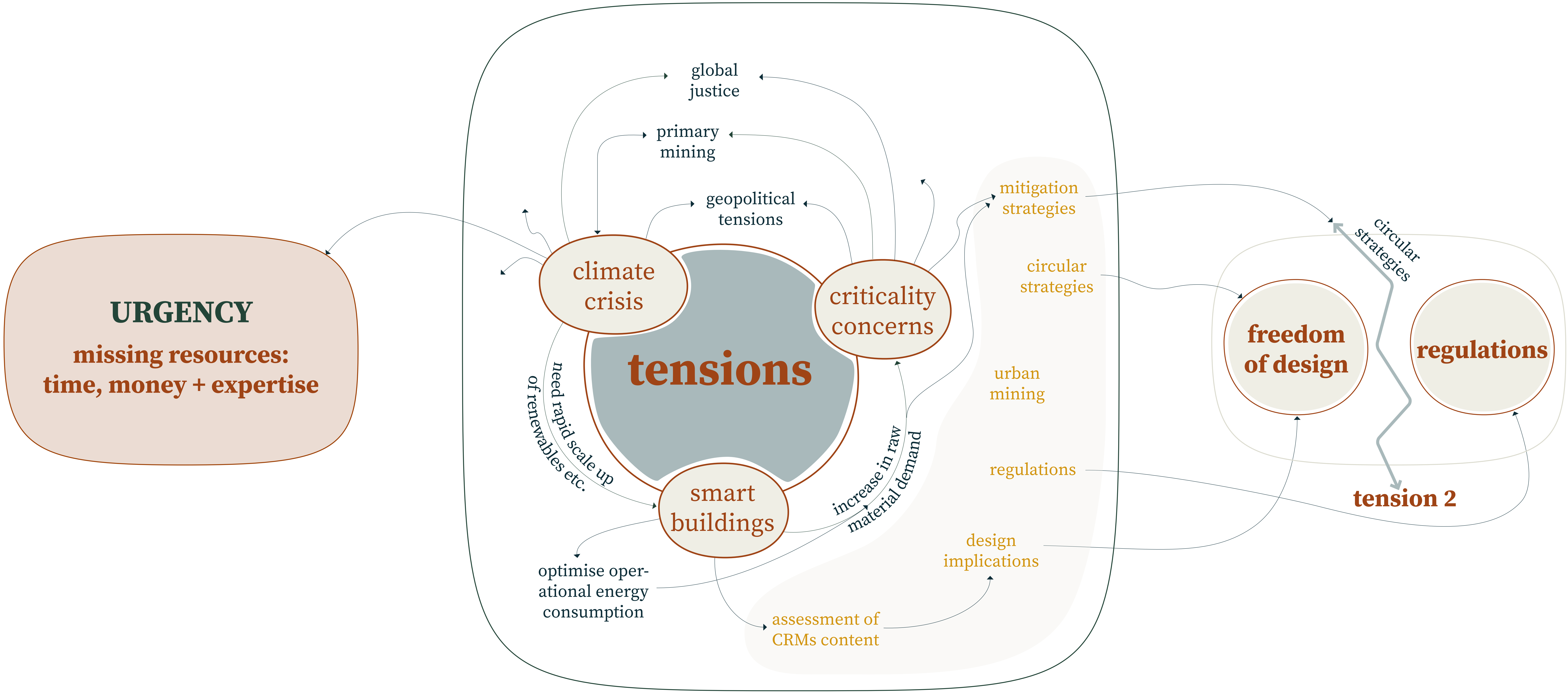
Tension | Smart buildings + climate crisis



Discussion

Tension | Urgency





URGENCY
missing resources:
time, money + expertise
global justice
primary mining
geopolitical tensions
climate crisis
criticality concerns
tensions
smart buildings
need rapid scale up of renewables etc.
increase in raw material demand
optimise operational energy consumption
mitigation strategies
circular strategies
urban mining
regulations
design implications
assessment of CRMs content
circular strategies
freedom of design
regulations
tension 2

Discussion
Tension | Urgency + Freedom of Design

Discussion
Further research

generate more CRM related data for the BE:
further analyse use of critical raw materials in all sectors of the built environment, available information is still very limited, need a more holistic view CRM concerns in the BE

policymaking and additional policy instruments
test policy redommendations with policymakers and other stakeholders

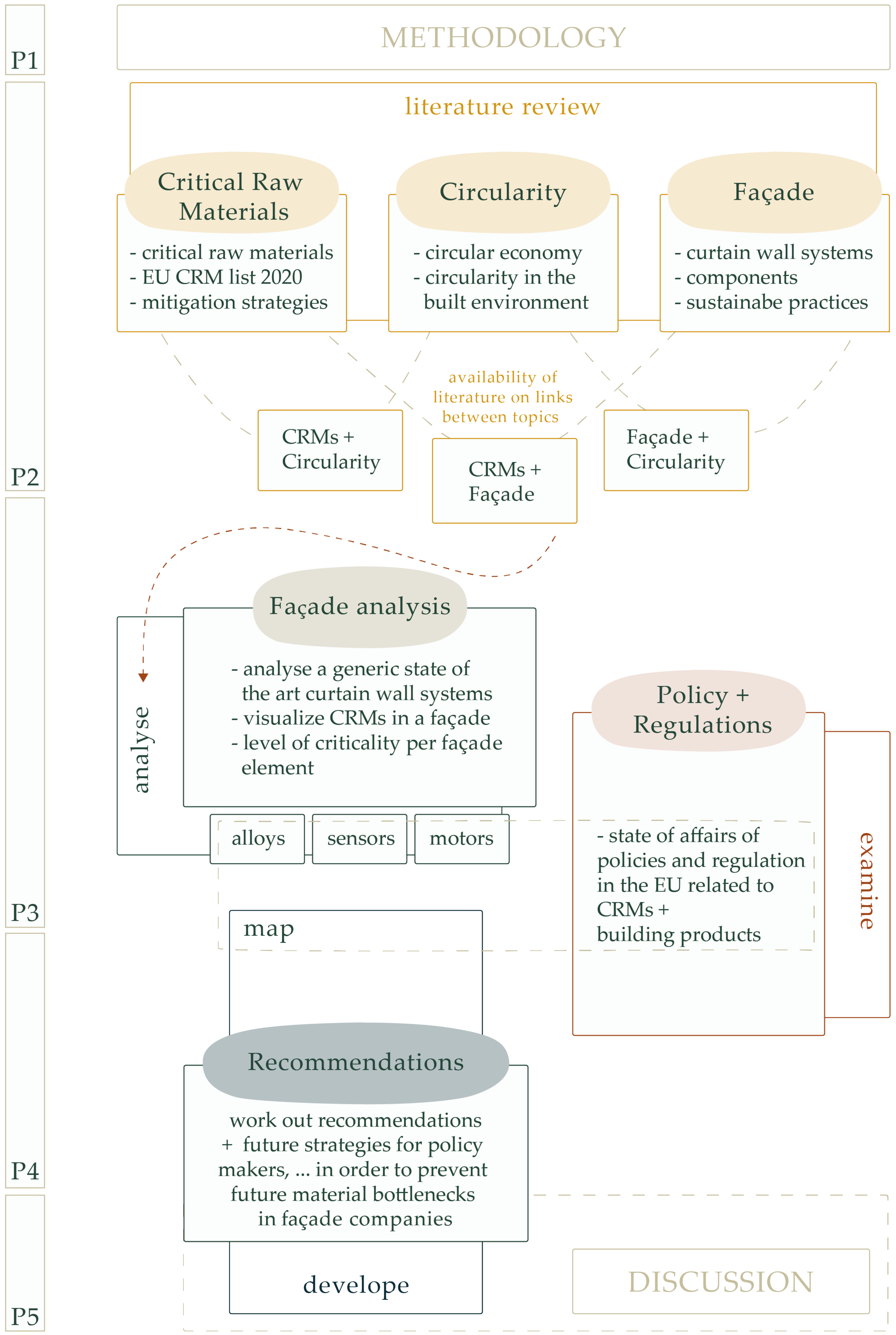
analyse 'smartness' of building vs. CRM concerns
is there a way to measure trade-offs like this

the role of design + optimisation
decision-making processes, ratio-optimisations of systems through material/resource conscient design

lifetime expansion vs supply and demand
not yet clear, how lifetime expansion will actually affect supply and demand of materials

thank you!

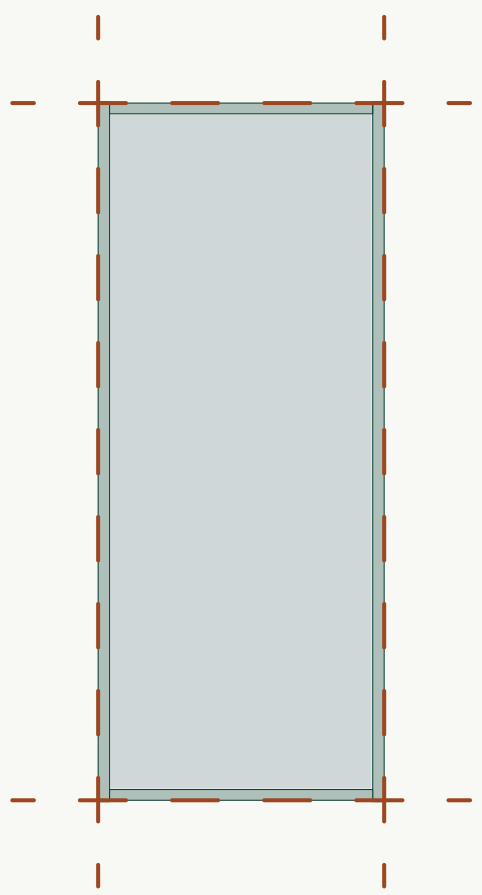
Appendix
Methodology



Appendix
Design + Optimisation

	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)	●		●

S1a



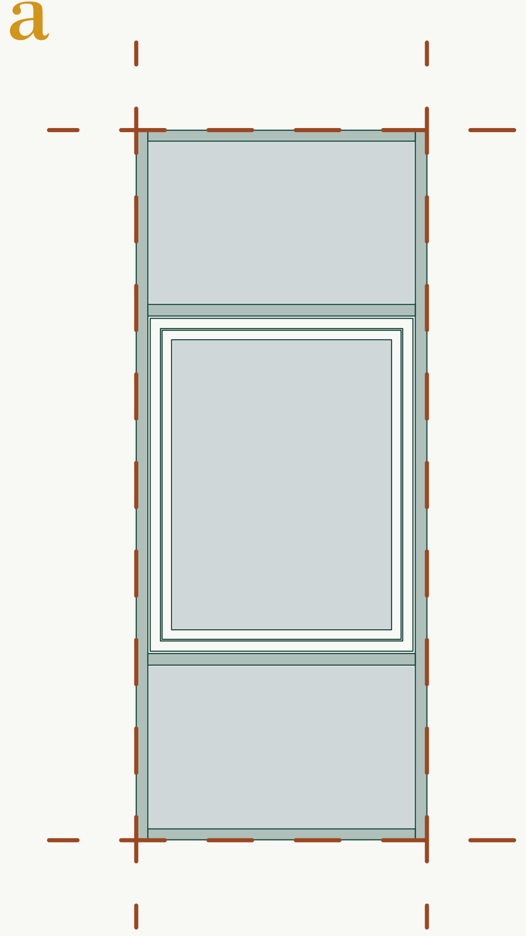
fully fixed glazing

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: 28.48kg

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%**

S2a



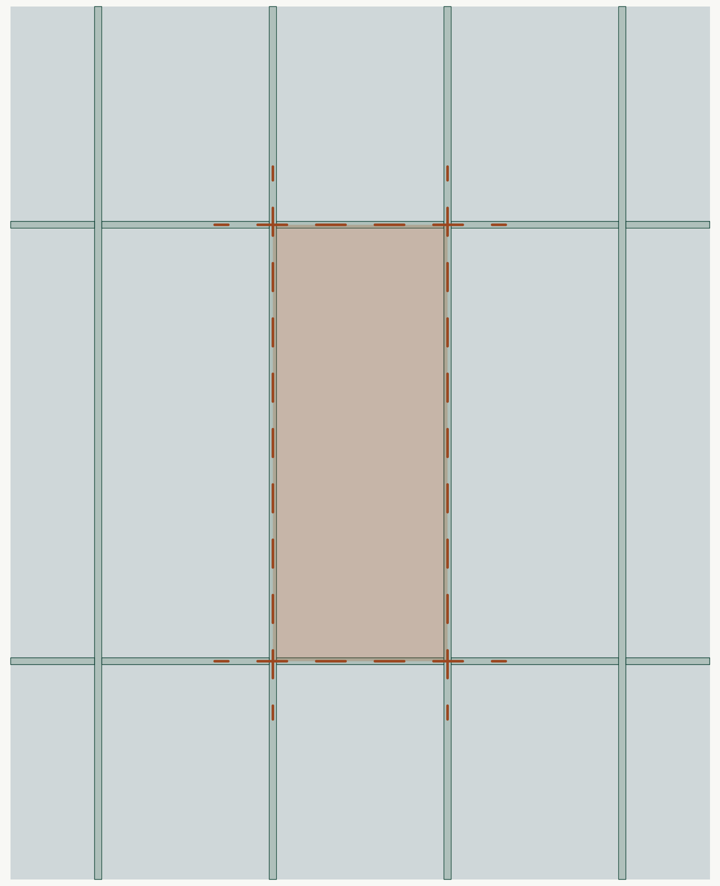
+ openable window

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	total %
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%**

S1b



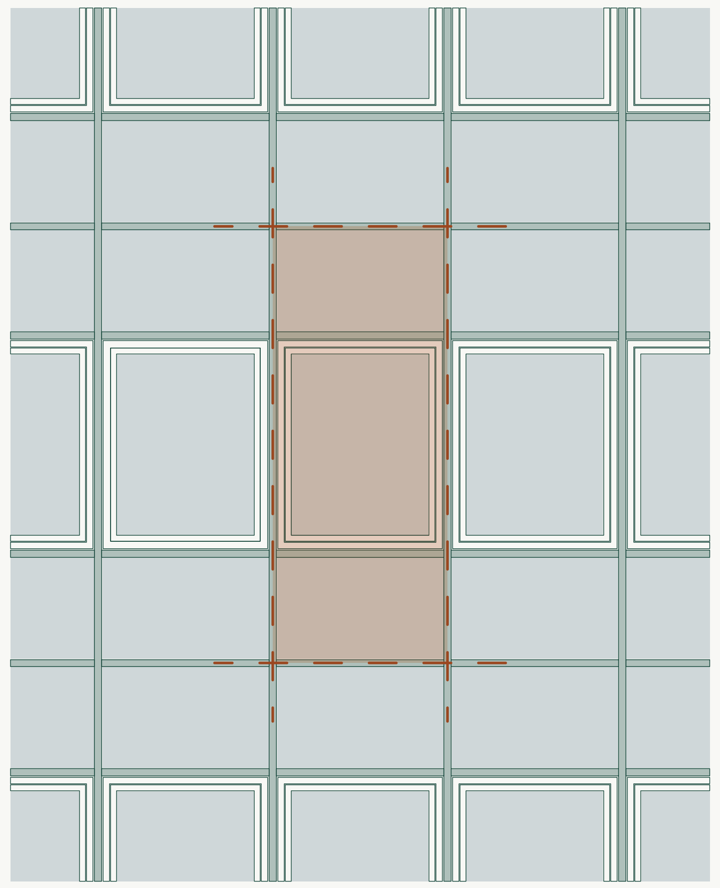
fully fixed glazing

element size: 3.6 m^2
glazing area: 3.4 m^2

volume total: 0,07 m^3
weight total: 150 kg
weight glass: 129.25 kg
weight CRMs: 14.7 kg

CRMs:	kg	total %
Al (aluminium):	14.28	9.52
Mg (magnesium):	0.1	0.067
Mn (manganese):	0.04	0.027
P (phosphorus):	0.0005	0.0003
Si (silicon metal):	0.06	0.04
Ti (titanium metal):	0.01	0.0067
Cu (copper):	0.01	0.0067
Ni (nickel):	0.21	0.14
CRMs total:	**14.70**	**9.8%**

S2b



+ 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%**

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

Recommendations

Recommendations + policy instruments

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)

Recommendations

Recommendations + policy instruments

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)

Recommendations

Recommendations + policy instruments

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)

Main results of the 2023 criticality assessment

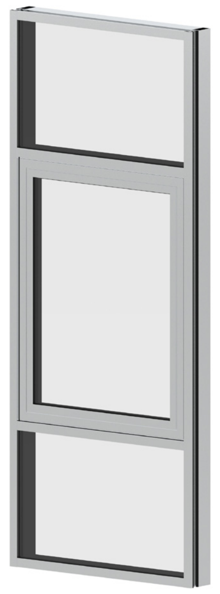
The following 34 raw materials are proposed for the CRM list 2023:

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**

2023 Critical Raw Materials (*Strategic Raw Materials 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**

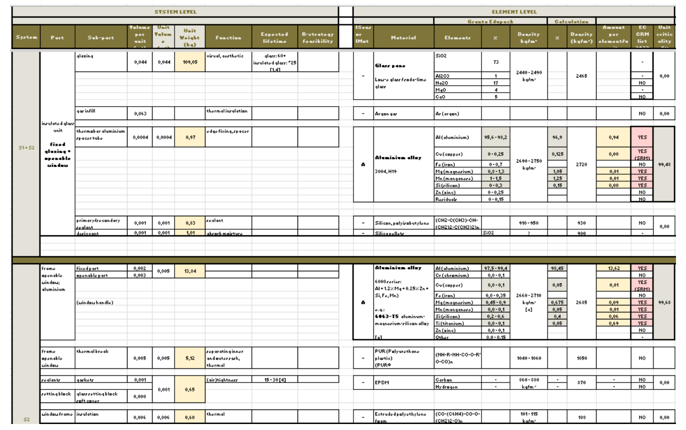
* Copper and nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials.

Appendix
Analysis set-up



1\. *define system*

[Rhino]

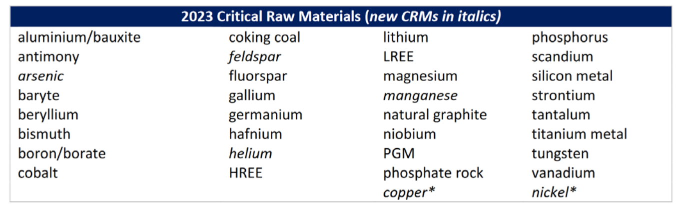


2\. *list components and volumes*

[Excel]

3\. *material composition*

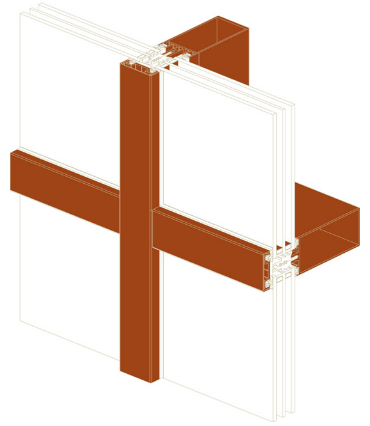
[Granta EduPack]



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**

4\. *compare with CRM list*

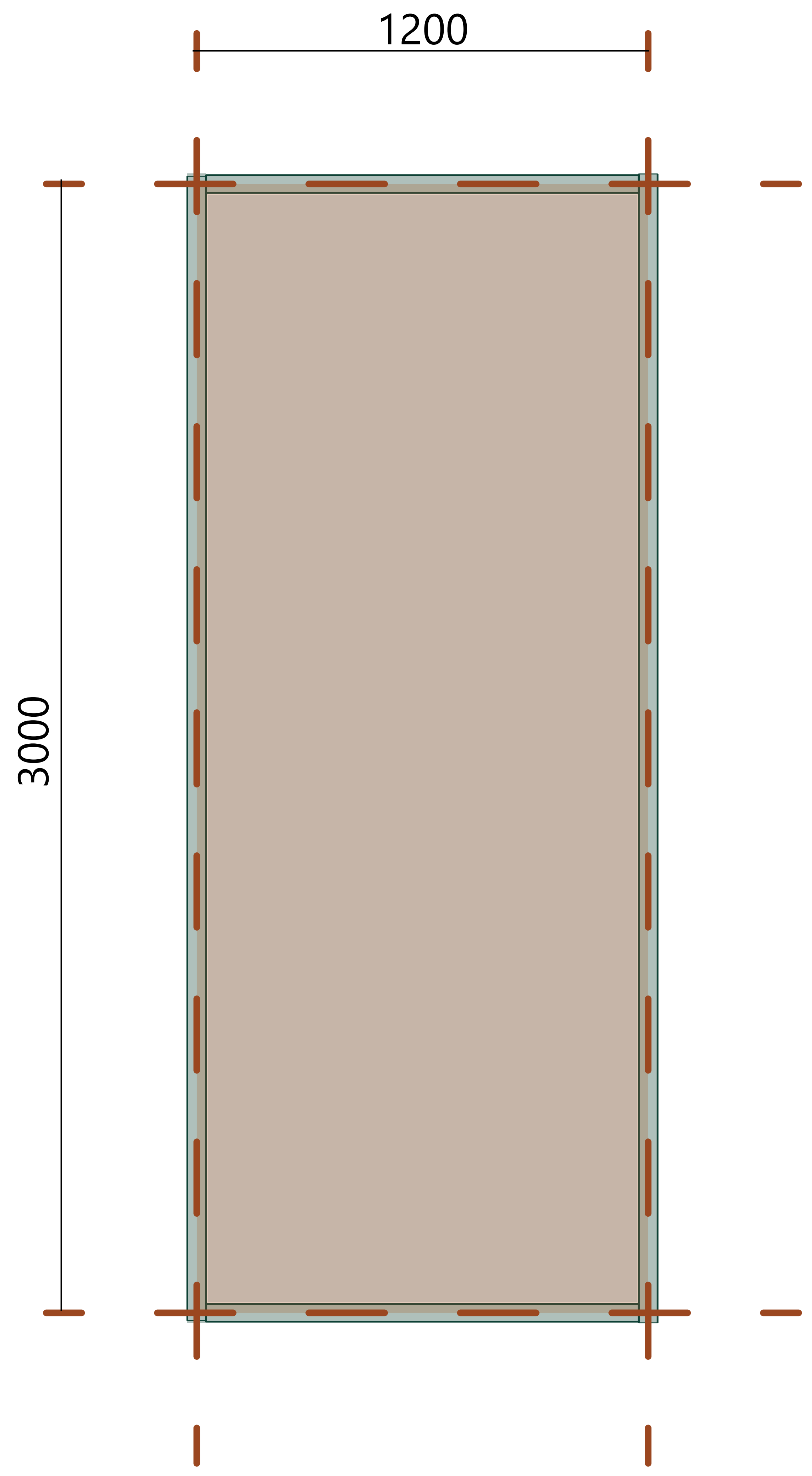
[European Commission]

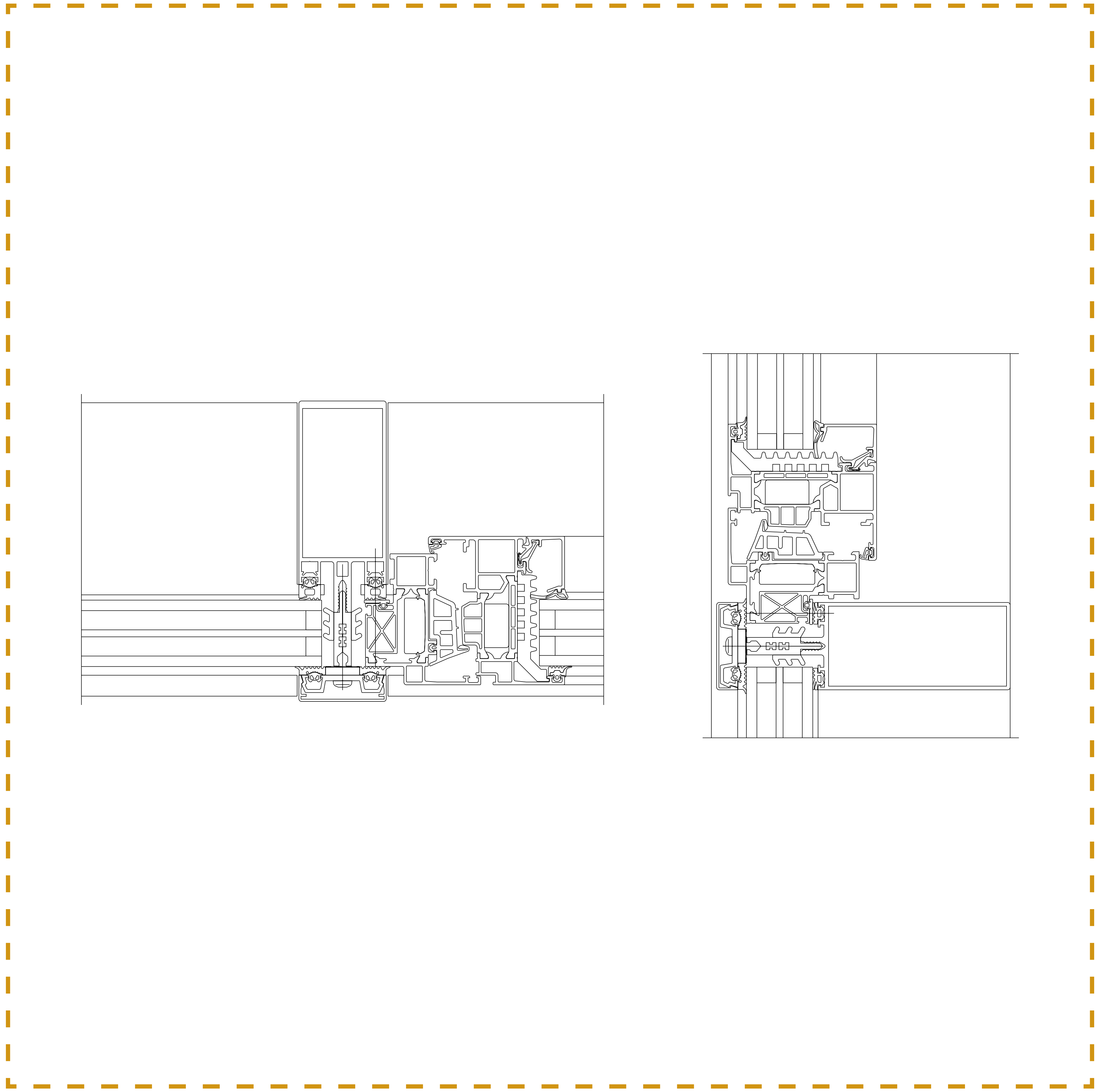


5\. *assess level of criticality*

[Rhino, Excel, Adobe]

1. *define system*
[Rhino]



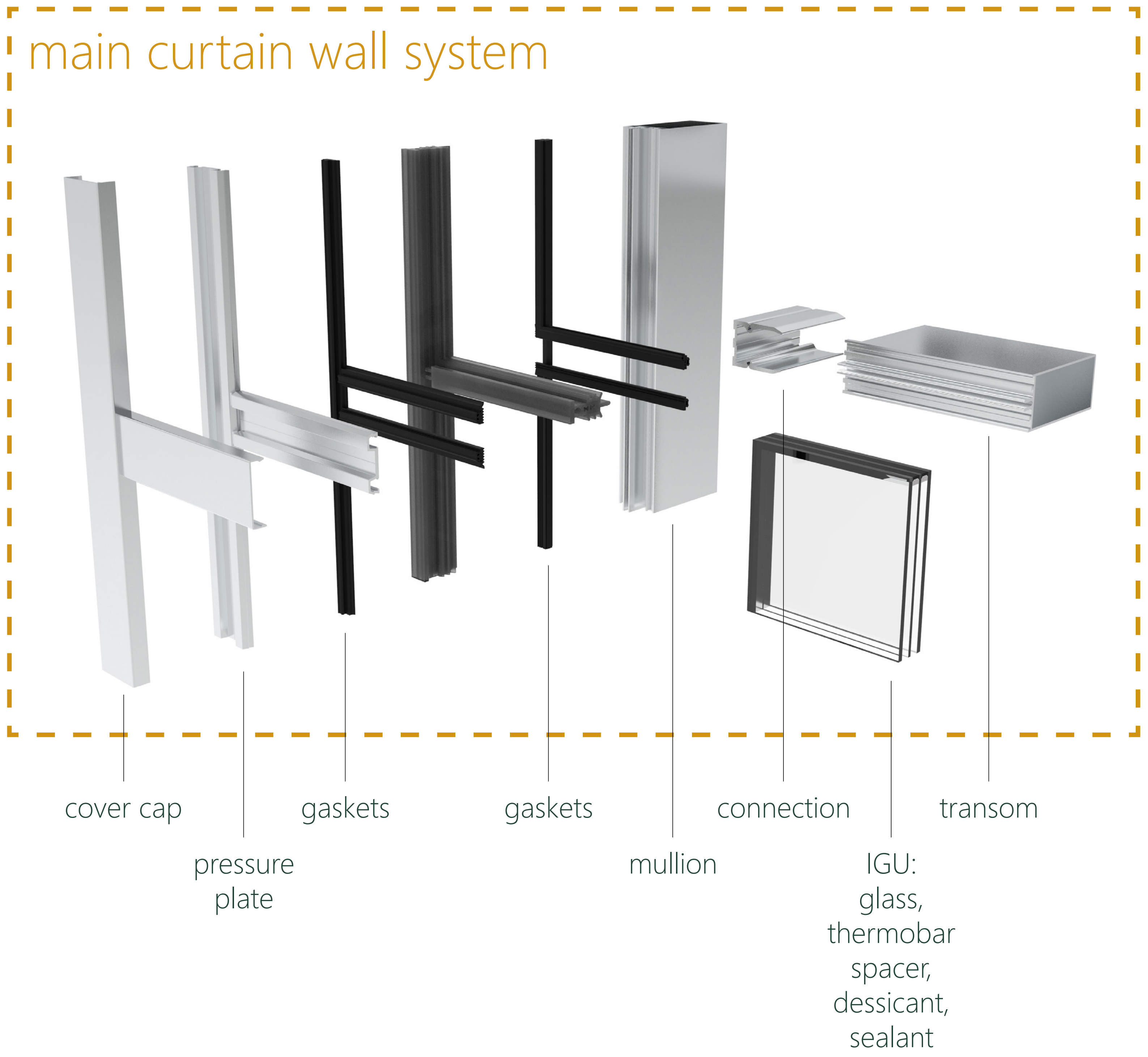


1. *define system*

[Rhino]

S1

S2-4



2. *list components and volumes*

[Excel]

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	(estimated) - careful when		/1000000000			or volume from Rhino model			/1000000000
Structure	Mullion	979	3000	2986958	2	5973916	0,007751726	979	3000	2986958	2	5973916	0,009529536
	Transom	768	1150	888905	2	1777810		768	1150	888905	4	3555620	
Pressure plate	Pressure plate mullion	170	3000	510000	2	1020000	0,001411	170	3000	510000	2	1020000	0,001802
	Pressure plate transom	170	1150	195500	2	391000		170	1150	195500	4	782000	
Cover cap	Cover cap mullion	112	3000	336000	2	672000	0,0008859	112	3000	336000	2	672000	0,0010998
	Cover cap transom	93	1150	106950	2	213900		93	1150	106950	4	427800	
Connection	transom to mullion connection piece	656	102	66860	4	267440	0,00026744	656	102	66860	8	534880	0,00053488
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	

3. *material composition*

[Granta EduPack]

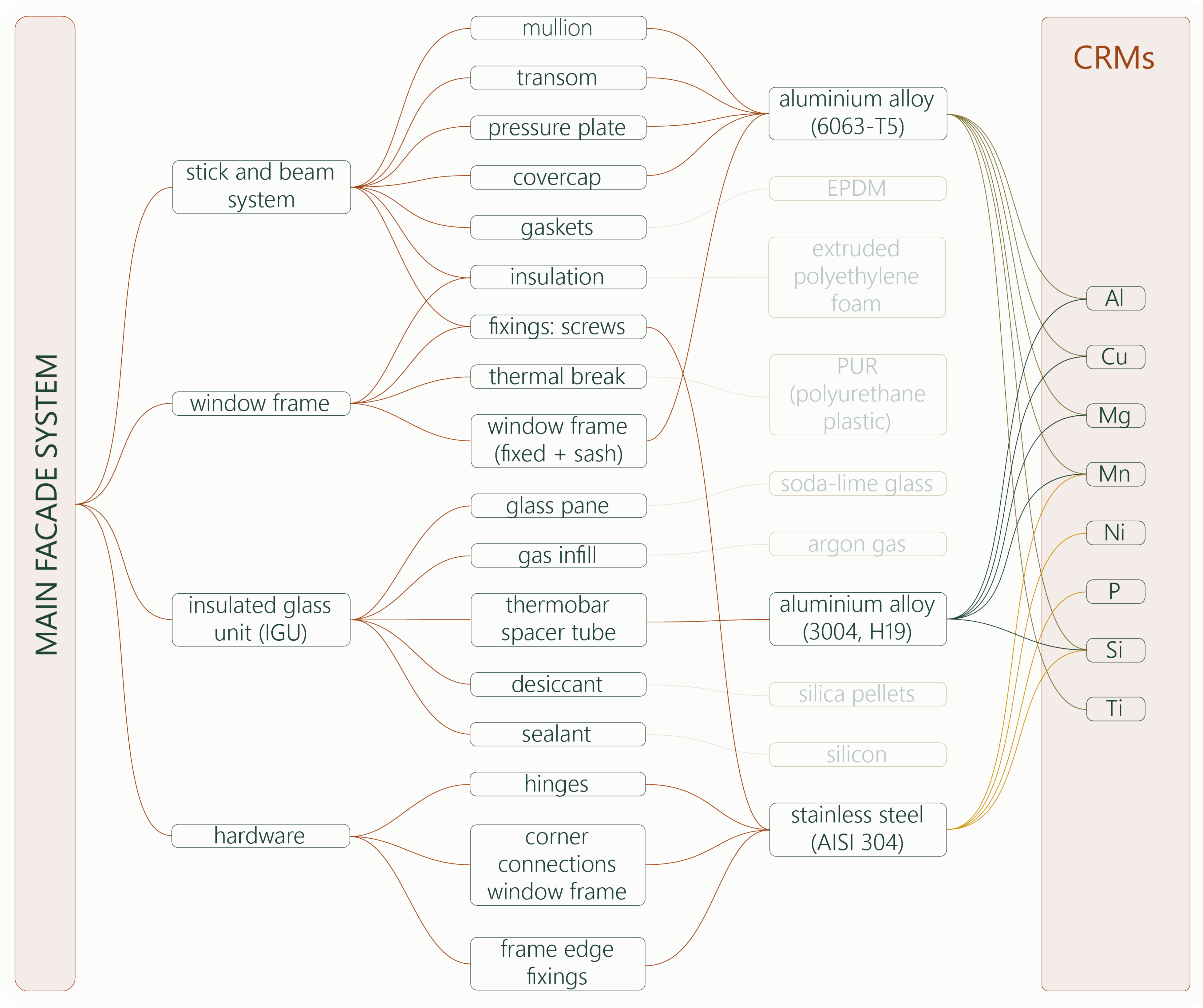
Databases

Introductory

ELEMENT LEVEL									
		Granta Edupack			Calculation numbers				
|Sensor |Motor |Alloy	Material	Elements	%	Density kg/m³	%	Density (kg/m³)	Amount per element/unit kg	EC CRM list 2023	Unit criticality ~%
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	27,27	YES	99,68
		Cr (chromium)	0,0 - 0,1					NO	
		Cu (copper)	0,0 - 0,1		0,05		0,01	YES (SRM)	
		Fe (iron)	0,0 - 0,35					NO	
		Mg (magnesium)	0,45 - 0,9		0,675		0,19	YES	
		Mn (manganese)	0,0 - 0,1		0,05		0,01	YES	
		Si (silicon)	0,2 - 0,6		0,4		0,11	YES	
		Ti (titanium)	0,0 - 0,1		0,05		0,01	YES	
		Zn (zinc)	0,0 - 0,1					NO	
		Other	0,0 - 0,15					-	
-	EPDM	Carbon	-	860 - 880 kg/m³	-	870	-	NO	0,00
		Hydrogen	-		-		-	NO	
-	Extruded polyethylene foam	(CO-(C6H4)-CO-O-(CH2)2-O)n		101 - 115 kg/m³		108		NO	0,00
A	**Stainless steel** AISI 304 (1/8) [a]	C (carbon)	0,0 - 0,08	7850 - 8060 kg/m³	0,04	7955		NO	10,57
		-	-		-				
		Cr (chromium)	18 - 20		19			NO	
		Fe (iron)	65,8 - 74		69,9			NO	
		Mn (manganese)	0 - 2		1		0,02	YES	
		Ni (nickel)	8 - 11		9,5		0,21	YES (SRM)	
		P (phosphorus)	0 - 0,045		0,0225		0,00	YES	
		S (sulfur)	0 - 0,03		0,015			NO	
		Si (silicon)	0 - 1		0,05		0,00	YES	
-	**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	
-	Argon gas	Ar (argon)						NO	0,00
A	**Aluminium alloy** 3004, H19	Al (aluminium)	95,6 - 98,2	2690 - 2750 kg/m³	96,9	2720	0,65	YES	99,48
		Cu (copper)	0 - 0,25		0,125		0,0008	YES (SRM)	
		Fe (iron)	0 - 0,7		0,35			NO	
		Mg (magnesium)	0,8 - 1,3		1,05		0,01	YES	
		Mn (manganese)	1 - 1,5		1,25		0,01	YES	
		Si (silicon)	0 - 0,3		0,15		0,00	YES	
		Zn (zinc)	0 - 0,25		0,125			NO	
		Residuals	0 - 0,15		0,075			NO	
-	Silicon, polyisobutylene	(CH2-C(CH3)-CH-(CH2)2-C(CH3)2)n		910 - 950		930		NO	0,00
-	Silica pellets		SiO2	?		900		-	

3. ***material composition***

[Granta EduPack]



4. *compare with CRM list*

[European Commission]

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**

5. *assess level of criticality*

[Rhino, Excel, Adobe]

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