Introduction to durability, sustainability and life cycle assessment of concrete structures

Lecture notes of the DuRSAAM training course held September 2020

Edited by

Stijn Matthys and Alessandro Proia

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DuRSAAM training course

held September 2020

The PhD Training Network on Durable, Reliable and Sustainable Structures with Alkali-Activated Materials

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Foreword

Concrete is one of the most popular building materials, making it also of concern when considering the environmental impact of the construction sector and the associated built environment. For example, the construction sector is responsible for over 35% of the EU's waste generation, buildings account for 40% of energy consumed, construction activities require a vast amount of resources and cement, being a major component of concrete, accounts for 5 to 8% of the carbon emissions. Although concrete performs quite well in terms of environmental impact compared to other construction materials, its wide use makes sustainability of concrete crucial in minimizing the environmental impact, as can be characterized from life cycle assessments.

The European Union is taking a lead in tackling climate change by the implementation of the 'Green Deal', an ambitious action plan to achieve the climate neutrality of the EU by 2050, among which the goal on zero greenhouse emissions by that time. This challenges construction companies, design engineers and all stakeholders involved, to act on durability and sustainability of buildings and infrastructure. To steer the construction sector further towards a more sustainable built environment, amongst others, growing emphasis is emerging on:

- The **sustainability** performance of construction products and solutions, including the possible introduction of secondary raw materials (recycled materials and by-products);
- The promotion of measures to improve the **durability** and adaptability of built assets in line with circular economy principles for building and infrastructure design and maintenance;
- A more quantified performance assessment of construction technologies over their life cycle, e.g. by integrating **life cycle assessment** in public procurement.

This vision represent a significant change with respect to just 10 years ago, when the reduction of carbon emission was mainly focussed on the optimization of energy performance of buildings in terms of design of thermal insulation and heating/cooling systems. Although energy performance remains very relevant, also growing emphasis is given on quantified durability and sustainability of building materials, looking into the entire life cycle, from manufacturing of constituents of building materials and solutions, over longevity of structures, up to end-of-life scenarios. Furthermore, this is increasingly considered in a framework of circular economy.

Eco-friendly or circular concrete solutions are investigated widely in view of lowering environmental impact, while keeping the high technical performance expected from contemporary building solutions. The durability, sustainability and life cycle assessment of such emerging solutions is of considerable importance in the framework of the Green Deal or similar visions, and highlights the need for engineers skilled in these subjects. This also formed the motivation in organizing an introductory training course on durability, sustainability and life cycle assessment of concrete structures, which is at the basis of this eBook.

This initiative has taken in the framework of the European Training Network on Durable, Reliable and Sustainable Structures with Alkali-Activated Materials (DuRSAAM), which organized the mentioned training course online on 14 till 17 September 2020. This open source book collects the lecture notes by the teachers of this training course and provides researchers, building professionals and stakeholders basic insights on the sustainability aspects of concrete structures, having eco-friendly concretes in mind as emerging building technology.

Stijn Matthys
Alessandro Proia
Ghent, 2020

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1. Outline

Stijn Matthys

Concrete is a popular and efficient building material. Nevertheless, the durability and sustainability of concrete structures cannot be taken for granted, and has a large impact on its service life, environmental and economic impact. Given the growing number of concrete types, including emerging more eco-friendly concrete mix designs, evaluation of durability and assessing sustainability in a life cycle assessment framework, is challenging.

The information bundled in this eBook is that of a 3-day course, formatted as a training school open to researchers, practicing engineers, etc., in fact, for all those who want to obtain profound starting knowledge on durability, sustainability and life cycle assessment of concrete structures, also in the wider framework of circular concrete solutions. The original training course, specifically developed and delivered collaboratively by the DuRSAAM action, was held online, summer 2020. A course introduction video, as given at the start of the training course, is provided here (time to watch 10 minutes).

The **outline** of the teaching material bundled in this book, is as follows:

- ➔ "Damage to concrete" (Chapters 2 till 4):
  - Setting the scene on damage to concrete structures & degradation due to inappropriate design and errors during casting.
  - Specific concrete degradation mechanisms: volume stability, ASR, acid attack and freezing-thawing.
  - Reinforcement corrosion, including further discussion on carbonation.
- ➔ "Sustainability" (Chapters 5 till 7):
  - Introduction to sustainable development in the built environment
  - Life cycle assessment applied to building materials
  - Practical exercise on modelling LCA
- ➔ "Circular economy" (Chapters 8 till 10):
  - Introduction to circular economy
  - Circular economic modelling
  - Securing the future supply of secondary raw materials

The **aim** of the teaching material is to impart basic understanding as well as up-to-date knowledge about concrete durability, and life cycle assessment and circular economy for the construction sector. The specific **learning objectives** are as follows:

- ✓ Deepen your knowledge on concrete durability (and service life prediction).
- ✓ Build knowledge on environmental impact and life cycle assessment aspects.
- ✓ Get acquainted with circular economy.
- ✓ Being able to recognize the value of circular economy for concrete, as well as the difference between sustainability and concrete durability.

In short, for the reader of this eBook to grasp today's emphasis on sustainability and eco-dimensions of building materials, and concrete in particular.

For further reading on the teaching material presented in the eBook, reference is made to the following literature:

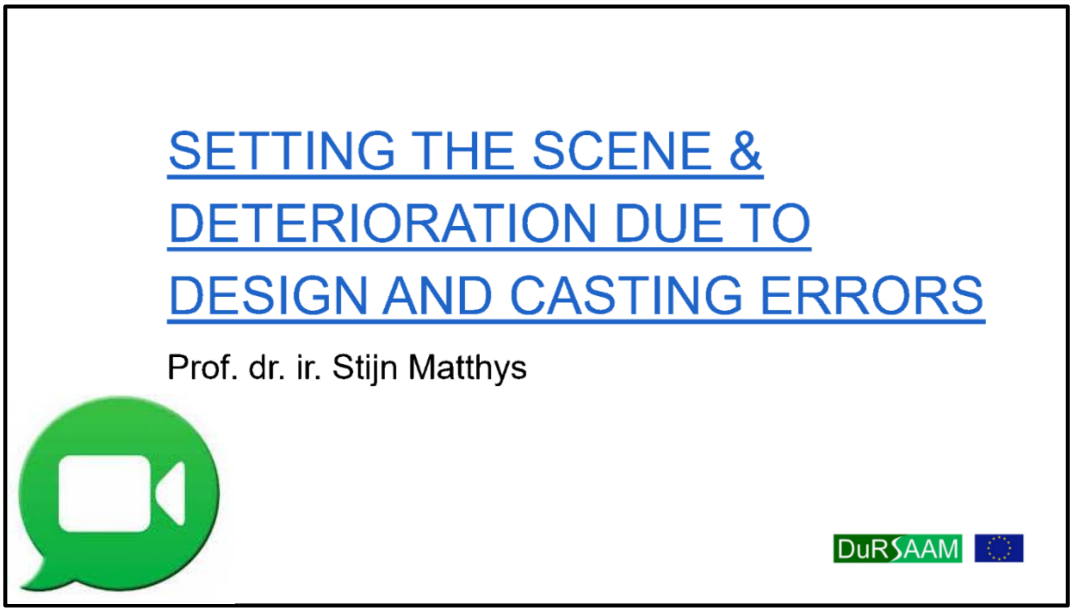
1. G. De Schutter. (2012). *Damage to concrete structures*. CRC Press - Taylor & Francis Group. ISBN 9780415603881.
2. K. Scrivener, R. Snellings, B. Lothenbach. (2016). *A Practical Guide to Microstructural Analysis*. CRC Press - Taylor & Francis Group. ISBN 9781138747234.
3. O. Jolliet, M. Saade-Sbeih, S. Shaked, A. Jolliet, P. Crettaz. (2015). *Environmental Life Cycle Assessment*. Taylor & Francis Group. ISBN 9780429111051. https://doi.org/10.1201/b19138.
4. Ellen MacArthur Foundation. (2019). *Completing the Picture: How the Circular Economy Tackles Climate Change*. www.ellenmacarthurfoundation.org/publications.

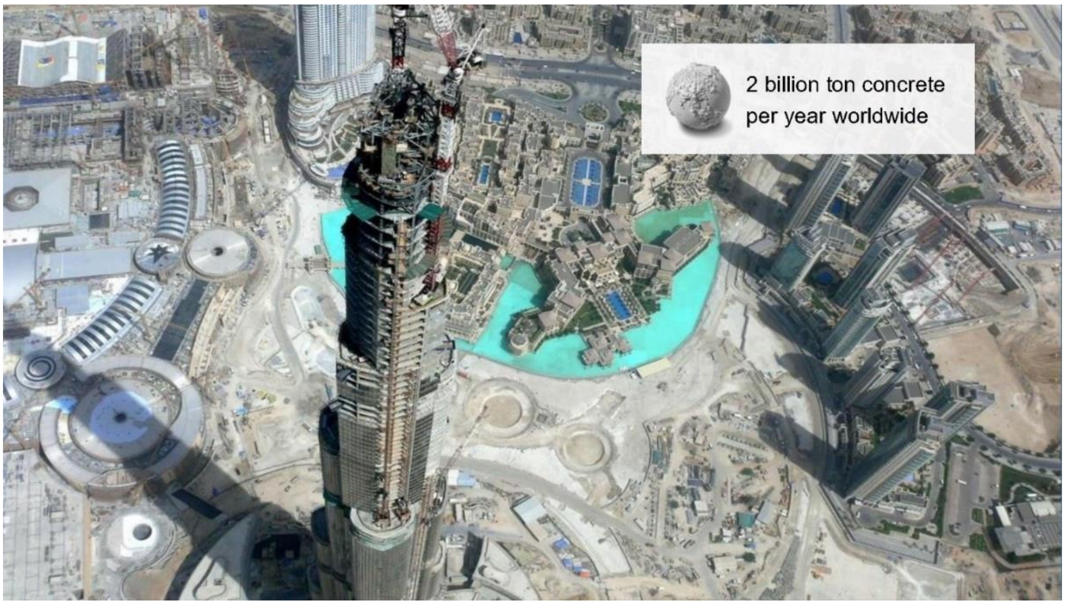
2. Setting the scene & degradation due to inappropriate design and errors during casting

Stijn Matthys

In this chapter a brief introduction is given on how to approach damage to concrete structures, how to define durability and service life and which practical durability approaches can be used. Next, a discussion is provided on how damage to concrete structures can originate from inappropriate design and errors during casting.

A video recording with further explanation is provided here (28 minutes to watch).





Damage to concrete structures

1. The “timeline” approach
2. The “material” approach (EN1504-9)

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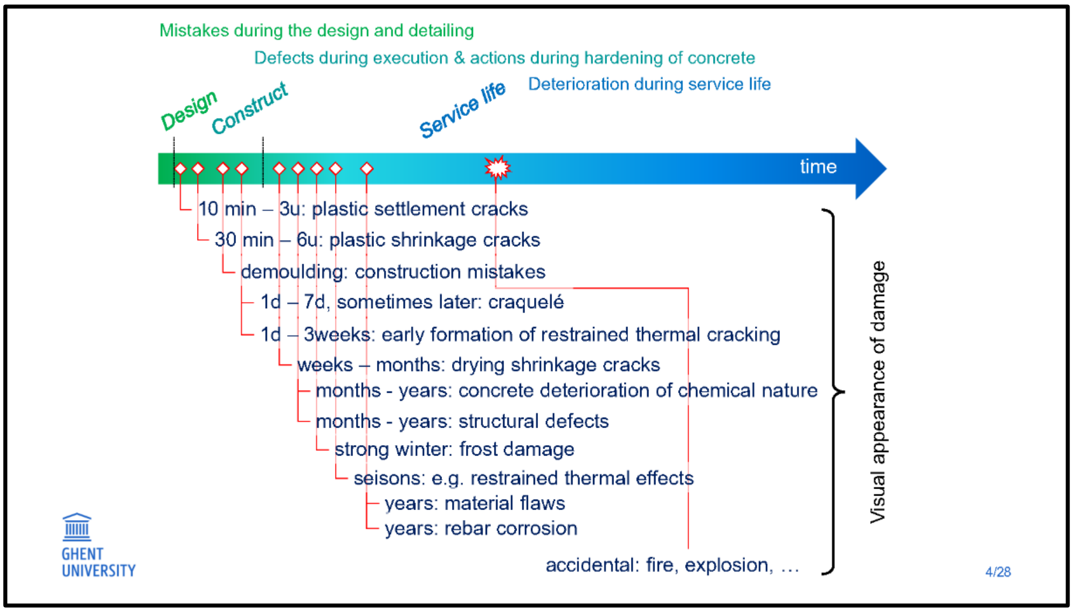

Mistakes during the design and detailing
Defects during execution & actions during hardening of concrete
Deterioration during service life
Design
Construct
Service life
time
10 min – 3u: plastic settlement cracks
30 min – 6u: plastic shrinkage cracks
demoulding: construction mistakes
1d – 7d, sometimes later: craquelé
1d – 3weeks: early formation of restrained thermal cracking
weeks – months: drying shrinkage cracks
months - years: concrete deterioration of chemical nature
months - years: structural defects
strong winter: frost damage
seisons: e.g. restrained thermal effects
years: material flaws
years: rebar corrosion
accidental: fire, explosion, …
Visual appearance of damage
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Inappropriate detailing or design
Poor workmanship
Mechanical actions (e.g. impact)
Fire
Mistakes during design, detailing and execution
Accidental actions
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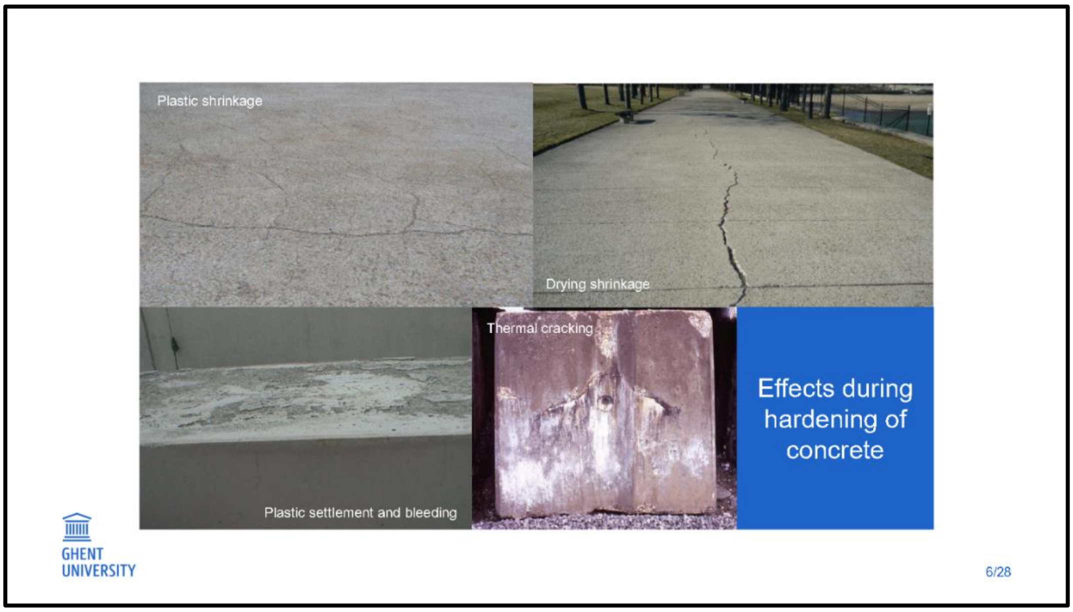
Plastic shrinkage
Drying shrinkage
Thermal cracking
Plastic settlement and bleeding
Effects during hardening of concrete
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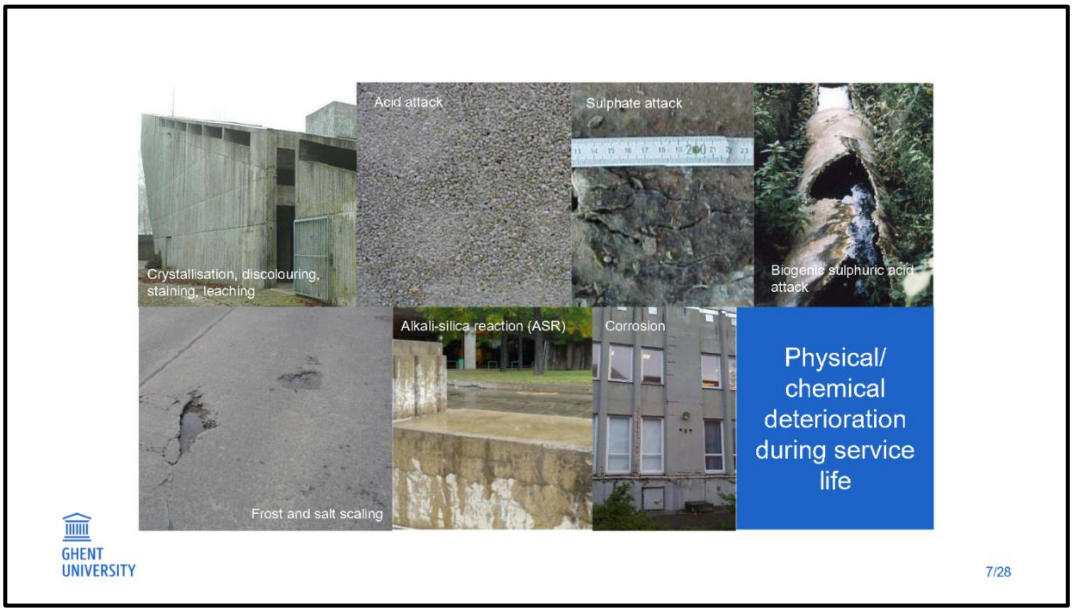
Acid attack
Sulphate attack
Crystallisation, discolouring, staining, leaching
Biogenic sulphuric acid attack
Alkali-silica reaction (ASR)
Corrosion
Frost and salt scaling
Physical/ chemical deterioration during service life
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Damage to concrete structures

1. The “timeline” approach
2. The “material” approach (EN1504-9)

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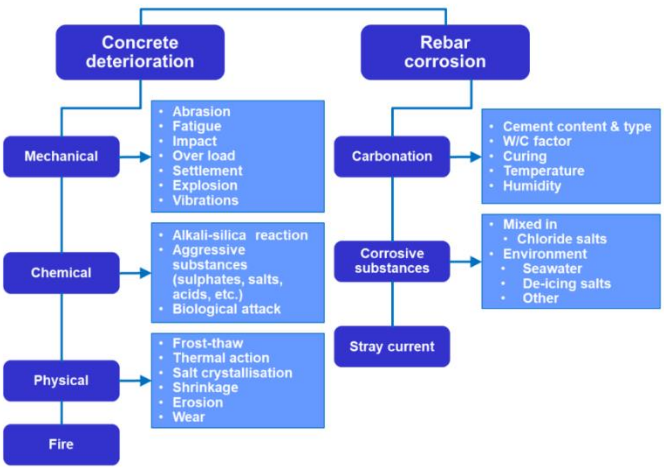
EN 1504-9: damage causes



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Concrete durability issues: why now?

- Reinforced concrete = relatively new construction material
  Application in buildings and structures only after 1900; mainstream construction material only after WWII
- Exponential growth of construction industry in 1960s and 1970s
  After WWII: focus on timely building of structures rather than quality and durability
- Many degradation mechanisms require more than 20 years to develop visible damage
  Examples: reinforcement corrosion, alkali silica reaction, …
- Increased aggressiveness of the environment
  Due to increased industrial activity, waterways and atmosphere become more and more polluted, increasing the degradation risk
- More advanced design methods
  Ultimate limit state (ULS) design instead of elastic design; More slender concrete structures possible due to material development

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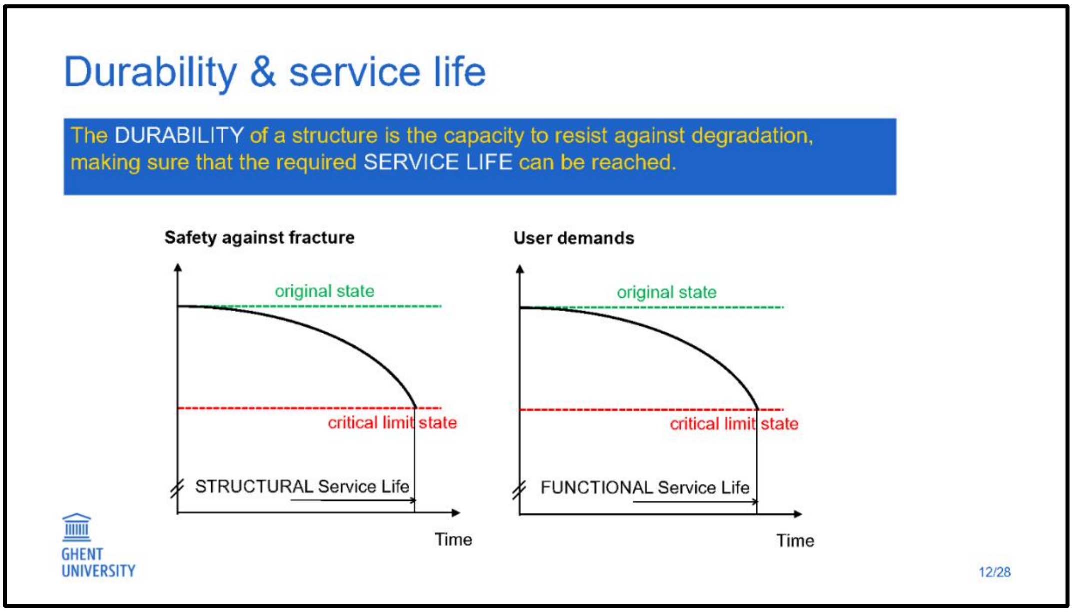
Structures in general, and concrete structures in particular, are designed to fulfil strength and functional requirements during a certain time period, without unexpected costs for maintenance or repair. This time period is called the SERVICE LIFE of the structure.

The DURABILITY is the property of the material or structure to withstand serious degradation mechanisms, making sure that the decline of the initial properties is kept within acceptable quality limits.


Durability & service life
The DURABILITY of a structure is the capacity to resist against degradation, making sure that the required SERVICE LIFE can be reached.
Safety against fracture
original state
critical limit state
STRUCTURAL Service Life
Time
User demands
original state
critical limit state
FUNCTIONAL Service Life
Time
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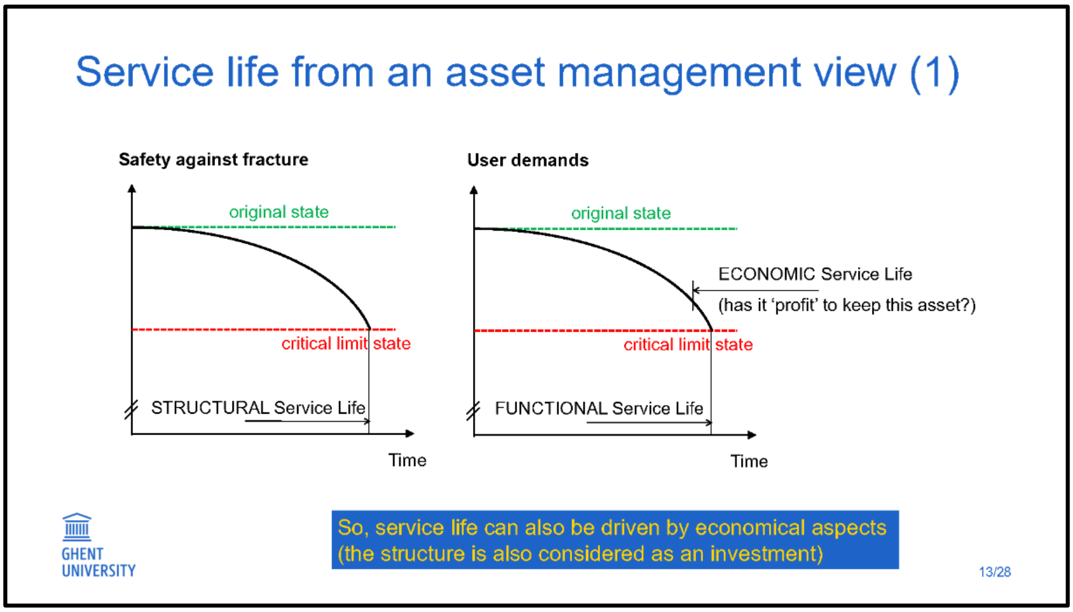
Service life from an asset management view (1)
Safety against fracture
original state
critical limit state
STRUCTURAL Service Life
Time
User demands
original state
ECONOMIC Service Life
(has it 'profit' to keep this asset?)
critical limit state
FUNCTIONAL Service Life
Time
So, service life can also be driven by economical aspects (the structure is also considered as an investment)
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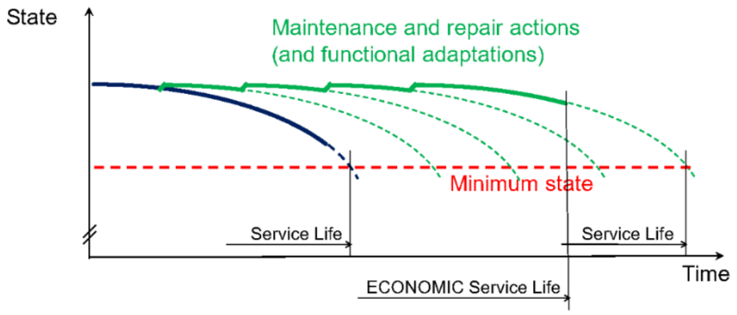
Service life from an asset management view (2)



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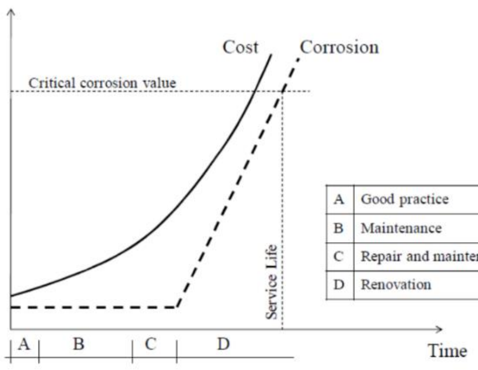
Cost strategies 'law of fives'



A	Good practice	€ 1,-
B	Maintenance	€ 5,-
C	Repair and maintenance	€ 25,-
D	Renovation	€ 125,-

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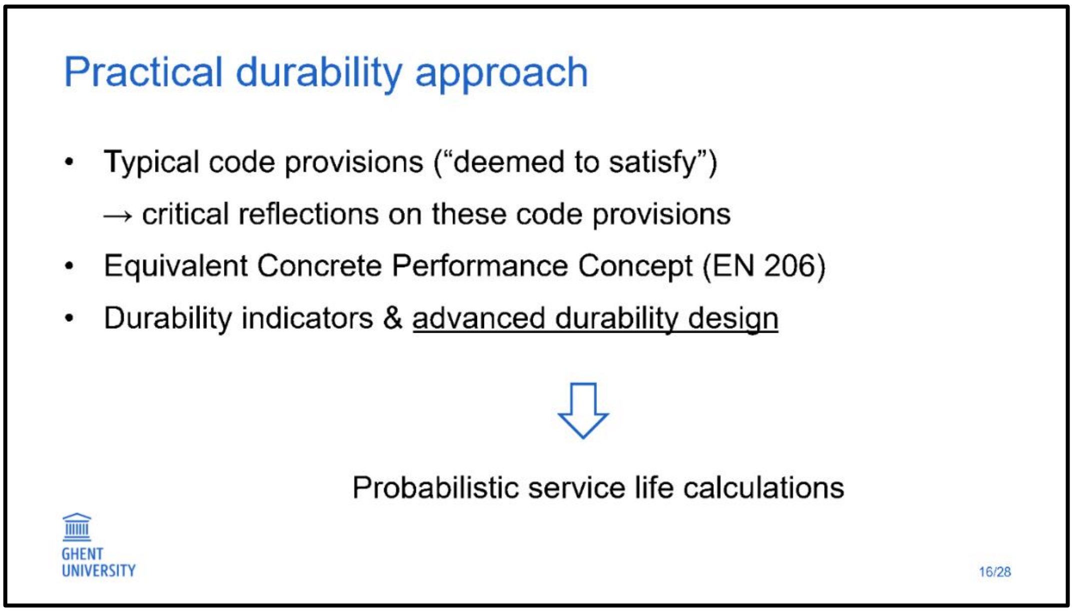
Practical durability approach
• Typical code provisions (“deemed to satisfy”)
→ critical reflections on these code provisions
• Equivalent Concrete Performance Concept (EN 206)
• Durability indicators & advanced durability design
Probabilistic service life calculations
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WOULD IT NOT BE BETTER TO CONCENTRATE ON THE FINAL PERFORMANCE OF THE CONCRETE, RATHER THAN TAKING E.G. MINIMUM CEMENT CONTENT PER M³ AS ONE OF THE MAIN CRITERIA?
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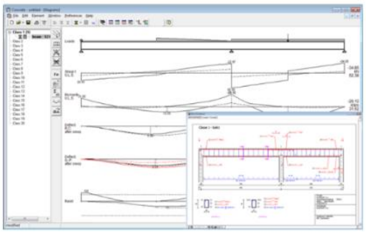
Design stage problems



- Inappropriate dimensions and detailing
- Wrong estimation of loading
- Inappropriate estimation of creep effects
- Inappropriate mix design

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Bridge collapse (Melle 1991)

Roof collapse (2012/13)

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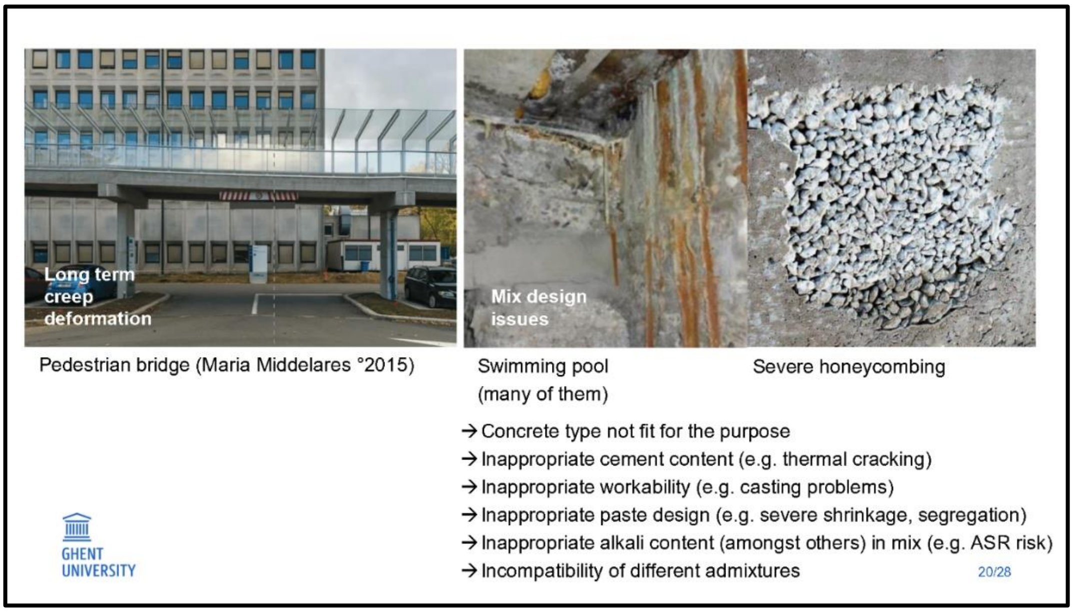
Long term creep deformation
Mix design issues
Pedestrian bridge (Maria Middelares °2015)
Swimming pool (many of them)
Severe honeycombing
→ Concrete type not fit for the purpose
→ Inappropriate cement content (e.g. thermal cracking)
→ Inappropriate workability (e.g. casting problems)
→ Inappropriate paste design (e.g. severe shrinkage, segregation)
→ Inappropriate alkali content (amongst others) in mix (e.g. ASR risk)
→ Incompatibility of different admixtures
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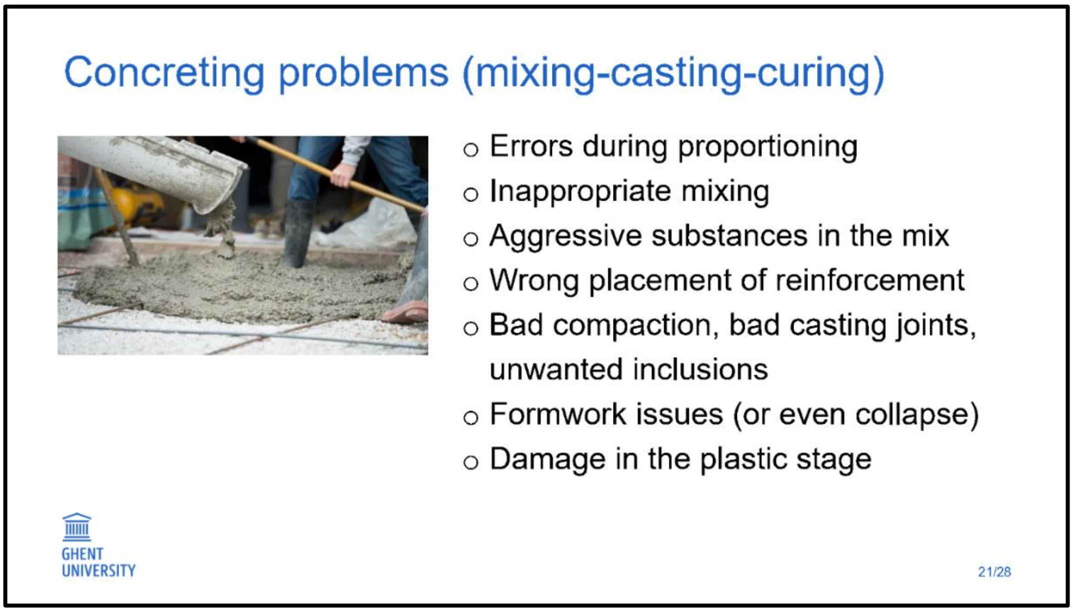
Concreting problems (mixing-casting-curing)
○ Errors during proportioning
○ Inappropriate mixing
○ Aggressive substances in the mix
○ Wrong placement of reinforcement
○ Bad compaction, bad casting joints, unwanted inclusions
○ Formwork issues (or even collapse)
○ Damage in the plastic stage
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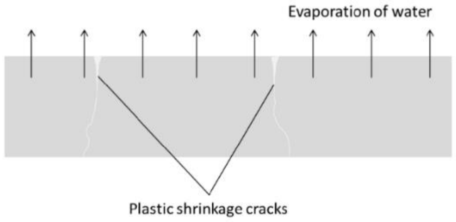
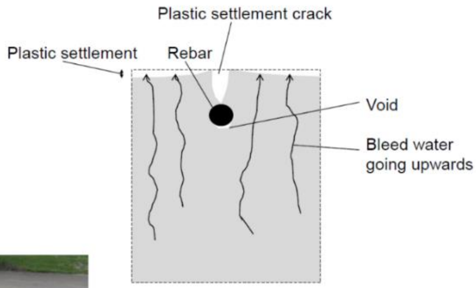
Damage in the plastic stage





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More explanation about concrete deterioration also in the following teaching blocks by my colleagues

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Chapel of Kerselare (2015)


Complex Patio Sevilla at Maastricht
(NL, collapse 2003)
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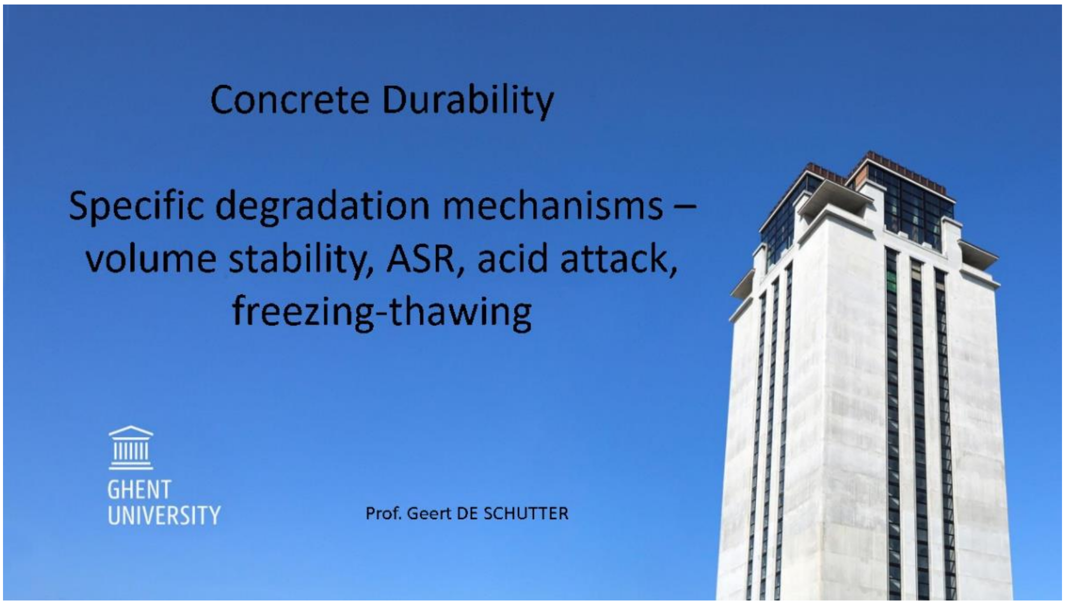
3. Specific concrete degradation mechanisms: volume stability, ASR, acid attack and freezing-thawing

Geert De Schutter

This chapter highlights damage to concrete structures resulting from actions during the service life of the structure. More specifically focus is given to concrete deterioration mechanisms related to volume stability, ASR, acid attack and freezing-thawing. The deterioration mechanisms are discussed, as well as influencing factors and possibilities for mitigation. Damage to concrete resulting from reinforcement corrosion is covered in the next chapter.

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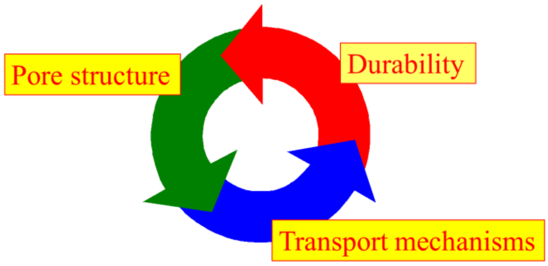
3

Reasons why durability issues related to concrete structures have become more prominent during the last decades

- Reinforced concrete is a relatively new construction material
- Exponential growth of construction industry in the 1960s and 1970s
- Many degradation mechanisms require a time period of about 20 years before damage becomes visible
- Due to the increased industrial activity, the aggressiveness of the environment is increased
- More advanced design methods



- Durability not only depends on the intrinsic quality of the concrete, but also – and sometimes even more importantly – on the execution:
  - **Concrete cover**
  - **Concrete compaction / vibration**
  - **Concrete curing**

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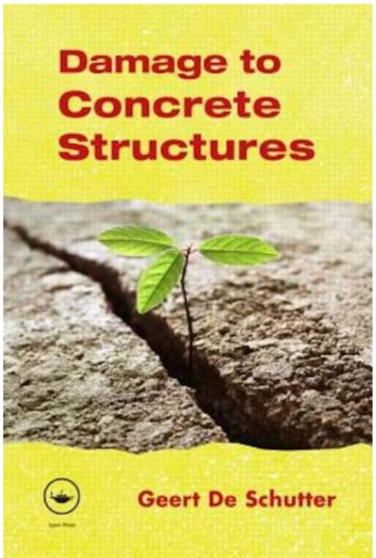
Damage due to:

- ➢Inappropriate design (Chapter 2)
- ➢Errors during casting (Chapter 3)
- ➢Actions during hardening (Chapter 4)
- ➢Actions during service life (Chapter 5)



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Actions during service

- Mechanical actions
- Physical actions
  - Frost damage
  - Frost in combination with de-icing salts
  - Shrinkage
  - Erosion
  - Thermal effects
  - Crystallisation and discolouring due to moisture movement
- Chemical actions
  - Alkali silica reaction (ASR)
  - Sulfate attack and delayed ettringite formation
  - Acid attack
  - Biogenic sulfuric acid attack
- Reinforcement corrosion
  - Carbonation-induced corrosion
  - Chloride-induced corrosion

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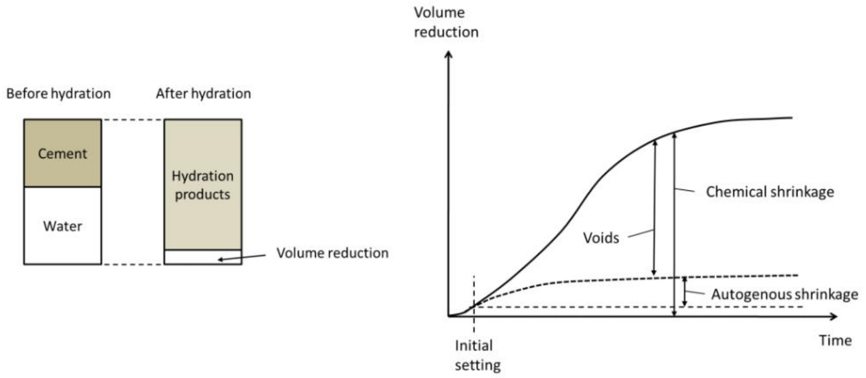
Autogenous shrinkage

Mechanism



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Autogenous shrinkage

Influencing parameters

- Mineral composition of cement (e.g. C_3A)
- Mineral additions and chemical admixtures
  - Fly ash: typically lower
  - Silica fume: typically higher
- Water/Cement ratio
- Paste volume

Mitigation

- Increase Water/Cement ratio (but conflict with other requirements!)
- Good selection of cement type (avoid high C_3A content)
- Apply internal curing
  - Fine LWA
  - SAP

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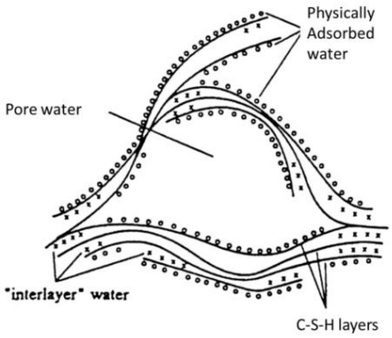
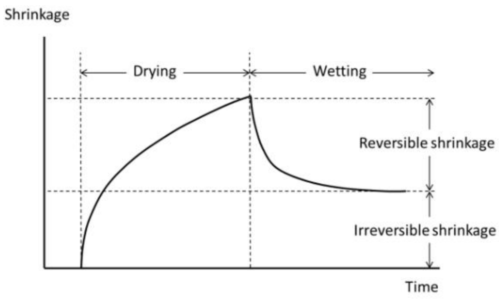
Drying shrinkage

Mechanism





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Drying shrinkage

Influencing parameters

- Parameters related to the concrete composition
  - Paste volume, aggregate content
  - Water/cement ratio
  - Cement content (through paste volume and Water/cement ratio)
  - Cement type
    - Small effect on ultimate shrinkage strain
    - Time development influenced by reaction rate
  - Additions and admixtures
- Geometrical parameters
  - Fictitious thickness ($A_c/(u/2)$)
    - Faster drying shrinkage development for smaller fictitious thickness
    - Minor influence on ultimate shrinkage
- Atmospheric parameters
  - Relative humidity!
  - Influence of temperature not very significant (somewhat lower final shrinkage for lower curing temperature)

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Drying shrinkage

Influencing parameters

- Technological parameters during execution
  - When drying starts at an earlier age, the ultimate shrinkage value will be higher
  - The duration of the curing period thus is important for the drying shrinkage strains occuring as soon as curing is ended

Mitigation

- Lower Water/Cement ratio
- Limited paste volume
- Curing times long enough
- A good casting scheme can also contribute to a lower risk of drying shrinkage cracking

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Drying shrinkage

Example

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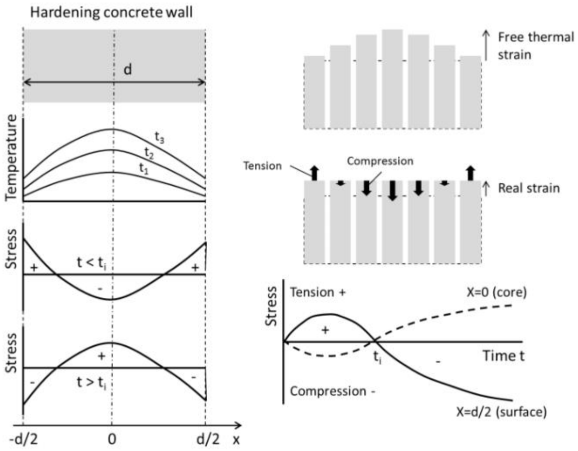
Thermal shrinkage

Mechanism
Internal restraint



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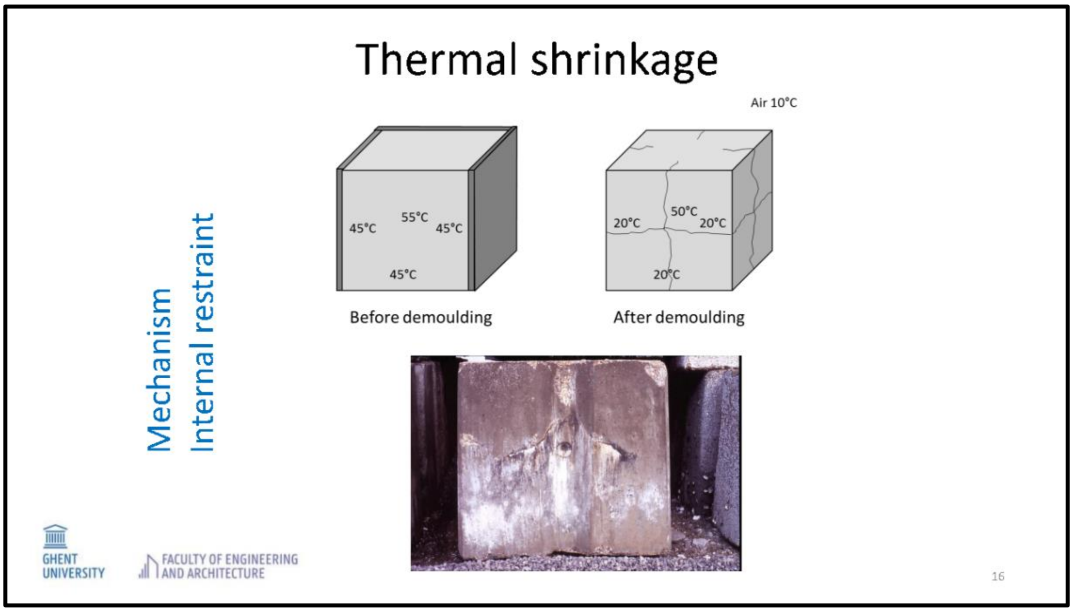
Thermal shrinkage
Mechanism
Internal restraint
Air 10°C
45°C
55°C
45°C
45°C
50°C
20°C
20°C
20°C
Before demoulding
After demoulding
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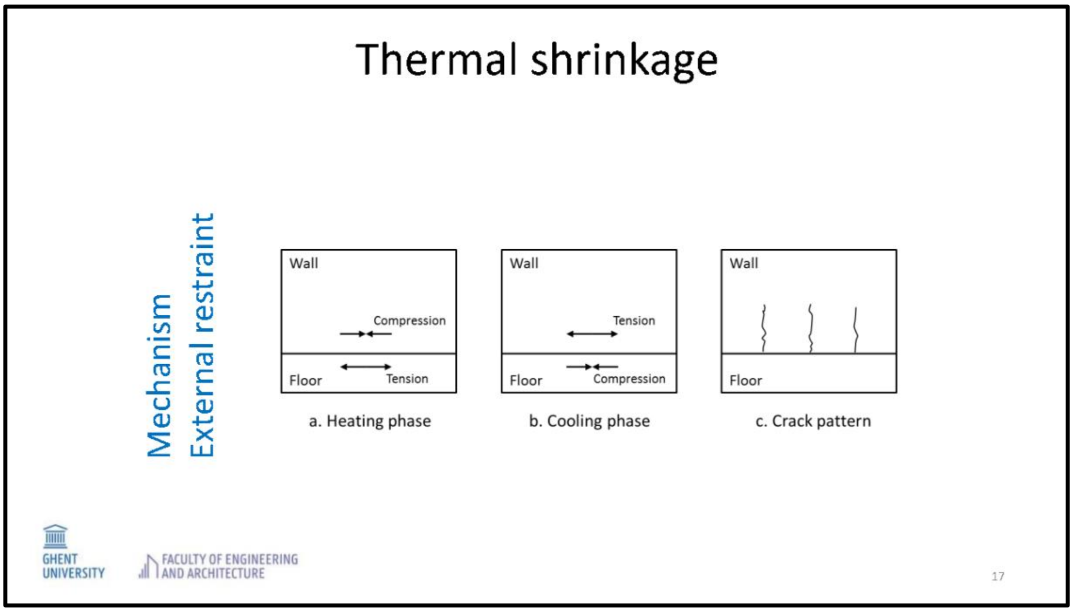
Thermal shrinkage
Mechanism
External restraint
Wall
Compression
Floor
Tension
a. Heating phase
Wall
Tension
Floor
Compression
b. Cooling phase
Wall
Floor
c. Crack pattern
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Thermal shrinkage

Influencing parameters

- Parameters related to the concrete composition
  - Cement type
  - Cement content
  - Puzzolan or mineral additions
  - Aggregate size …
- Geometrical parameters
  - Massivity / Equivalent thickness
- Atmospheric parameters
  - Temperature of environment
  - Wind
- Technological parameters during execution
  - Formwork conditions
  - Cooling measures

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Thermal shrinkage

Mitigation

- Cement type with low heat of hydration
- Partial cement replacement by puzzolan materials
- Coarser aggregate type… could lead to lower required paste volume
- Retarders? Not always!
- Reinforcement? Only helpful to control crack width and spacing
- Appropriate choice of formwork type, to be studied case by case

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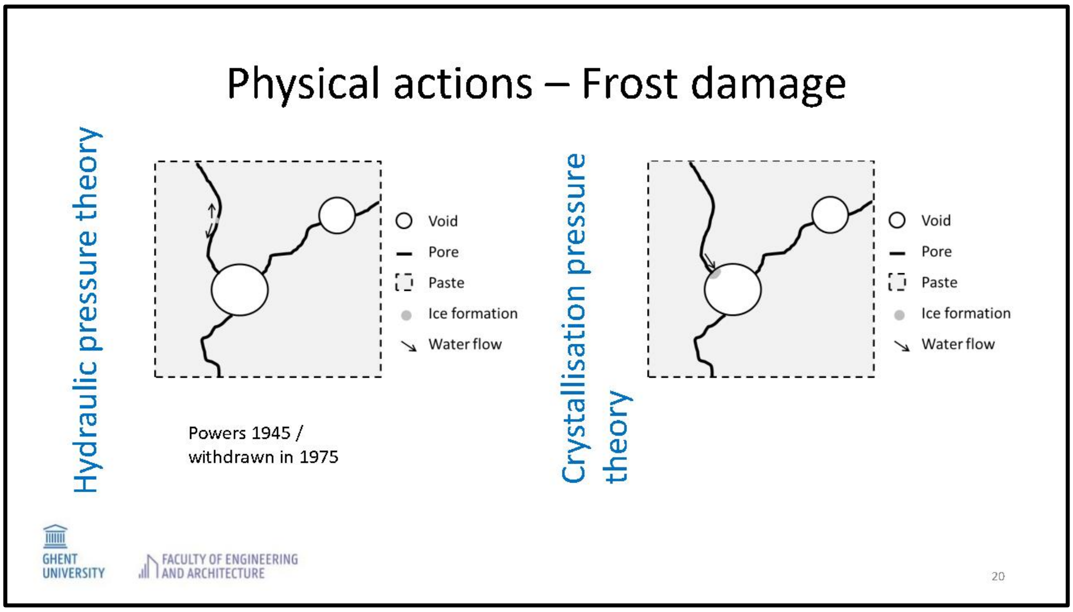
Physical actions – Frost damage
Hydraulic pressure theory
Void
Pore
Paste
Ice formation
Water flow
Powers 1945 / withdrawn in 1975
Crystallisation pressure theory
Void
Pore
Paste
Ice formation
Water flow
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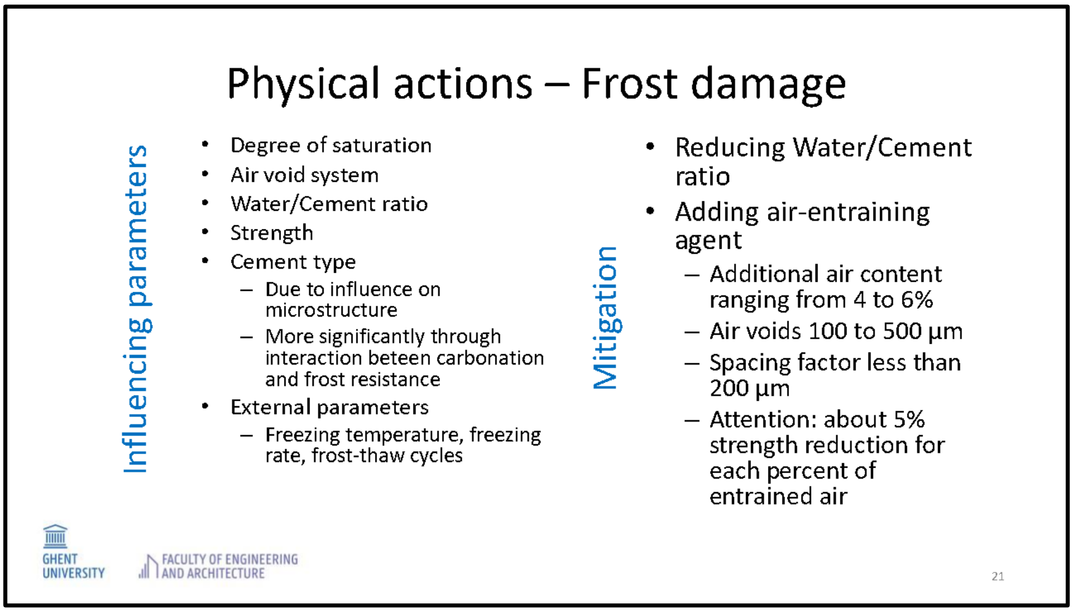
Physical actions – Frost damage
Influencing parameters
• Degree of saturation
• Air void system
• Water/Cement ratio
• Strength
• Cement type
– Due to influence on microstructure
– More significantly through interaction beteen carbonation and frost resistance
• External parameters
– Freezing temperature, freezing rate, frost-thaw cycles
Mitigation
• Reducing Water/Cement ratio
• Adding air-entraining agent
– Additional air content ranging from 4 to 6%
– Air voids 100 to 500 µm
– Spacing factor less than 200 µm
– Attention: about 5% strength reduction for each percent of entrained air
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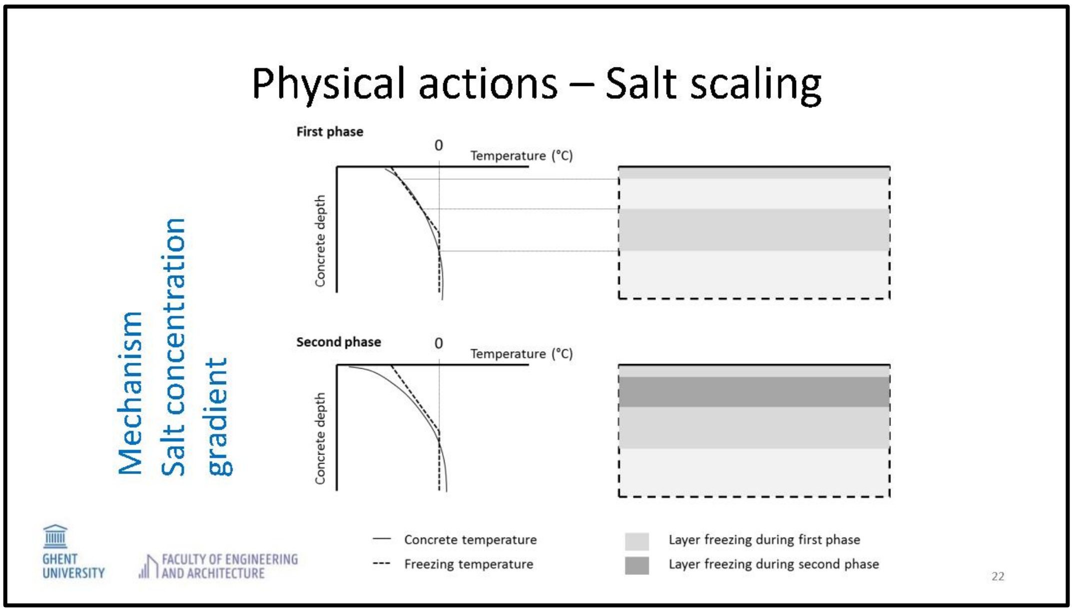
21


Physical actions – Salt scaling
Mechanism
Salt concentration gradient
First phase
0
Temperature (°C)
Concrete depth
Second phase
0
Temperature (°C)
Concrete depth
Concrete temperature
Freezing temperature
Layer freezing during first phase
Layer freezing during second phase
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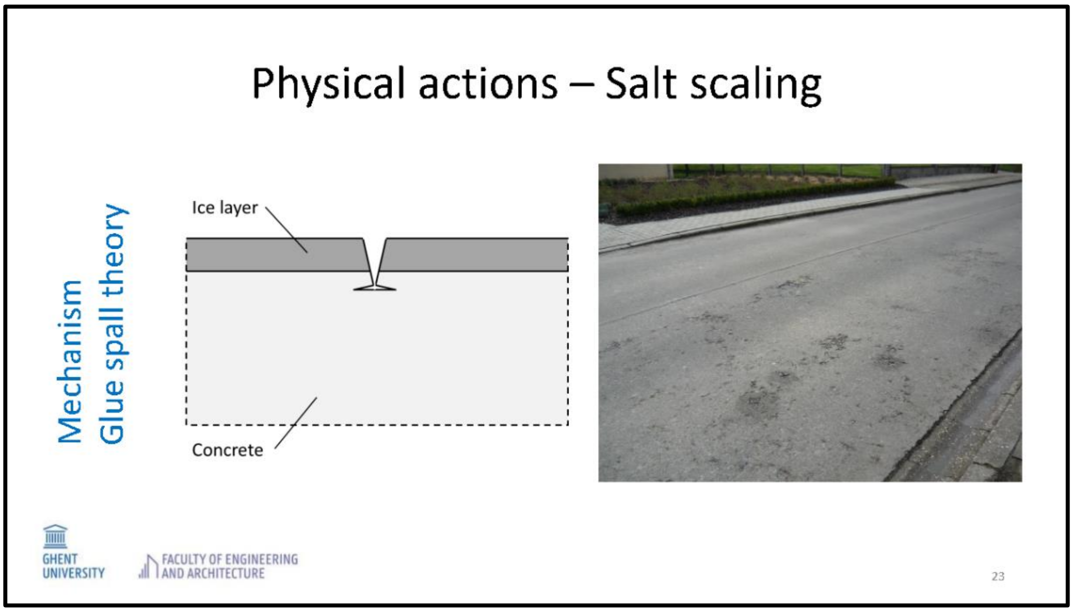
Physical actions – Salt scaling
Mechanism
Glue spall theory
Ice layer
Concrete
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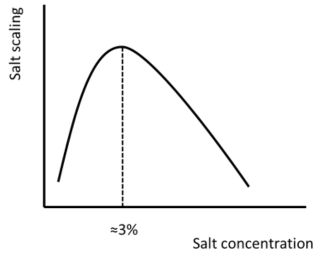
23

Physical actions – Salt scaling

Influencing parameters

- Salt concentration



- Ice layer thickness
  - The higher the ice layer thickness, the higher the frost scaling damage
- Quality of the concrete
  - Higher strength => higher resistance against mechanical action of ice
  - Air entrainment has beneficial effect, in spite of lower strength, because water movement induces slight contraction, reducing thermal incompatibility with ice layer

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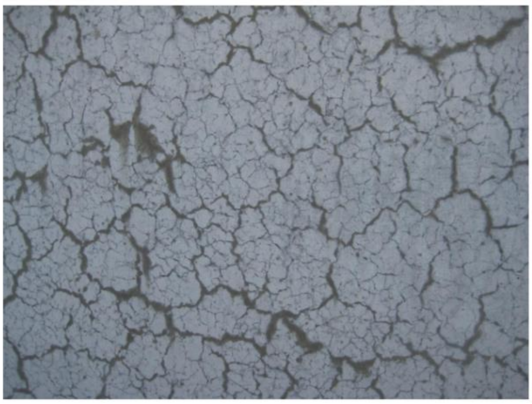
Chemical actions – ASR

Mechanism



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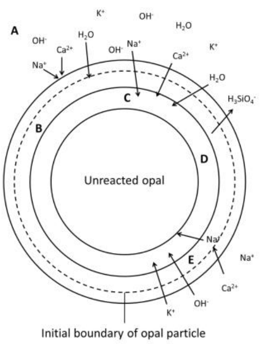
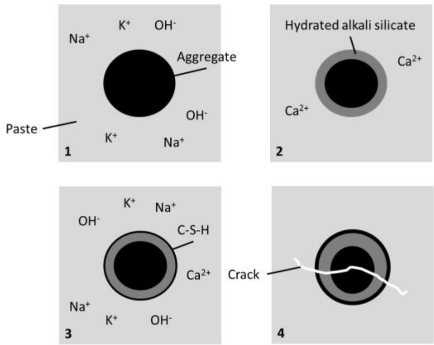
Chemical actions – ASR

Mechanism



Principles of the ASR damage model by Powers and Steinour (1955).



Modified model of ASR (Ichikawa and Miura 2007)

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Chemical actions – ASR

Influencing parameters

- For ASR to occur, three necessary conditions have to be fulfilled:
  - Potentially reactive aggregates have to be present in the concrete
  - The alkali concentration in the pore solution has to be significantly high
  - Moisture has to be present in sufficient quantities

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Acid attack

Mechanism

- As concrete is a calcium rich alkaline environment, it will react with nearly all possible acids.

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Acid attack

Mechanism

- The main effect of the acid is the dissolution of the cement matrix, leading to a degradation of the concrete.
- In contrast with typical cases of sulfate attack, the degradation process in case of acid attack is not linked to any significant expansion reaction, as ettringite and thaumasite are not stable in acid environment.
- The level of degradation is largely depending on the type of acid to which the concrete is exposed.
- Furthermore, waste waters can contain different acids, making the degradation process very complex. The resulting degradation cannot be predicted by simply considering a superposition of the degradation caused by each acid separately

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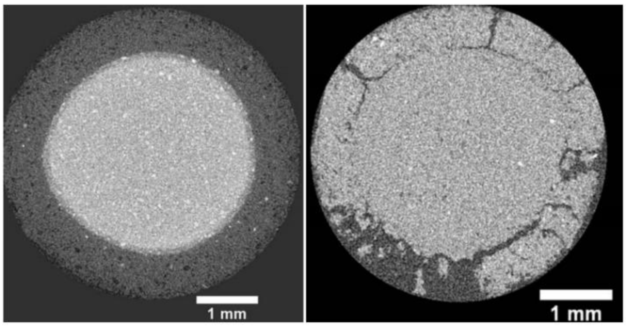
Acid attack

Example



X-ray computed microtomography scan of paste sample exposed to lactic and acetic acid, after 25 h (left) and 21 days (right) of exposure (Boel et al. 2008).

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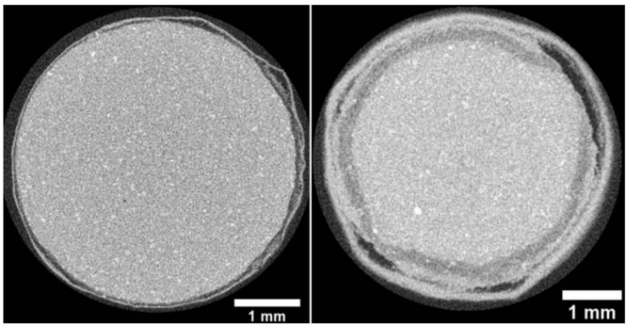
Acid attack

Example



X-ray computed microtomography scan of paste sample exposed to sulfuric acid, after 21 h (left) and 21 days (right) of exposure (Boel et al. 2008).

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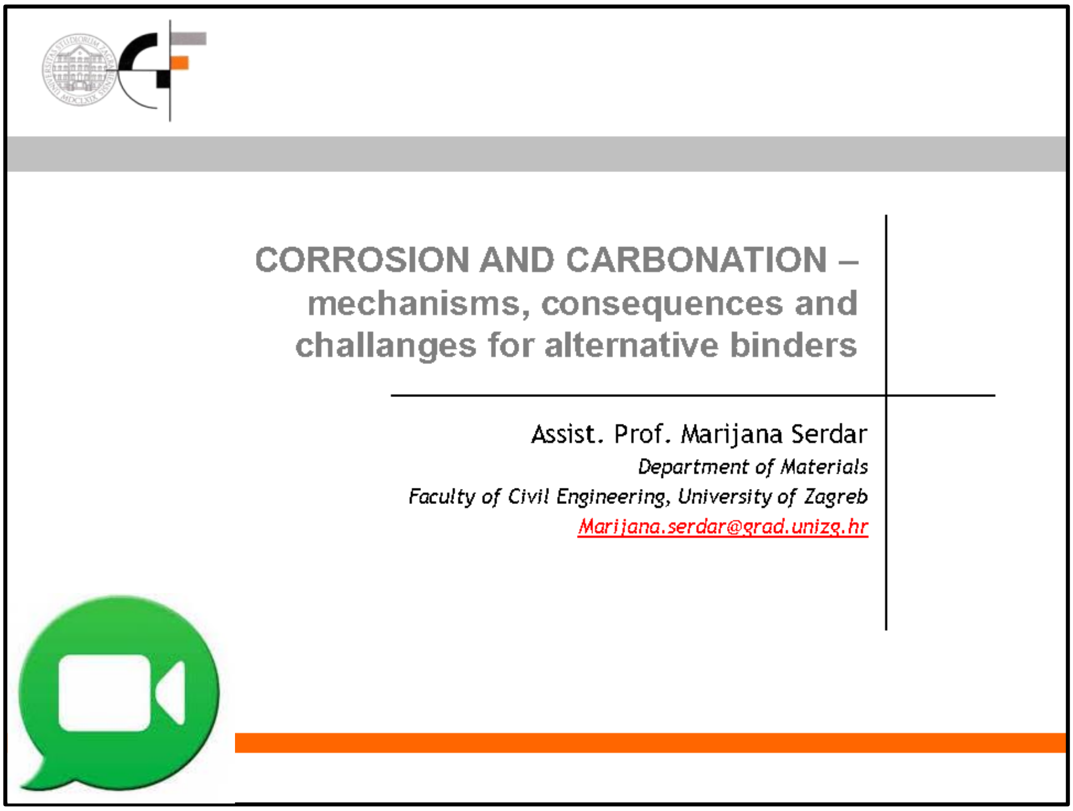
4. Reinforcement corrosion, including further discussion on carbonation

Marijana Serdar

This chapter discusses about carbonation and chloride induced reinforcement corrosion, and further focusses on the aspect of carbonation. Further to discussing the mechanisms behind corrosion and carbonation, special attention is given to the influence of alternative binder systems.

A video recording with further explanation is provided here (28 minutes to watch).

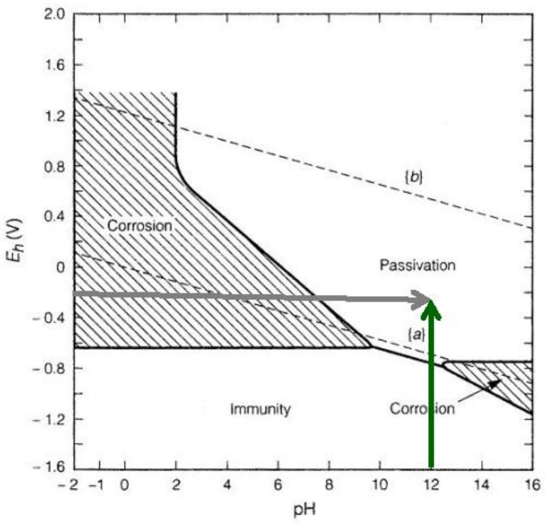


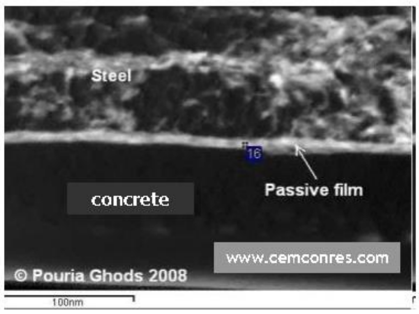
Content

- Corrosion / carbonation
  - Mechanism of degradation
  - Consequences on different scales
  - Influence of binder change
  - Challenges that remain

2

CONCRETE - the best environment for steel





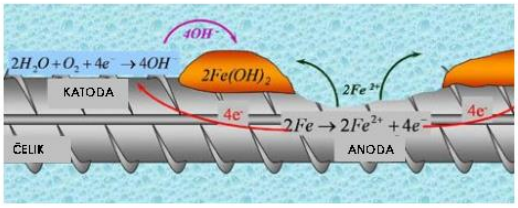
3

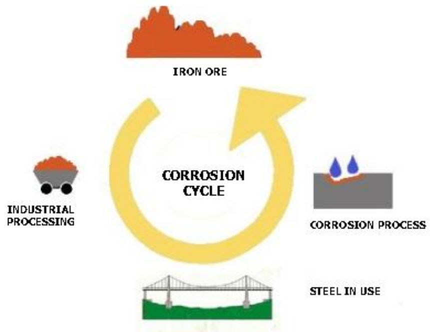
CORROSION MECHANISM

Anode
$2Fe \rightarrow 2Fe^{2+} + 4e^-$

Cathode
$4e^- + O_2 + 2H_2O \rightarrow 4OH^-$

Corrosion products (rust)
$2Fe^{2+} + 4OH^- \rightarrow 2Fe(OH)_2$





Bentur, A. ; Diamond, S. ; Berke, S.N. Steel corrosion in concrete : fundamentals and civil engineering practice, London, E & FN Spon, 1997

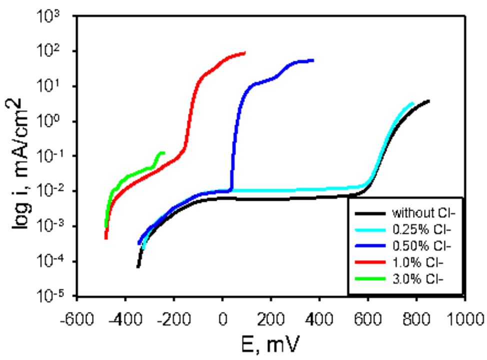
CORROSION MECHANISM

- Chloride ions react with iron ions
  - Competing processes
  - Inhibiting formation of passive film

$Fe \rightarrow Fe^{2+} + 2\,e^-$

$Fe^{2+} + 2\,Cl^- \rightarrow FeCl_2$

$FeCl_2 + H_2O + OH^- \rightarrow Fe(OH)_2 + 2\,Cl^- + H^+$

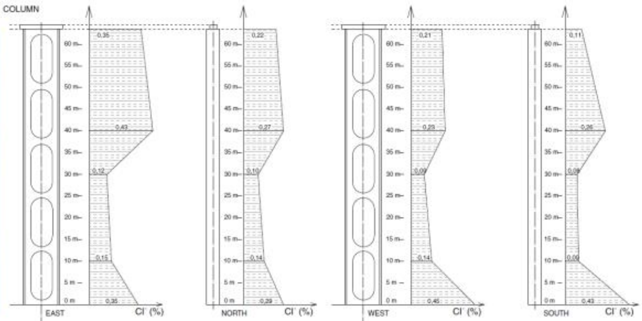


Bjegović, Dubravka; Stipanović, Irina; Serdar, Marijana
Corrosion of Prestressing Steel in High Performance Grouts // Proceedings of the 12th International Congress on the Chemistry of Cement / Beaudoin, J.J. ; Makar, J.M. ; Raki, L. (ur.). Montreal, 2007.

CHLORIDE-INDUCED CORROSION - example

Krk Bridge

- 1976 - 1980
- Total span 1430 m, big arch span 390 m



I. Stipanovic Oslakovic, D. Bjegovic, D. Mikulic, Evaluation of service life design models on concrete structures exposed to marine environment, Materials and Structures (2010) 43:1397-1412

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CHLORIDE-INDUCED CORROSION - example

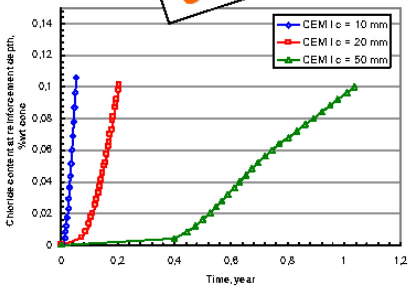
Maslenica Bridge

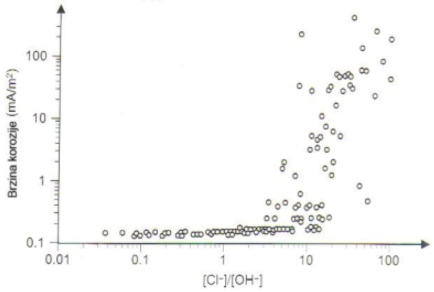
- 1995 - 1996
- Span 200 m

CONCRETE - the best environment for st...

NOT UNCONDITIONALLY

- PHYSICAL BARRIER
  - Permeability, diffusion, migration, convection
  - Thickness
  - Pore structure
- CHEMICAL BARRIER
  - pH of pore solution
  - Binding capacity



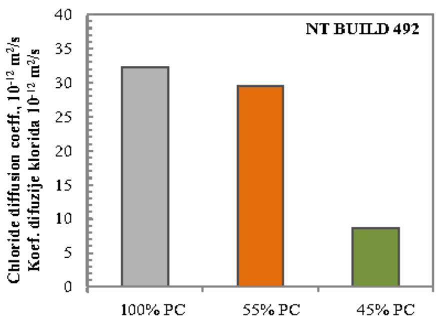


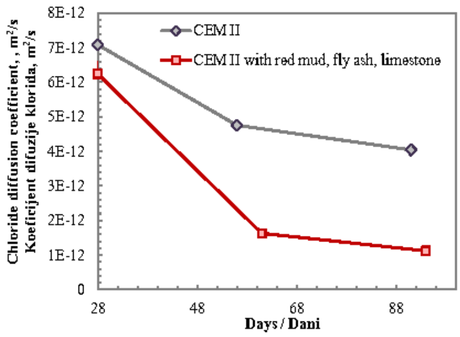
Bertolini, L. ; Elsener, B. ; Pedeferri, P. ; Polder, R. Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2004

8

INFLUENCE OF ALTERNATIVE BINDERS

- Changes in permeability / diffusion ability





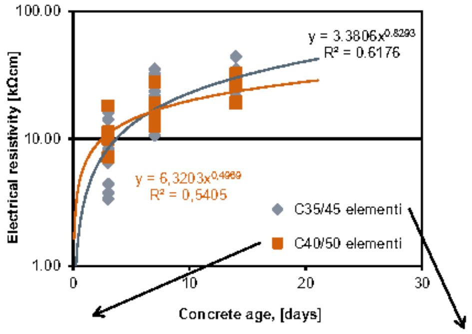
Bjegović, D., Štirmer, N., Serdar, M. Durability properties of concrete with blended cements, Materials and corrosion. 63 (2012) , 12; 1087-1096

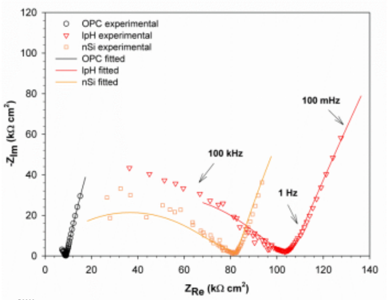
Serdar, Marijana; Biljecki, Ivan; Bjegović, Dubravka. High-Performance Concrete Incorporating Locally Available Industrial By-Products. // Journal of materials in civil engineering. 1 (2016)

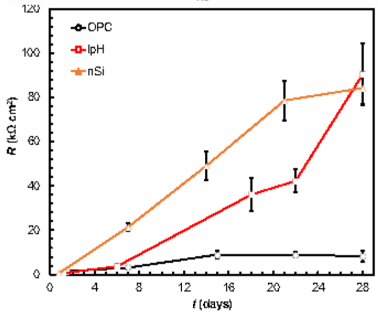
9

INFLUENCE OF ALTERNATIVE BINDERS

- Changes in electrical conductivity / resistivity







Silica fume and CEM II

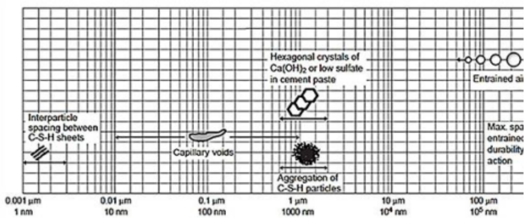
CEM III with 66% - 80% slag

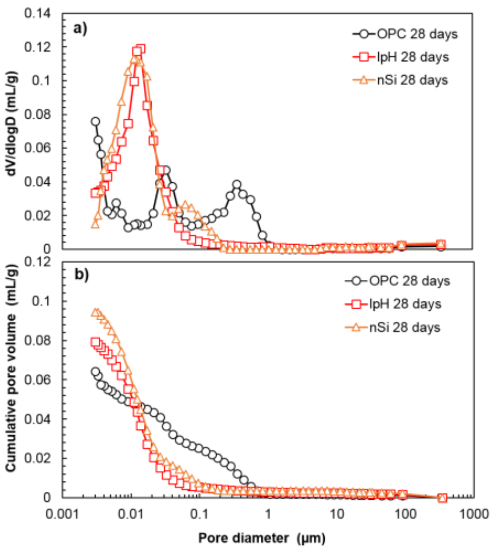
Serdar, Marijana; Peric, Vice; Bjegovic, Dubravka
Compliance assessment of durability indicators on new Port of Gazenica // Performance-based approaches for concrete structures / Beushausen, Hans (ur.). Cape Town, 2016.

10

INFLUENCE OF ALTERNATIVE BINDERS

- Differences in pore structure





P. Mehta, Paulo J. M. Monteiro Concrete: Microstructure, Properties, and Materials, McGraw-Hill Education, 2006

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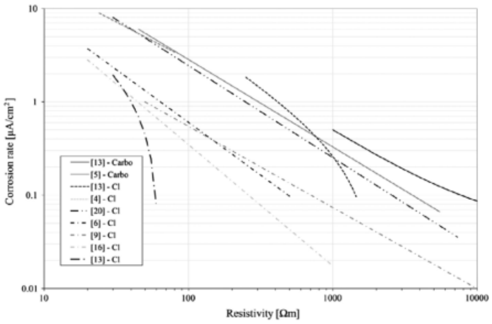
CHALLANGES REMAIN

- Each new combination of binders changes the environment around steel
  - pH difference – very high or low
  - Amount of sulphates
  - Binding (chemical and physical)

- Testing methods correlated to engineering units



Hornbostel, K., Larsen, C., Geiker, M.R. Relationship between concrete resistivity and corrosion rate - A literature review, Cement and Concrete Composites, Volume 39, May 2013, Pages 60-72

12

CARBONATION MECHANISM

- Reaction between CO_2 from the atmosphere and Ca bearing phases (traditionally mainly) $Ca(OH)_2$ from cement matrix

$$CO_2 + H_2O \rightarrow H_2CO_3$$

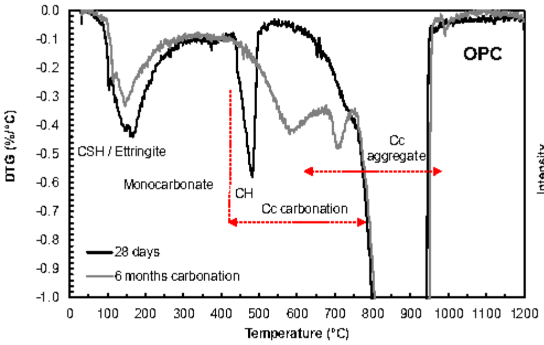
$$CO_2 + Ca(OH)_{2\,(aq)} \rightarrow CaCO_3 + H_2O$$

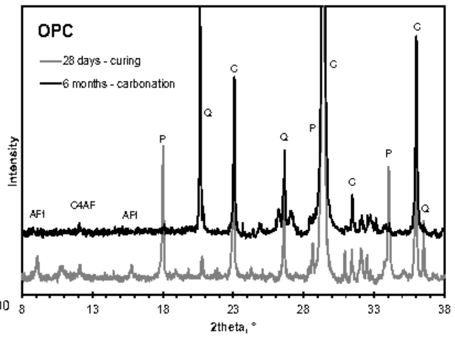
$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O$$

Bentur, A. ; Diamond, S. ; Berke, S.N. Steel corrosion in concrete : fundamentals and civil engineering practice, London, E & FN Spon, 1997

CARBONATION MECHANISM

- Non-carbonated vs carbonated concrete





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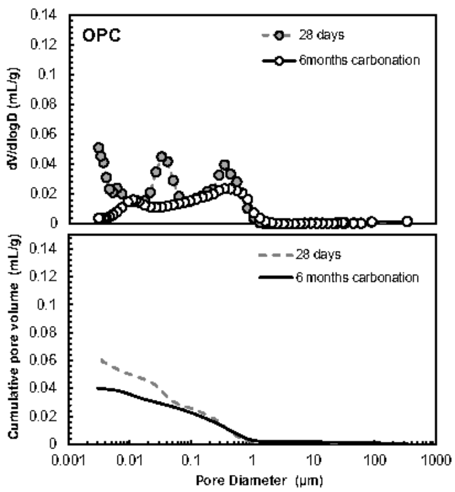
CONCRETE – protection mechanism

- $CaCO_3$ has bigger molar volume than $Ca(OH)_2$ → influence on porosity
- Freed water during carbonation – hidration of unhydrated cement



M. Serdar, S. Poyet, V. L'Hostis, D. Bjegovic Carbonation of low-alkalinity mortars: influence on corrosion of steel and on mortar microstructure, // Cement and concrete research : including Advanced cement based materials, 101 (2017), 33-45

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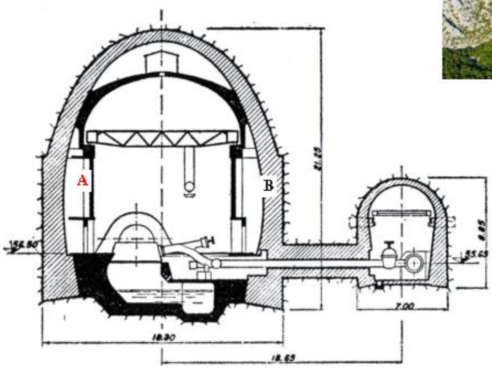
CARBONATION - example

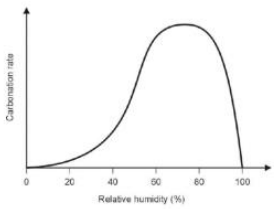
HE Vinodol

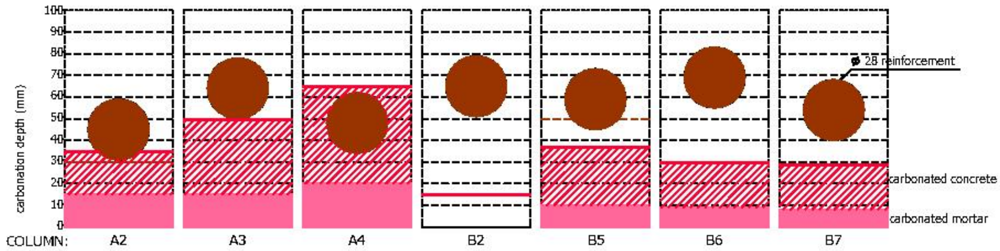
- In use since 1952



CARBONATION - example

- Area A high humidity (65%)
- Area B dry (40%)





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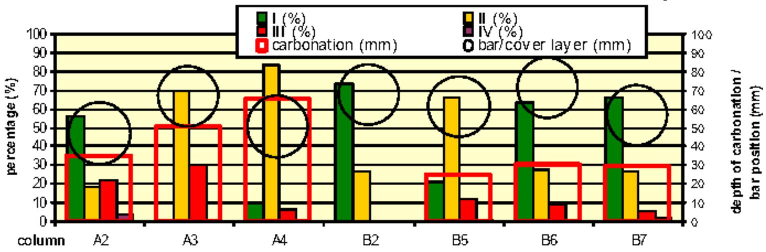
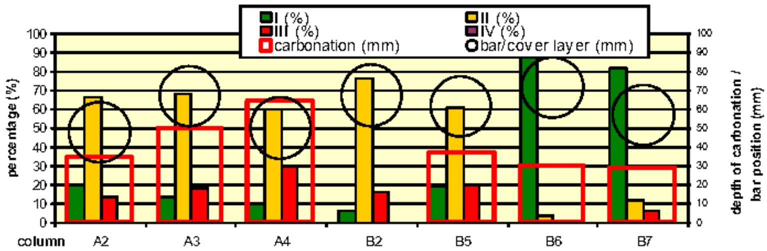
CONCRETE - protection mechanism

NOT UNCONDITIONALLY





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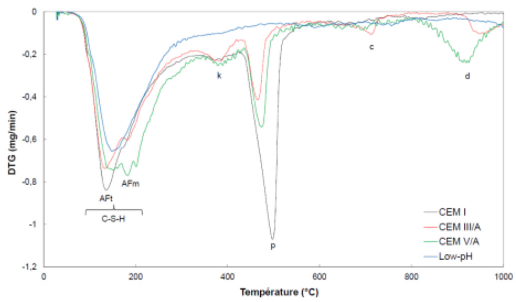
CONCRETE - protection mechanism

NOT UNCONDITIONALLY

$$x = \sqrt{\frac{2Dc}{a}} \times \sqrt{t}$$

- x - carbonation depth (m),
- c - concentration of ambient CO_2 (kg/m^3)
- a - concentration of carbonatable material (kg/m^3),
- D - diffusion coefficient of CO_2 (m^2/s),
- t - time, s
- c - 0,03 % in rural, 0,3% in industrial atmospheres and cities



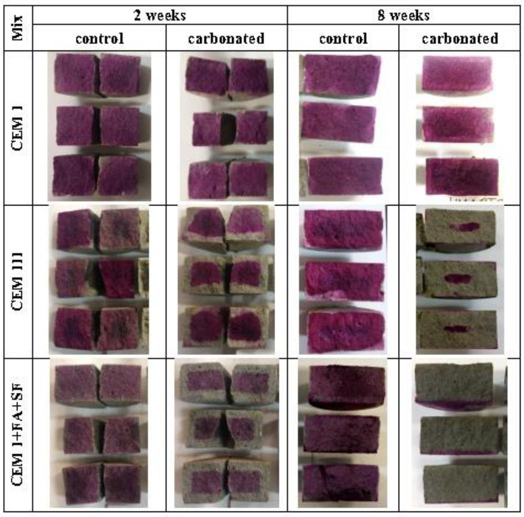
	CEM I	CEM III	CEM V	Low-pH (T1)
Portlandite (mol/L)	5.3	1.8	2.3	0

M. Auroy, S. Poyet, P. Le Bescop, J-M. Torrenti Impact of carbonation on the durability of cementitious materials: water transport properties characterization, EPJ Web of Conferences 56, 01008 (2013)

19

INFLUENCE OF ALTERNATIVE BINDERS

- 3% CO_2, 55% RH i 25°C



Serdar, M.; Husnjak, D.; Matić, D.; Šajna, A. Carbonation induced changes in durability properties of blended cement mortars, Proceedings of the 4th International Conference on Service Life Design for Infrastructures (SLD4), Delft: RILEM Publications S.A.R.L., 2018, 59-67

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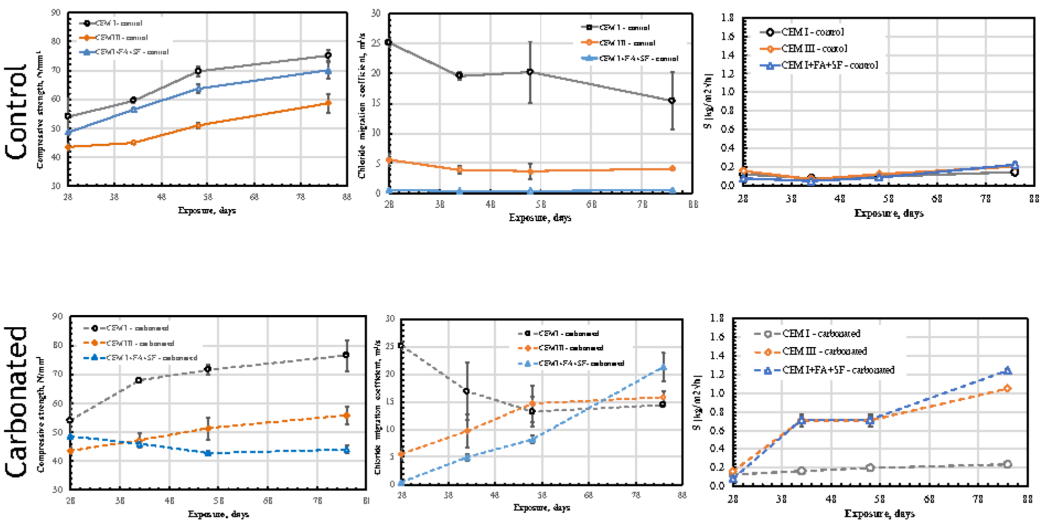
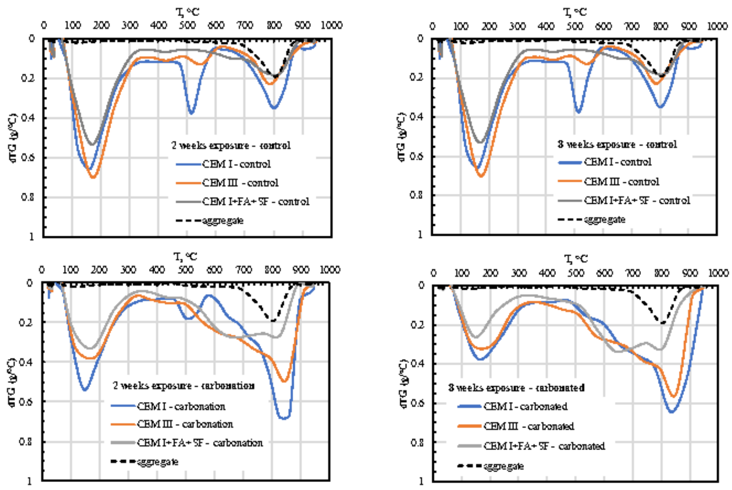
Effect on engineering properties



- Serdar, M.; Husnjak, D.; Matić, D.; Šajna, A. Carbonation induced changes in durability properties of blended cement mortars, Proceedings of the 4th International Conference on Service Life Design for Infrastructures (SLD4), Delft: RILEM Publications S.A.R.L., 2018, 59-67

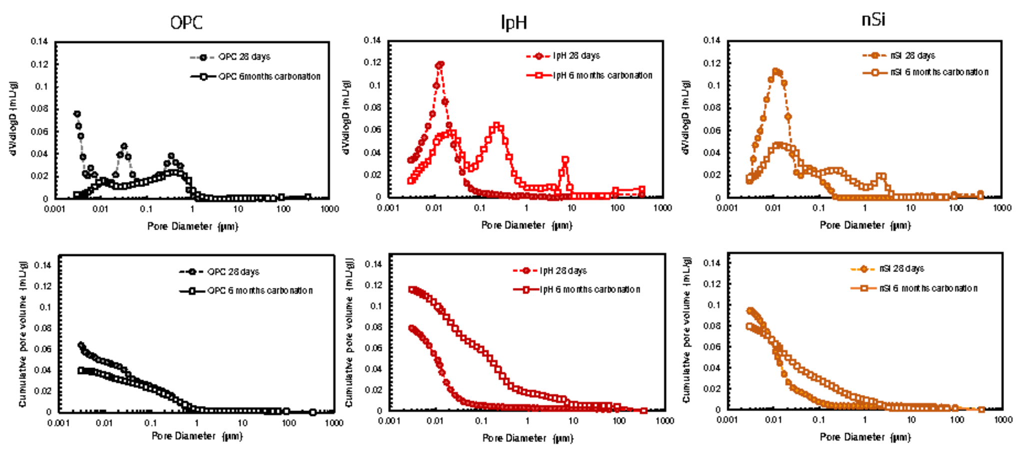
Effect on microstructure



Serdar, M.; Husnjak, D.; Matić, D.; Šajna, A. Carbonation induced changes in durability properties of blended cement mortars, Proceedings of the 4th International Conference on Service Life Design for Infrastructures (SLD4), Delft: RILEM Publications S.A.R.L., 2018, 59-67

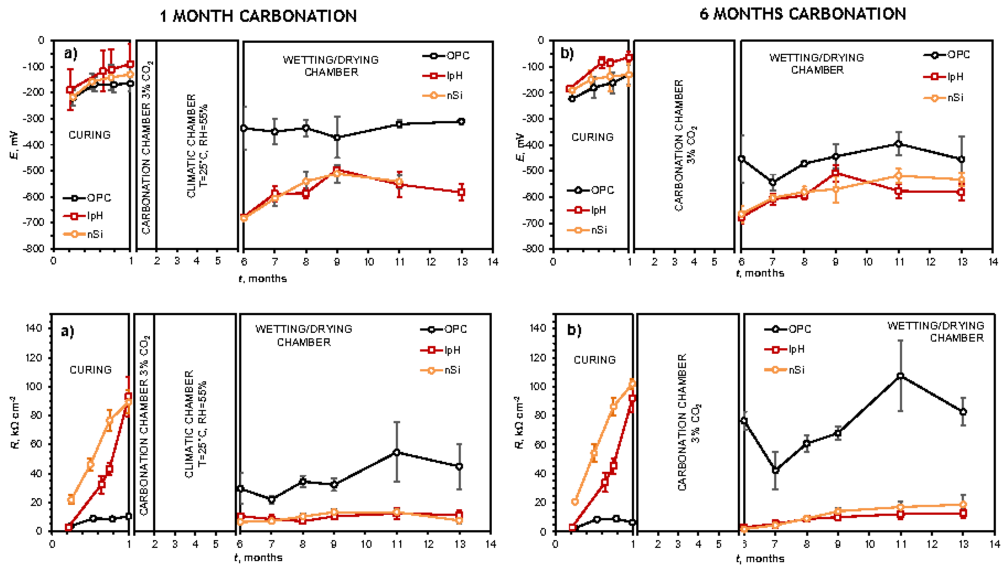
22

Effect on microstructure



Serdar, M.; Poyet, S.; L'Hostis, V.; Bjegović, D. Carbonation of low-alkalinity mortars: Influence on corrosion of steel and on mortar microstructure // Cement and concrete research : including Advanced cement based materials, 101 (2017), 33-45

Effect on corrosion



Serdar, M.; Poyet, S.; L'Hostis, V.; Bjegović, D. Carbonation of low-alkalinity mortars: Influence on corrosion of steel and on mortar microstructure // Cement and concrete research : including Advanced cement based materials, 101 (2017), 33-45

Challanges remain

- Natural vs accelerated carbonation
- Influence on microstructure and engineering properties
- Pre-exposure advantage – post-exposure disadvantage?

$$x = \sqrt{\frac{2Dc}{a}} \times \sqrt{t}$$

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t}\right)^{m}$$ → aging factor for chloride diffusion

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5. Introduction to sustainable development in the built environment

Guillaume Habert

This chapter presents sustainable development goals, starting at a global level and reflecting further on this at the level of the built environment. A discussion is provided on issues typically associated in dealing with sustainability indicators, as well as how they are influenced by the uncertainty on the service life of construction materials.

A video recording with further explanation is provided here (20 minutes to watch).

ETH zürich

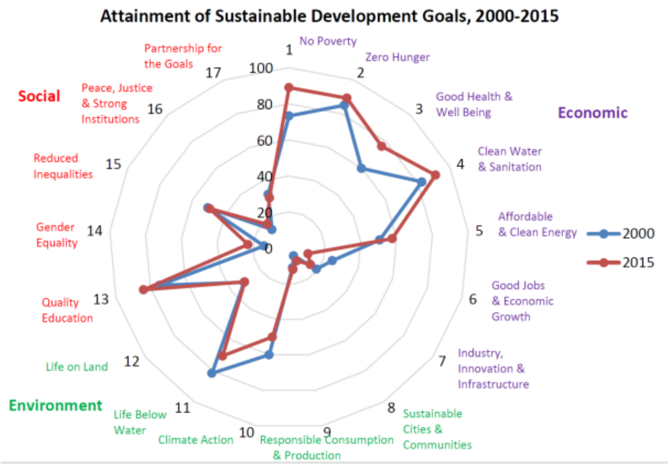
SDGs

1987 1992 2000 2012

ETH zürich

SDGs

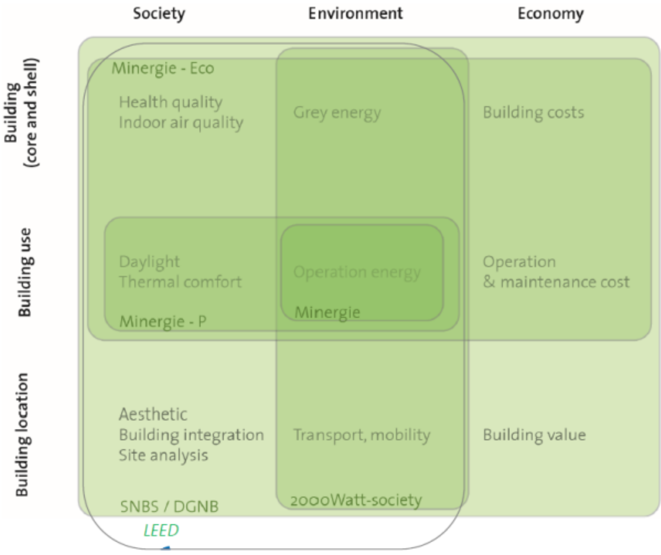
The 17 Sustainable Development Goals positioned in relation to the biosphere foundation and the safe operating space for humans on Earth. Rockström and Sukhdev (2014)



Barbier and Burgess. 2017. The Sustainable development goals and the systems approach to sustainability. Economics, 11.

ETHzürich

SDGs for buildings = Sustainability labels



Alina Galimshina 29.10.2019 71

ETHzürich

SDGs for buildings = Sustainability labels

We measure what we care about

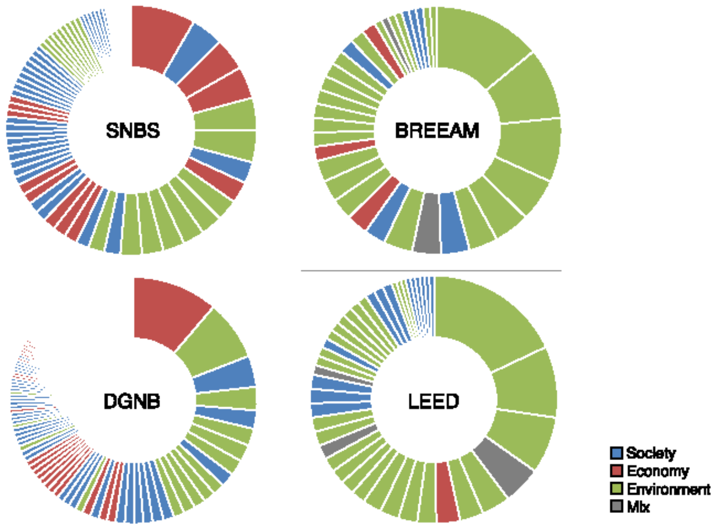
We care about what we measure

| 15.09.2020 | 7

ETH zürich

SDGs for buildings = Sustainability labels

Identify driving criteria



Sce: S. Breit, T. Peters, D. Petrovic, K. Stankiewicz, Building labels, *WISBA2014*.

ETH zürich

Sustainable indicators… attempt to muddy the water

Attempt to muddy the water

n°	Indicators used in EN 15-8054	Units
	Environmental impact indicator	
1	Global warming potential	kg CO_2 eq.
2	Ozone layer depletion	kg CFC-11 eq.
3	Acidification	kg SO_2 eq.
4	Eutrophication	kg PO_4^{-} eq.
5	Photochemical oxydation	kg C_2H_4 eq.
6	Abiotic depletion for non fossil resources (ADP-elements)	kg Sb eq.
7	Abiotic depletion for fossil resources (ADP-fossil fuels)	MJ
	Resource Use indicator	
8	Use of renewable primary energy *excluding renewable primary energy resources used as raw materials*	MJ
9	Use of renewable primary energy resources used as raw materials	MJ
10	Use of non renewable primary energy *excluding non renewable primary energy resources used as raw materials*	MJ
11	Use of non renewable primary energy resources used as raw materials	MJ
12	Use of secondary materials	kg
13	Use of renewable secondary fuels	MJ
14	Use of non-renewable secondary fuels	MJ
15	Use of net fresh water	m^3
	Waste category indicator	
16	Hazardous waste disposed	kg
17	Non hazardous waste disposed	kg
18	Radioactive waste disposed	kg
	Output flow indicators	
19	Components for re-use	kg
20	Materials for recycling	kg
21	Materials for energy recovery	kg
22	Exported energy	MJ

Other indicators in near future

GWP from fossil carbon
GWP from biogenic carbon
GWP from land use and transformation

Eutrophication aquatic fresh water
Eutrophication aquatic marine

Human toxicity, cancer effect
Human toxicity, non cancer effect
Land use related impacts
Particulate matter emissions
Ionizing radiation
Water scarcity
...

Too many indicators are hiding the main message
Too many information is confusing

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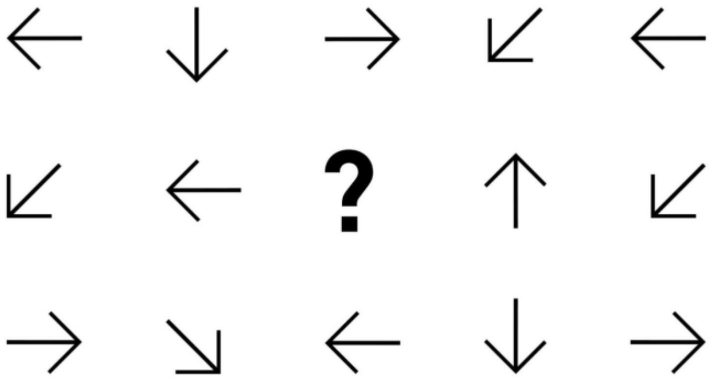
Sustainable indicators… attempt to muddy the water

Attempt to muddy the water



When more information is too much information

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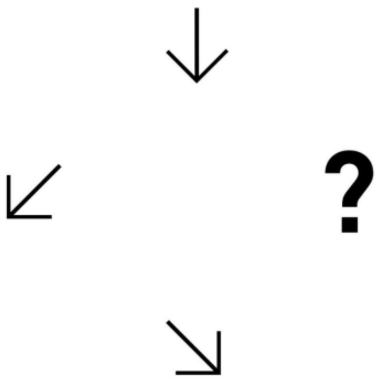
Sustainable indicators… attempt to muddy the water

Attempt to muddy the water

Need for simplification



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Sustainable indicators… attempt to muddy the water

Attempt to muddy the water

Accept the intangible

↓

↙

And try to understand the underlying physical concepts…

↘

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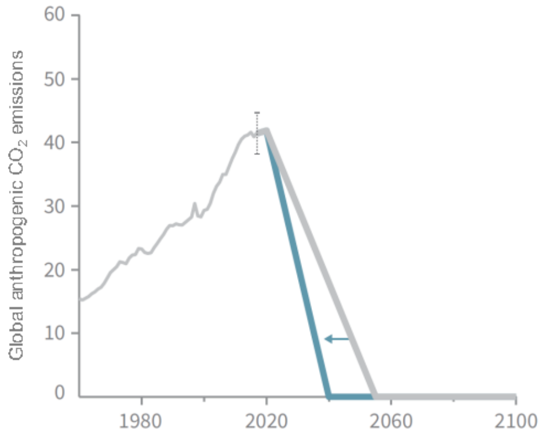
One emergency

One lens

Devide CO_2 emissions by 50% in the next 10 years and reach net Zero in 2040



Sce: IPCC. 2019. 1.5°C report

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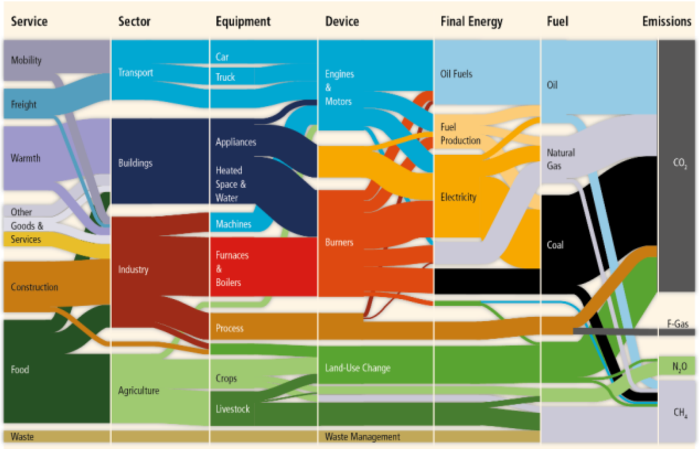
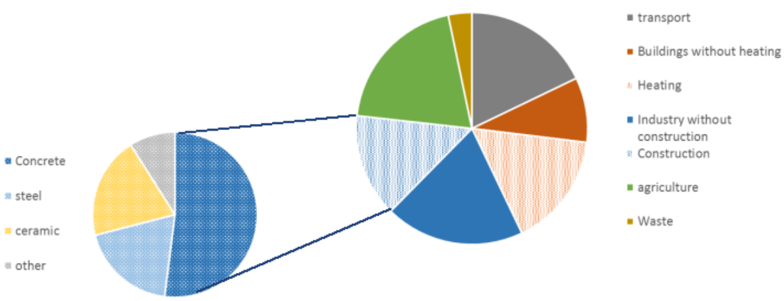
Where to act ?



Construction and operation of building have a similar and significant share on GHG emissions

Sce: Bajželj B., Allwood J.M., Cullen J.M. 2013. Designing Climate Change Mitigation Plans That Add Up. *Environmental Science & Technology*, 47, 8062 – 8069.

Materials matter



Sce: Bribián et al. 2011. *Building and environment*, 46, 1133-1140.

Sce: Bajželj et al. 2013. *Environmental Science & Technology*, 47, 8062 – 8069.

Construction, operation and mobility = 50% of all human activities
Construction in emerging countries, operation in developed countries

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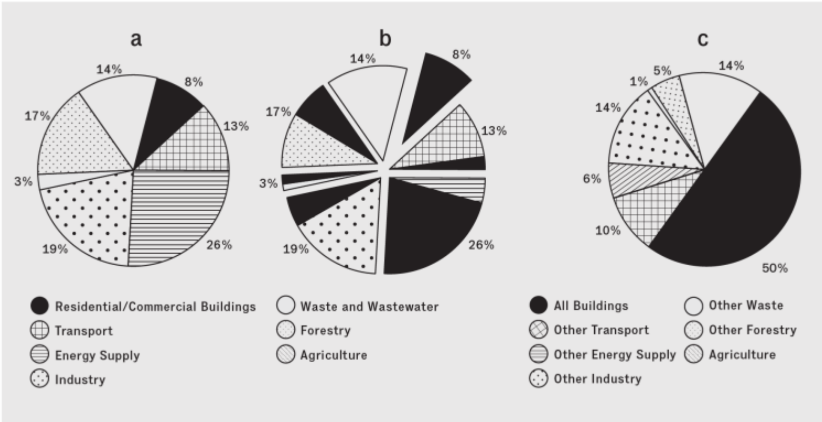
Share of buildings and construction sector in emissions… around 50% ?



Percentage of global CO_2 emissions attributed to residential and commercial buildings by the IPCC (a), CO_2 emissions in other sectors indirectly related to the building sector (b), and an estimate of the overall percentage of CO_2 emissions from buildings for both direct and indirect sources (c).

Image source: Forrest Meggers et al., "Reduce CO_2 from buildings with technology to zero emissions," *Sustainable Cities and Society* 2, no. 1 (2012): 30; redrawn by Something Fantastic.

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Share of construction sector in emissions with no double counting

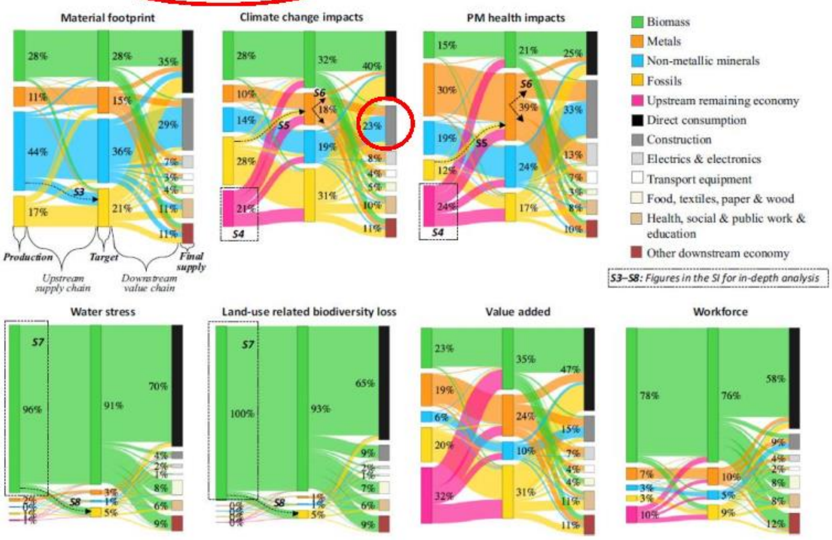

Fig. 2. Sectoral shares and linkages of the global material supply chain and the related environmental impacts and socio-economic benefits from production (left bar), target (middle bar), and final supply perspective (right bar, Reference year: 2011). Note that the category '*direct consumption*' refers to materials directly consumed by the final demand and that the other categories of the final supply perspective refer to materials used by the remaining economy (non-target sectors). Further in-depth analysis of the marked sectors and flows are shown in the SI (Figs. S3–S8).

Sce: Cabernard L., Pfister S., Hellweg S. 2019. A new method for analyzing sustainability performance of global supply chains and its application to material resources. *Science of Total environment*

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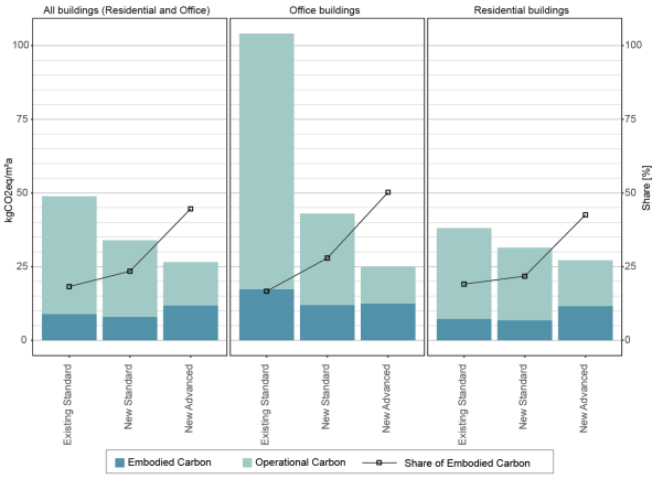
We have made progress for heating buildings
We made NO significant progress for building them



Sce: Röck M., Mendes Saade M.R., Balouktsi M., Rasmussen F.N., Birgisdottir H., Frischknecht R., Habert G., Lützkendorf T., Passer A. 2019. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied energy.*

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Considering the life cycle of one building,
What matter are the structural materials

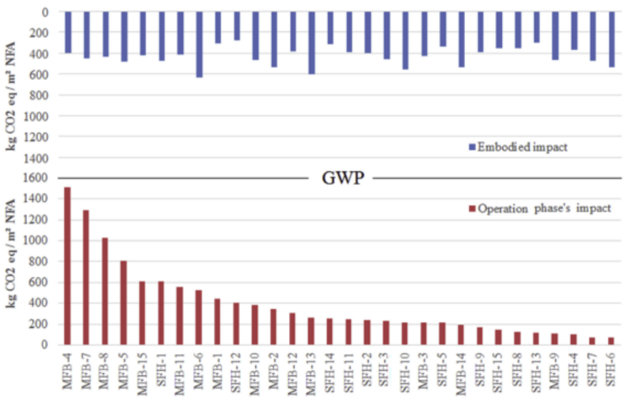

Fig. 6. Variation of the impacts of materials and exploitation phase for the NRE and GWP indicators.

No correlation between embodied and operation energy

Sce: 30 new construction (multifamily and single family houses)
Hoxha et al, 2017. Journal of cleaner production

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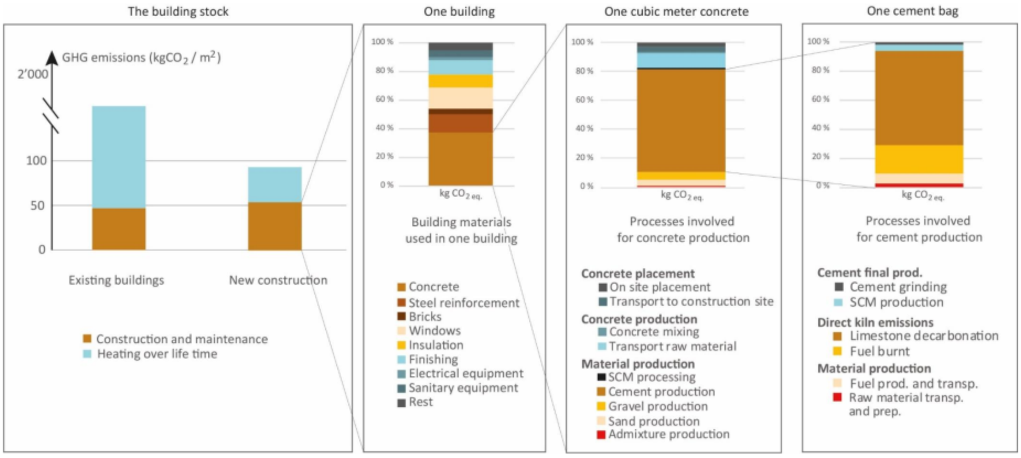
Considering the life cycle of one building, What matters are the structural materials



Concrete is the main responsible of CO_2 emissions in Buildings.
It comes from cement production.
Mainly from limestone decomposition

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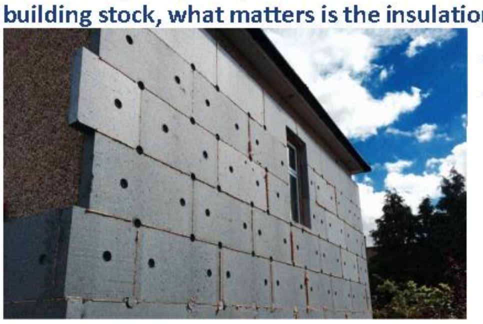
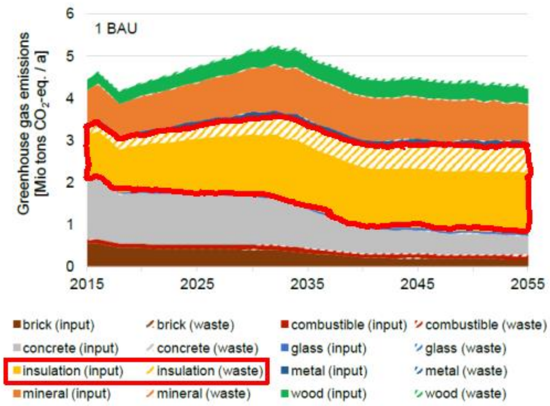
Considering the yearly emissions related with the construction activities on the European building stock, what matters is the insulation materials.. *(because we renovate more than we build new construction)*



We currently use fossil based insulation which will contribute significantly to CO_2 emissions



Sce: Heeren & Hellweg. 2019. Tracking Construction Material over Space and Time: Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows. *Journal of Industrial ecology*

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Summary:

Global South:

Embodied energy is the most important aspect

(no need for heating and cooling and electricity is greener and greener)

Structural materials are key.

(Need low carbon and very widely available)

Europe:

Existing buildings are the main CO_2 emitters

(Comes from low energy performance building – high operation energy required)

Insulation materials are the main responsible for emission from construction

(Need low carbon and very widely available)

USA:

Another story…

Building with high turnover, construction and operation are important…

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2- Lessons from COVID

The last 'normal' photo on your phone

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Lessons from COVID

The more you wait to engage the transition the more painful (and costly) it is do it…
(because you anyway need to do it at one point).

Crisis is an accelerator for the use and implementation of new technologies, but you barely have time to develop something from scratch.

There is no magic in here.
All available solutions are there, it’s just a question on when do you implement them. Waiting for the ultimate ground breaking solution is deadly.

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Lessons from COVID

It’s the same for climate change and the Resources for the built environment.
All is here, we just need the willingness (or the fear pressure) to implement them.

But which pathway do we decide to walk down?
Constraining or aspiring?

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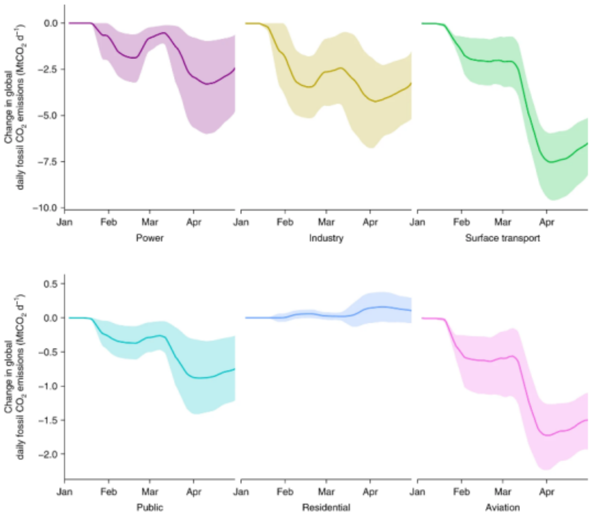
Fig. 4: Change in global daily fossil CO_2 emissions by sector ($MtCO_2$ d^{-1}).

From: Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement



Sce: Le Quéré, C., Jackson, R.B., Jones, M.W. et al. 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nature Climate Change. https://doi.org/10.1038/s41558-020-0797-x

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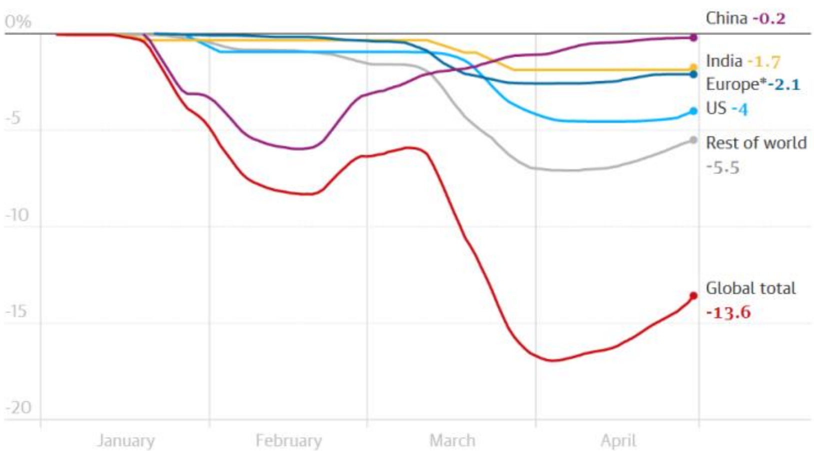
Daily global fossil CO2 emissions fell by 17% in early April 2020 compared with 2019

% change in global daily fossil CO2 emissions attributed to each country or region



Guardian graphic. Source: Nature Climate Change. Note: Europe = EU27 plus UK

Sce: Le Quéré, C., Jackson, R.B., Jones, M.W. et al. 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nature Climate Change. https://doi.org/10.1038/s41558-020-0797-x

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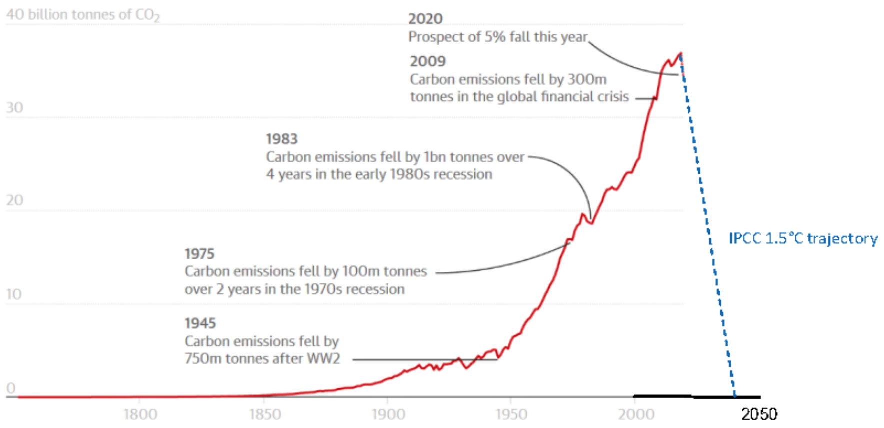
Lessons from COVID

The coronavirus pandemic could result in a 5% fall in global carbon emissions



Guardian graphic. Source: Global Carbon Project (GCP), Carbon Dioxide Information Analysis Center (CDIAC)

We're on the right trajectory to reach the target, but do we want to walk down that path?
(meaning next year 4 months of lock down and not 2, etc...)
Or do we develop other societal model? *(social justice, thriving society...)*

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Uncertainties related with service life

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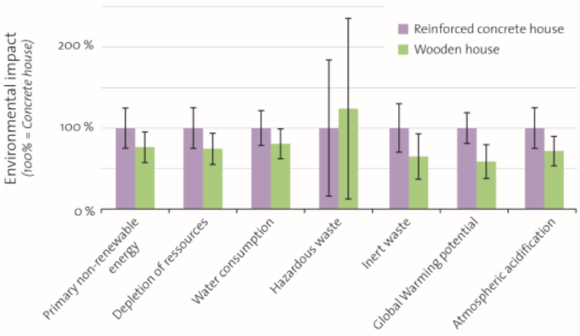
Uncertainty on material's service life

Comparison between two projects

Take into consideration uncertainties on:
- process efficiency between industrial plants
- Effective service life of building materials



Need to know which materials are causing this uncertainty

Sce: Hoxha et al. 2014. Method to analyse the contribution of material's sensitivity in buildings' environmental impact. *Journal of Cleaner Production*, 66, 54-64.

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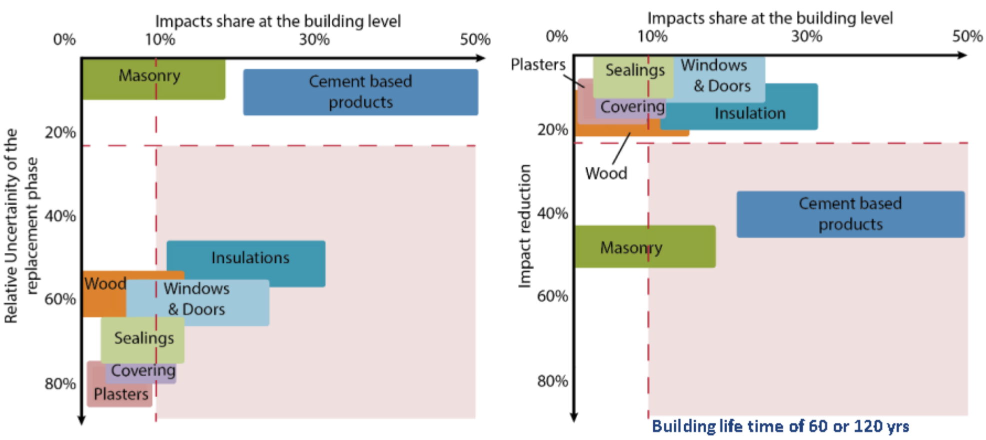
Uncertainty on material's service life

Contribution of materials to total impact and total uncertainties

considering uncertainty on material service life **considering uncertainty on Building service life**



Sce: Häfliger et al. 2017. Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. *Journal of Cleaner Production*. 156, 805-816.

02-05th Sept.

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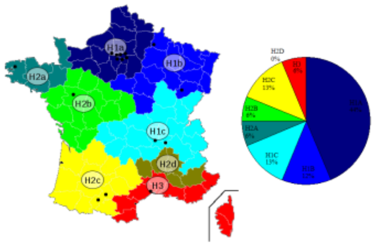
Uncertainty on material's service life



Sce: Hoxha et al. 2017. Influence of construction material uncertainties on residential building LCA reliability. Journal of Cleaner Production, 144, 33-47

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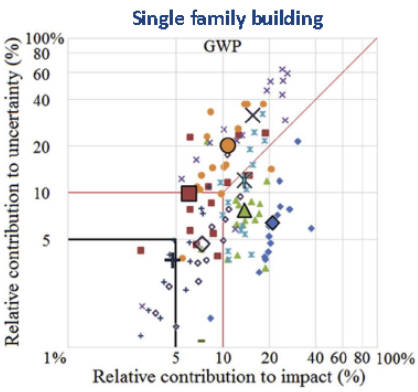
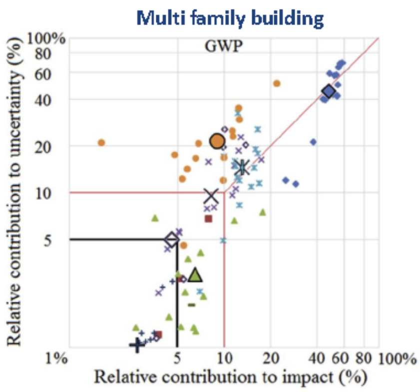
Uncertainty on material's service life





♦ Structure (steel & concrete) ■ Other structural elements (brick, blocks, wood) ▲ Non structural elements × Insulation
× Openings (windows & doors) ● Finishing (peinture/carrelage) + Electrical equipment ▪ Sanitary equipment
– Energy equipment ◇ Rest ○ Contoured with black (averages)

→ Concrete have large contribution to impact
→ Insulation material have large contribution on uncertainties

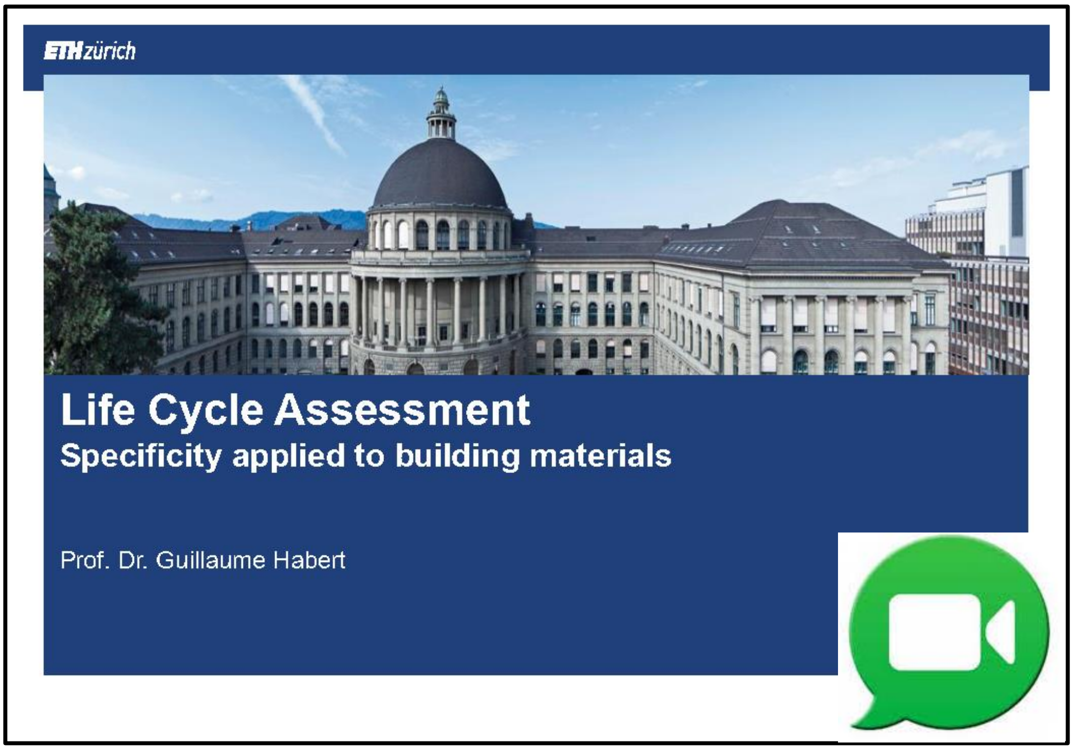
Sce: Hoxha et al. 2017. Influence of construction material uncertainties on residential building LCA reliability. Journal of Cleaner Production, 144, 33-47

6. Life cycle assessment applied to building materials

Guillaume Habert

Life cycle assessment is presented as a method to evaluate the environmental impact of building materials. Amongst other, the importance of the considered functional unit is highlighted, as well as allocation methods.

A video recording with further explanation is provided here (30 minutes to watch).



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LCA methodology

I. Grey energy

II. LCA theory

III. LCA Challenges

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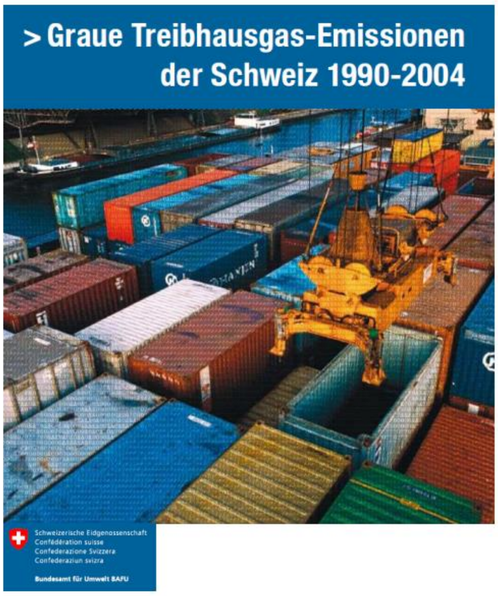
Grey energy

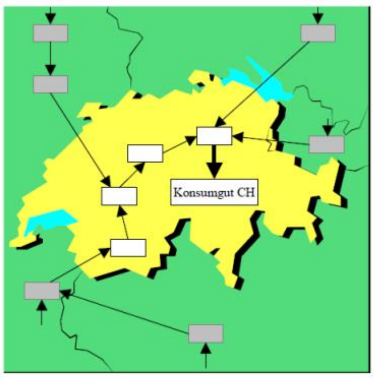
Imported energy



See: Jungbluth et al., 2007. Graue Treibhausgas-Emissionen der Schweiz 1990–2004. Umwelt-Wissen Nr. UW-0711. BAFU.

Abb. 1 > Unterscheidung zwischen «weissen» und «grauen» Emissionen: Konsum in der Schweiz.

Die bei der Herstellung eines Konsumgutes in der Schweiz anfallenden Emissionen werden als weisse, diejenigen die im Ausland anfallen als graue Emissionen bezeichnet.



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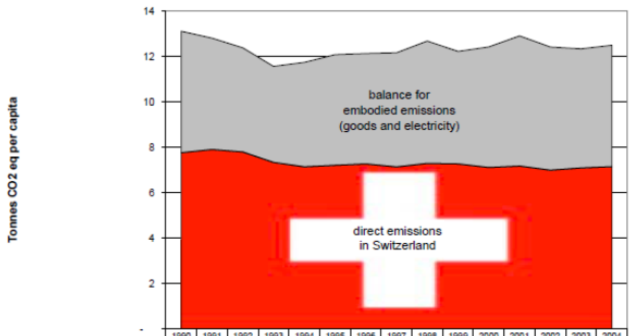
Grey energy
Imported energy

Fig. B > Development of direct and embodied greenhouse gas emissions of Switzerland (tonnes CO_2 eq. per capita per year).

Direct per capita emissions of the inhabitants of Switzerland have decreased somewhat since 1990 due to constant absolute emissions and a rise in the number of people living in Switzerland. When including the embodied emissions, no clear trend of per capita emissions is visible. Embodied emissions of the services sector are not included in this graph.



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
total of direct and embodied emissions	13.1	12.8	12.4	11.6	11.8	12.1	12.1	12.2	12.7	12.2	12.4	12.9	12.4	12.3	12.5
balance for goods and electricity	5.4	4.9	4.6	4.2	4.6	4.9	4.9	5.0	5.4	5.0	5.3	5.7	5.4	5.3	5.4
direct emissions of Switzerland	7.8	7.9	7.8	7.3	7.1	7.2	7.3	7.1	7.3	7.3	7.1	7.2	7.0	7.1	7.2

Source: Calculations ESU-services GmbH.

Sce: Jungbluth et al., 2007. Graue Treibhausgas-Emissionen der Schweiz 1990–2004. Umwelt-Wissen Nr. UW-0711. BAFU.

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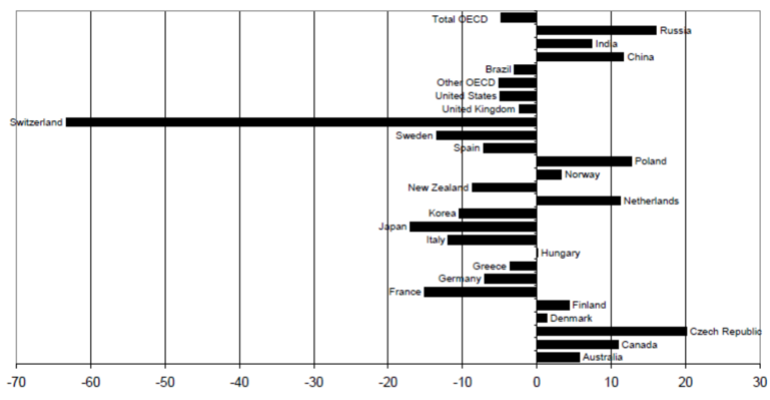
Grey energy
Imported energy

Abb. 31 > Handelsbilanz der CO_2-Emissionen im Jahr 1995 – Prozentanteil an den Inland-Emissionen für OECD-Länder.



Quelle: (Ahmad & Wyckoff 2003: Figure 1, Eigene Berechnungen für die Schweiz)

Sce: Jungbluth et al., 2007. Graue Treibhausgas-Emissionen der Schweiz 1990–2004. Umwelt-Wissen Nr. UW-0711. BAFU.

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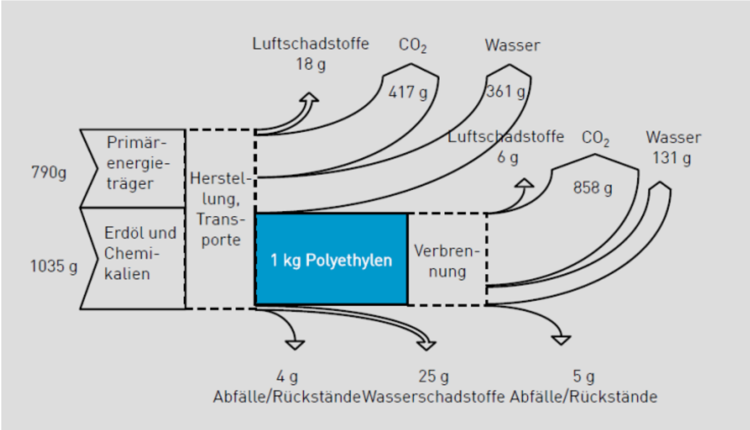
Grey energy
Energy used before or after



See: Graue energie von Baustoffe, 1995, BAFU

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Grey energy
Energy indirectly linked with the use of a product

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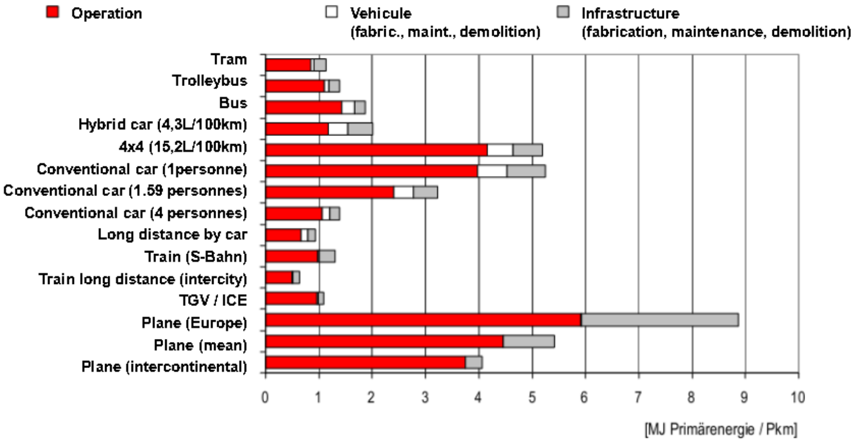
Grey energy

Energy indirectly linked with the use of a product



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LCA

A Method

Life Cycle Analysis (LCA)

Part I : Theory

Part II: Challenges

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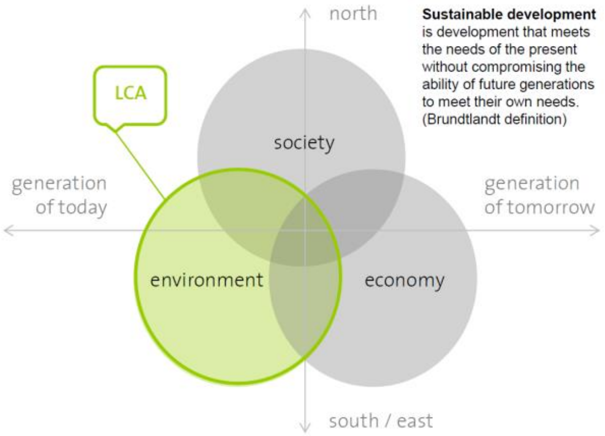

Sce: V. John, 2012. *Derivation of reliable simplification strategies for the comparative LCA of individual and "typical" newly built Swiss apartment buildings. Diss. ETH n° 20608*

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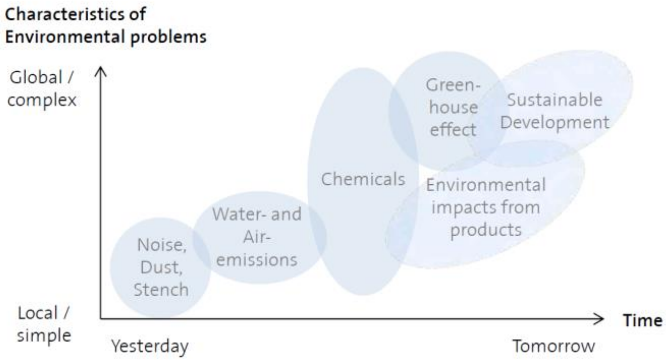
ETH zürich **LCA**



Sce: V. John, 2012. *Derivation of reliable simplification strategies for the comparative LCA of individual and "typical" newly built Swiss apartment buildings. Diss. ETH n° 20608*

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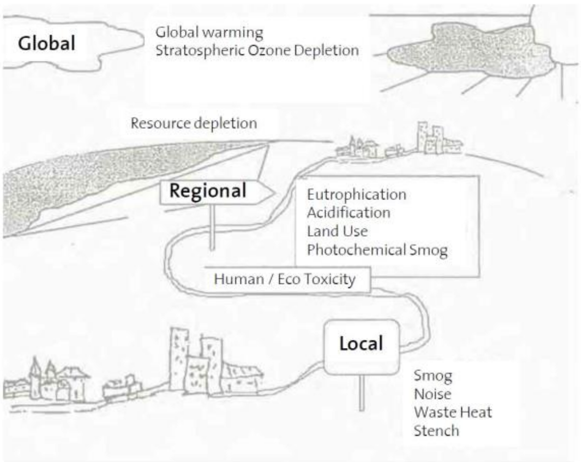
ETHzürich **LCA**



See: V. John, 2012. *Derivation of reliable simplification strategies for the comparative LCA of individual and "typical" newly built Swiss apartment buildings. Diss. ETH n° 20608*

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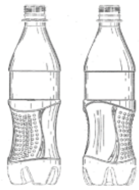
ETHzürich **LCA**



History

- Energy flow analysis
  - *H. Teasley (1969) Packaging of Coca Cola bottles (Plastic vs glass)*
- Complexification (Europe, USA) : Materials and emission flows.
- Applied to industry
- Acceleration in 1990 :
  - Working group : SETAC…
  - Scientific part : CML (Institute for Environmental Science, University of Leiden)
- international standards ISO 14040 à 14044 (2006)

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LCA

Life time

Coca Cola bottle = 1 year **House = 50 year**

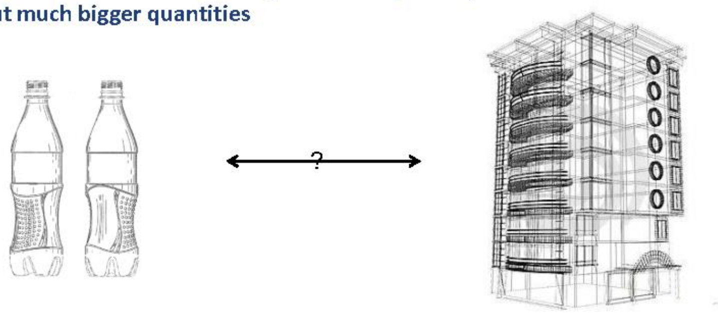
Not the same technology for recycling when it is built and destroyed
Different ratio between production and use

Impacts

Not so dangerous

except specific case such as Asbestos
Structural materials = a few easy to calculate impacts CO2, acidification...

But much bigger quantities



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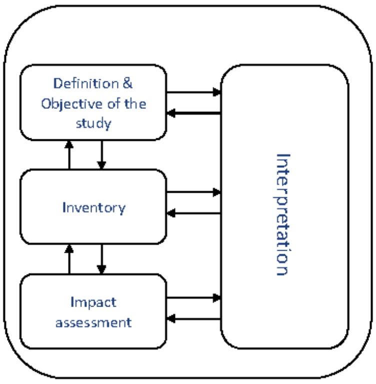
LCA

LCA by the ISO 14040

Boundaries of the system
Functional unit

Data collection
Life Cycle Inventory

Choose environmental impacts
Impact Assessment



ISO 14040

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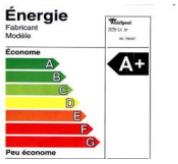
LCA
Functional Unit

Comparison of two fridge



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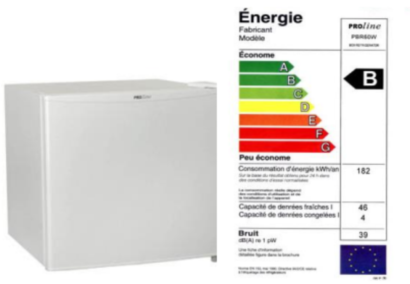
LCA
Functional Unit

Comparison of two fridge



Choice of Functional Unit

FU = 1m^3 cooled

A+ << B

FU = 1 fridge per household

401 kWh/yr >> 182 kWh/yr

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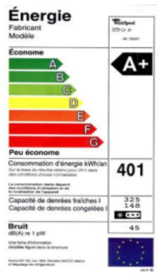
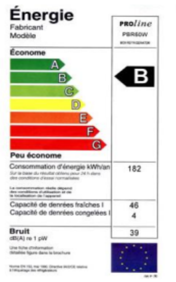
LCA
Functional Unit

Comparison of two fridge





Here, energy is only the energy for operation and not for the fabrication and dismanteling of the fridge.

LCA is usually from Cradle to Grave

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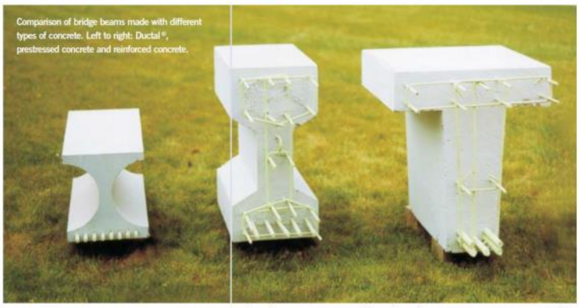
LCA
Functional Unit

Functional unit
The two products that we want to compare need to fulfill the same function.



[Lafarge, Sustainable development report, 2006]

Results for 1 m^3 of concrete are different than for 1 linear meter of beam

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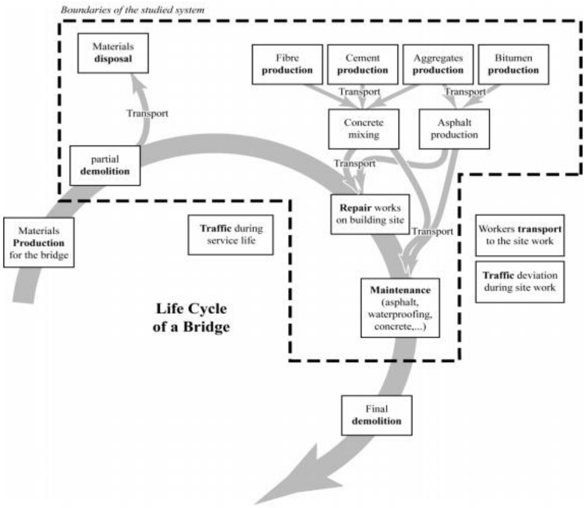
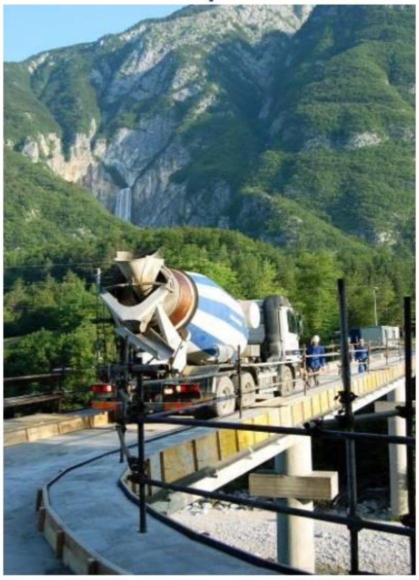
System boundaries





Sce: Habert et al. 2013. Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cement and Concrete Composites*, 38, 1-11.

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LCA
System boundaries

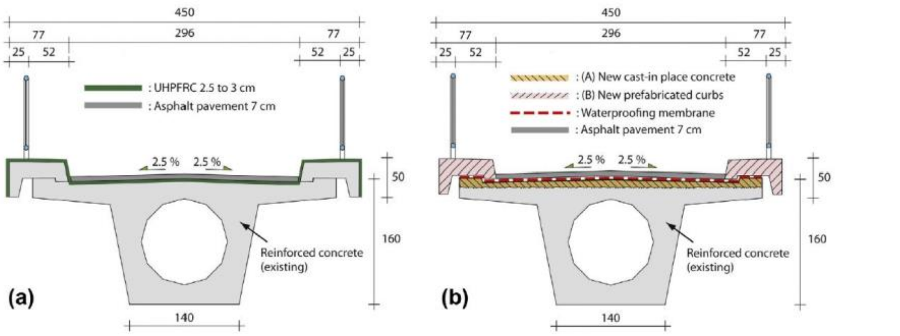

Fig. 3. Rehabilitation systems. (a) Concept of application of the local "hardening" of bridge superstructures with UHPFRC; (b) traditional rehabilitation systems using conventional concrete (C30/37) and a waterproofing membrane.

Sce: Habert et al. 2013. Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cement and Concrete Composites*, 38, 1-11.

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System boundaries

Table 2
Materials mix design. Mix design for traditional concrete were calculated using BetonlabPro software [29].

UHPFRC rehabilitation system					Traditional rehabilitation system		
Material	UHPFRC		Eco UHPFRC		Material	Concrete C30/37	
Components	Quantity (kg.m^{-3})	Distance (km)	Quantity (kg.m^{-3})	Distance (km)	Components	Quantity (kg.m^{-3})	Distance (km)
Cement	1434	950	763	55	Cement	385	55
Limestone filler			763	188	Sand	690	35
Micro sand	80	1100			Gravel	1060	35
Microsilica	373	1000	153	1000	Water	185	
Steel fibers[a]	707	760	707	760	Super plasticiser	4.9	10
Water	189		224		Steel rebars	80	150
Superplasticiser[a]	47.5	10	55	10	Bitumen sealing	27.6	250
For comparison					For comparison		
Superplaticiser[a] (wt.% of cement + limestone filler)	3.3%		3.6%		Superplaticiser[a] (wt.% of cement + limestone filler)	1.3%	

[a] Total = liquid + dry extract.

Sce: Habert et al. 2013. Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cement and Concrete Composites*, 38, 1-11.

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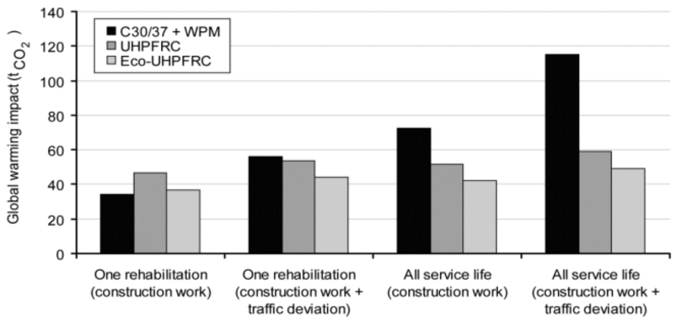
System boundaries

UHPFRC reduces road interruption.
And it is more important than the reduction in the concrete volume used (for CO2 aspects)



A rigorous scientific approach is needed:
Hypothesis / Data & method / Results / Discussion

Sce: Habert et al. 2013. Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cement and Concrete Composites*, 38, 1-11.

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Inventory

Need to gather environmental data for all processes involved inside system boundaries

Life cycle inventory data sources:

- Professional life cycle inventory databases (e.g. Ecoinvent database http://www.ecoinvent.ch/)
- Open source inventory lists / databases (e.g. KBOB list http://www.eco-bau.ch/resources/uploads/KBOB_EMPFEHLUNG_2009_1_Juli_2012.pdf)
- Environmental Product Declarations type III (EPDs)
- Individual primary data

High data quality

Low data quality

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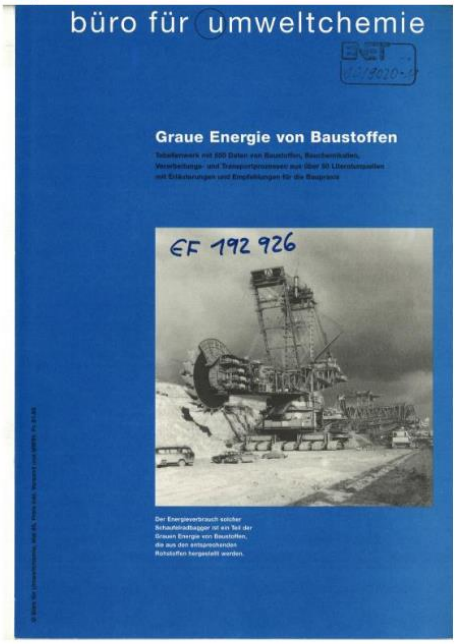
Different database



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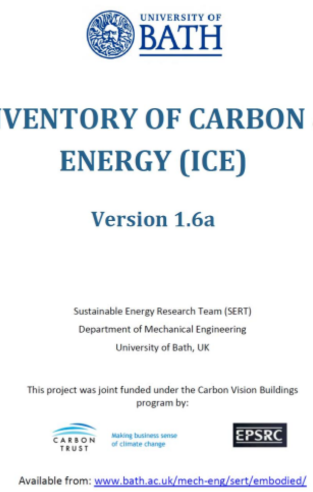
Different database: ICE



UNIVERSITY OF BATH

INVENTORY OF CARBON & ENERGY (ICE)

Version 1.6a

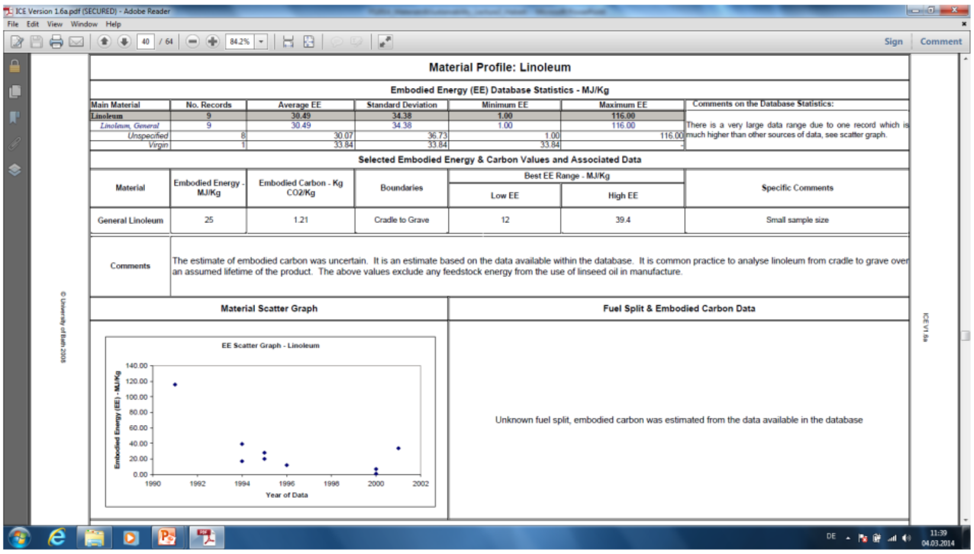
Sustainable Energy Research Team (SERT)
Department of Mechanical Engineering
University of Bath, UK

This project was joint funded under the Carbon Vision Buildings program by:

CARBON TRUST Making business sense of climate change   EPSRC

Available from: www.bath.ac.uk/mech-eng/sert/embodied/

Different database: ICE



Material Profile: Linoleum

Embodied Energy (EE) Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Linoleum	**9**	**30.49**	**34.38**	**1.00**	**116.00**	There is a very large data range due to one record which is much higher than other sources of data, see scatter graph.
Linoleum, General	9	30.49	34.38	1.00	116.00	
Unspecified	8	30.07	36.73	1.00	116.00	
Virgin	1	33.84	33.84	33.84	-	

Selected Embodied Energy & Carbon Values and Associated Data

Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2/Kg	Boundaries	Best EE Range - MJ/Kg		Specific Comments
				Low EE	High EE	
General Linoleum	25	1.21	Cradle to Grave	12	39.4	Small sample size

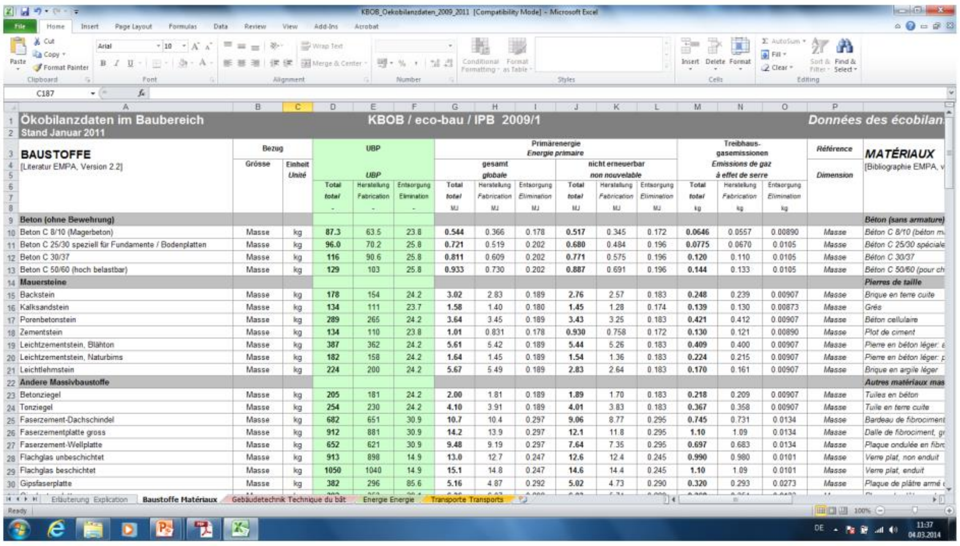
Comments: The estimate of embodied carbon was uncertain. It is an estimate based on the data available within the database. It is common practice to analyse linoleum from cradle to grave over an assumed lifetime of the product. The above values exclude any feedstock energy from the use of linseed oil in manufacture.

Material Scatter Graph

Fuel Split & Embodied Carbon Data

Unknown fuel split, embodied carbon was estimated from the data available in the database

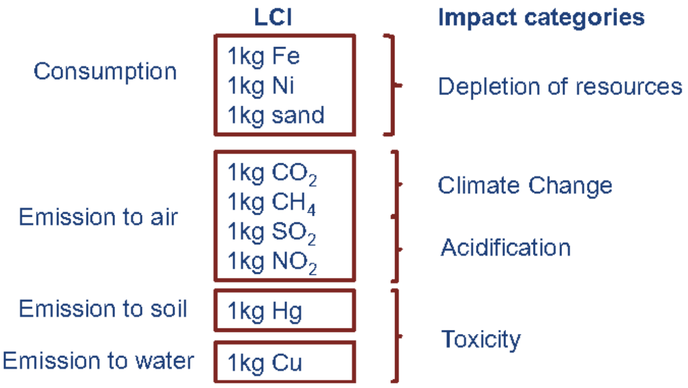
Different database: KBOB



Ökobilanzdaten im Baubereich, Stand Januar 2011 — BAUSTOFFE [Literatur EMPA, Version 2.2]	Bezug: Grösse	Bezug: Einheit *Unité*	UBP Total *total* -	UBP Herstellung *Fabrication* -	UBP Entsorgung *Elimination* -	Primärenergie *Energie primaire*, gesamt *globale*: Total *total* MJ	gesamt: Herstellung *Fabrication* MJ	gesamt: Entsorgung *Elimination* MJ	nicht erneuerbar *non nouvelable*: Total *total* MJ	nicht erneuerbar: Herstellung *Fabrication* MJ	nicht erneuerbar: Entsorgung *Elimination* MJ	Treibhausgasemissionen *Emissions de gaz à effet de serre*: Total *total* kg	Herstellung *Fabrication* kg	Entsorgung *Elimination* kg	*Référence* *Dimension*	*MATÉRIAUX* [Bibliographie EMPA, v
Beton (ohne Bewehrung)																***Béton (sans armature)***
Beton C 8/10 (Magerbeton)	Masse	kg	**87.3**	63.5	23.8	**0.544**	0.366	0.178	**0.517**	0.345	0.172	**0.0646**	0.0557	0.00890	*Masse*	*Béton C 8/10 (béton m*
Beton C 25/30 speziell für Fundamente / Bodenplatten	Masse	kg	**96.0**	70.2	25.8	**0.721**	0.519	0.202	**0.680**	0.484	0.196	**0.0775**	0.0670	0.0105	*Masse*	*Béton C 25/30 spéciale*
Beton C 30/37	Masse	kg	**116**	90.6	25.8	**0.811**	0.609	0.202	**0.771**	0.575	0.196	**0.120**	0.110	0.0105	*Masse*	*Béton C 30/37*
Beton C 50/60 (hoch belastbar)	Masse	kg	**129**	103	25.8	**0.933**	0.730	0.202	**0.887**	0.691	0.196	**0.144**	0.133	0.0105	*Masse*	*Béton C 50/60 (pour ch*
Mauersteine																***Pierres de taille***
Backstein	Masse	kg	**178**	154	24.2	**3.02**	2.83	0.189	**2.76**	2.57	0.183	**0.248**	0.239	0.00907	*Masse*	*Brique en terre cuite*
Kalksandstein	Masse	kg	**134**	111	23.7	**1.58**	1.40	0.180	**1.45**	1.28	0.174	**0.139**	0.130	0.00873	*Masse*	*Grés*
Porenbetonstein	Masse	kg	**289**	265	24.2	**3.64**	3.45	0.189	**3.43**	3.25	0.183	**0.421**	0.412	0.00907	*Masse*	*Béton cellulaire*
Zementstein	Masse	kg	**134**	110	23.8	**1.01**	0.831	0.178	**0.930**	0.758	0.172	**0.130**	0.121	0.00890	*Masse*	*Plot de ciment*
Leichtzementstein, Blähton	Masse	kg	**387**	362	24.2	**5.61**	5.42	0.189	**5.44**	5.26	0.183	**0.409**	0.400	0.00907	*Masse*	*Pierre en béton léger: e*
Leichtzementstein, Naturbims	Masse	kg	**182**	158	24.2	**1.64**	1.45	0.189	**1.54**	1.36	0.183	**0.224**	0.215	0.00907	*Masse*	*Pierre en béton léger: p*
Leichtlehmstein	Masse	kg	**224**	200	24.2	**5.67**	5.49	0.189	**2.83**	2.64	0.183	**0.170**	0.161	0.00907	*Masse*	*Brique en argile léger*
Andere Massivbaustoffe																***Autres matériaux mas***
Betonziegel	Masse	kg	**205**	181	24.2	**2.00**	1.81	0.189	**1.89**	1.70	0.183	**0.218**	0.209	0.00907	*Masse*	*Tuiles en béton*
Tonziegel	Masse	kg	**254**	230	24.2	**4.10**	3.91	0.189	**4.01**	3.83	0.183	**0.367**	0.358	0.00907	*Masse*	*Tuile en terre cuite*
Faserzement-Dachschindel	Masse	kg	**682**	651	30.9	**10.7**	10.4	0.297	**9.06**	8.77	0.295	**0.745**	0.731	0.0134	*Masse*	*Bardeau de fibrociment*
Faserzementplatte gross	Masse	kg	**912**	881	30.9	**14.2**	13.9	0.297	**12.1**	11.8	0.295	**1.10**	1.09	0.0134	*Masse*	*Dalle de fibrociment, gr*
Faserzement-Wellplatte	Masse	kg	**652**	621	30.9	**9.48**	9.19	0.297	**7.64**	7.35	0.295	**0.697**	0.683	0.0134	*Masse*	*Plaque ondulée en fibr*
Flachglas unbeschichtet	Masse	kg	**913**	898	14.9	**13.0**	12.7	0.247	**12.6**	12.4	0.245	**0.990**	0.980	0.0101	*Masse*	*Verre plat, non enduit*
Flachglas beschichtet	Masse	kg	**1050**	1040	14.9	**15.1**	14.8	0.247	**14.6**	14.4	0.245	**1.10**	1.09	0.0101	*Masse*	*Verre plat, enduit*
Gipsfaserplatte	Masse	kg	**382**	296	85.6	**5.16**	4.87	0.292	**5.02**	4.73	0.290	**0.320**	0.293	0.0273	*Masse*	*Plaque de plâtre armé*

Impact calculation

LCI results is a long list with input and outputs
But no environmental relevance



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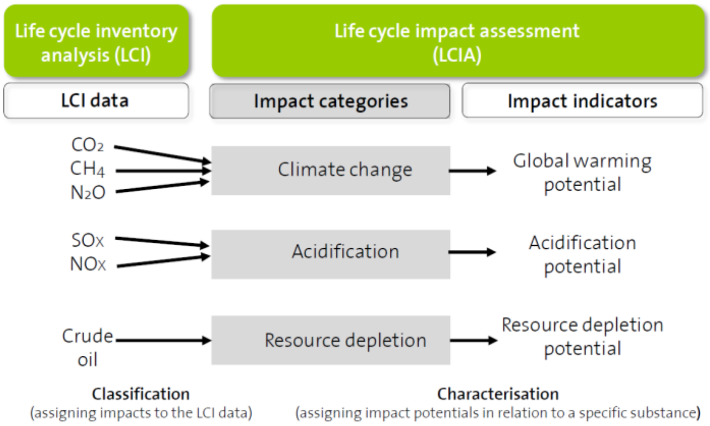
Impact calculation

LCI results is a long list with input and outputs
But no environmental relevance



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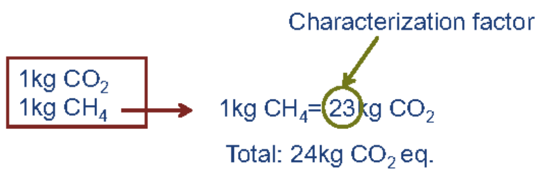
Impact calculation

LCI results is a long list with input and outputs
But no environmental relevance



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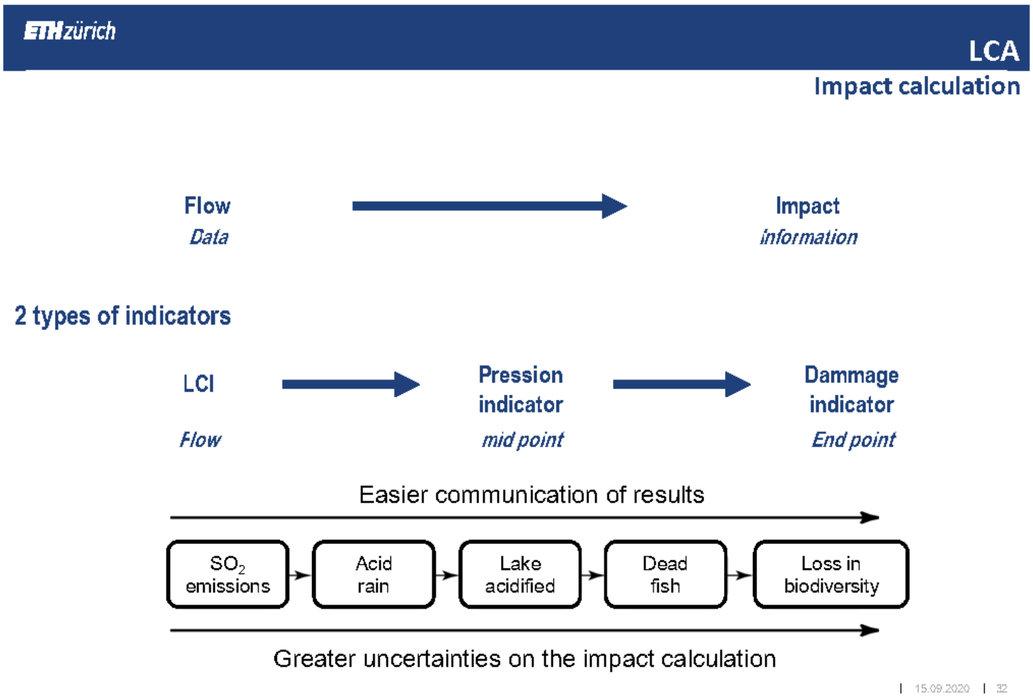
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LCA
Impact calculation
Flow
Data
Impact
information
2 types of indicators
LCI
Flow
Pression indicator
mid point
Dammage indicator
End point
Easier communication of results
SO_2 emissions
Acid rain
Lake acidified
Dead fish
Loss in biodiversity
Greater uncertainties on the impact calculation
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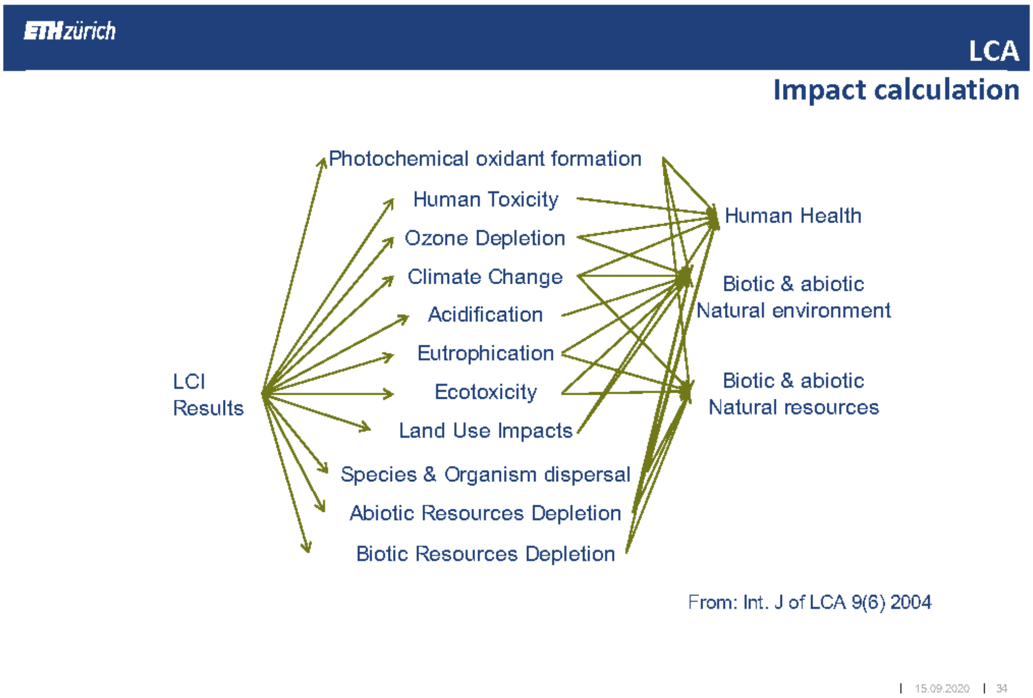
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LCA
Impact calculation
LCI Results
Photochemical oxidant formation
Human Toxicity
Ozone Depletion
Climate Change
Acidification
Eutrophication
Ecotoxicity
Land Use Impacts
Species & Organism dispersal
Abiotic Resources Depletion
Biotic Resources Depletion
Human Health
Biotic & abiotic Natural environment
Biotic & abiotic Natural resources
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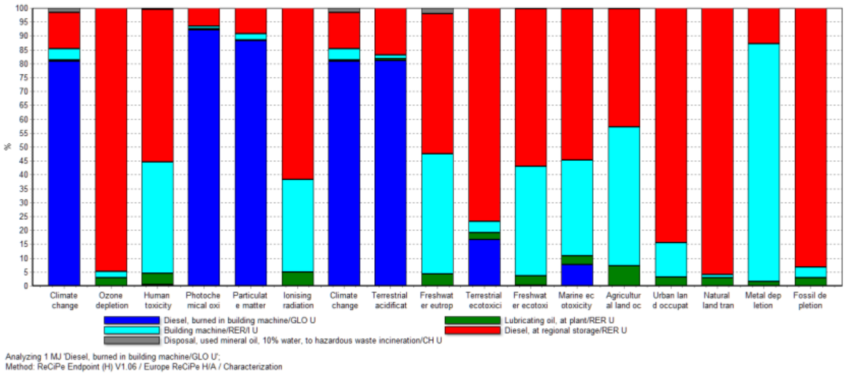
LCA

Impact calculation
Characterisation

Diesel, burned in building machine



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Comparison between impacts

Normalisation

Compare the relative importance of impact for different impact categories.
To do so, we devide the impact by the impact of a product taken as a reference.
This reference is often a territory.

For instance, the yearly emission of a european citizen in 1995.

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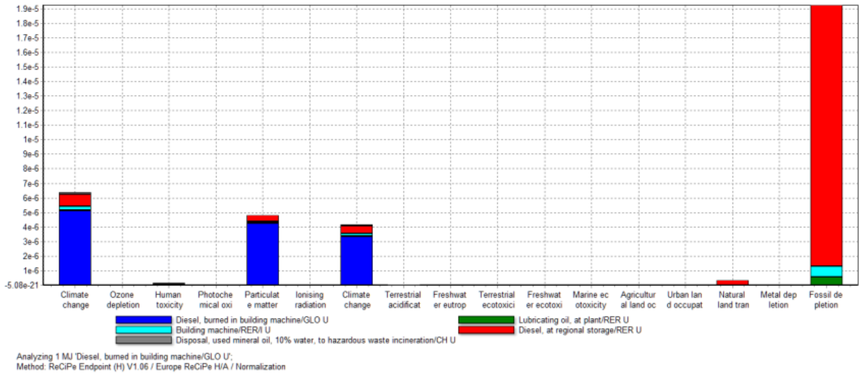
LCA
Impact calculation
Normalisation

Diesel, burned in building machine



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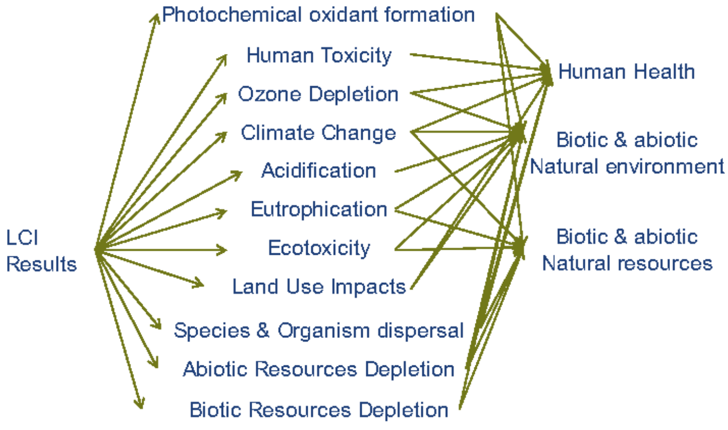
Impact calculation



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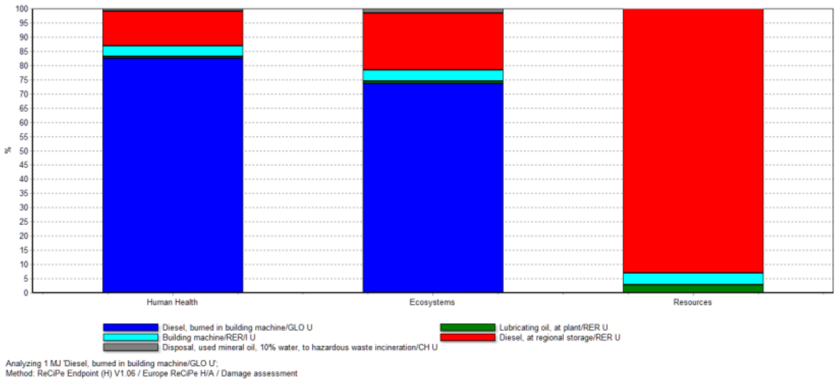
Impact calculation
Characterisation

Diesel, burned in building machine



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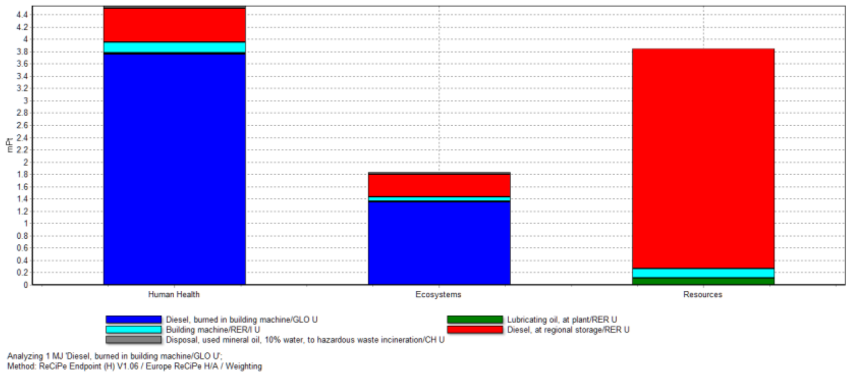
Impact calculation
Normalisation

Diesel, burned in building machine



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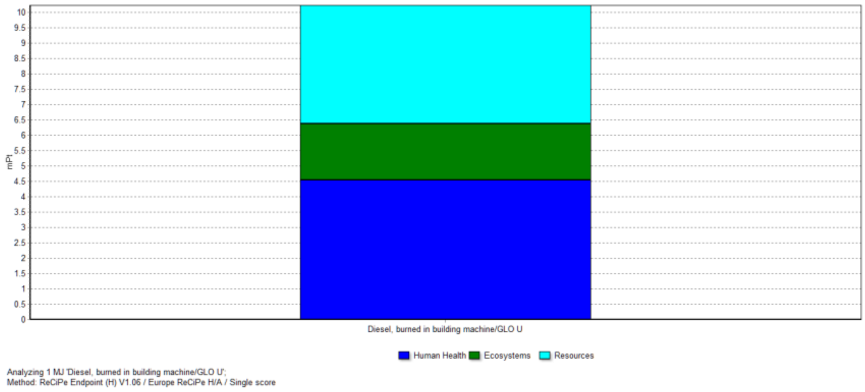
Diesel, burned in building machine



Cultural perspective in weighting

Hierarchist: 100 years time frame, seeks consensus, impacts can be avoided with proper management

Individualist: Short time frame (20 years), mankind has a high adaptive capacity through technological and economic development

Egalitarian: Long term perspective (500 years), nature is strictly accountable, the worst case scenario and preventive thinking are needed

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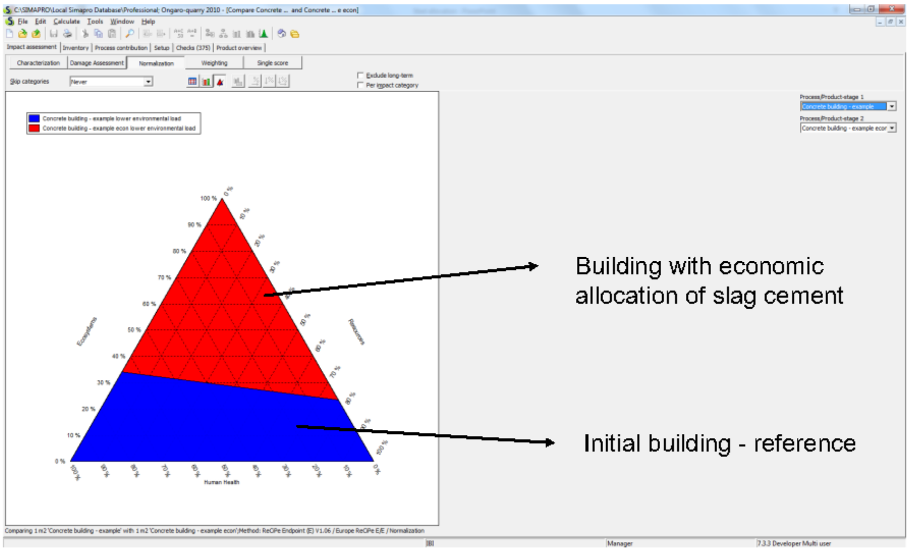
Impact calculation

Weighting

Cultural perspective in weighting



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Impact calculation

LCIA calculation methods

Midpoint methods

- CML
- EDIP
- ReCiPe
- Ecological Scarcity

Endpoint Methods

- Eco-indicator 99
- ReCiPe
- IMPACT 2002

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Mid-point categories: CML

Impact calculation

Impact Category	Substance	Factor	Unit
Abiotic depletion	Oil Gold Iron Calcite Silicon	18.4 89.5 $8.43*10^{-8}$ $2.83*10^{-10}$ $2.99*10^{-11}$	kg Sb eq / m^3 kg Sb eq / kg kg Sb eq / kg kg Sb eq / kg kg Sb eq / kg
Acidification	NH3 (Ammonia) SO2 (Sulfur Dioxide) Nitric oxide	1.6 1.2 0.76	kg SO2 eq / kg
Eutrophication	Phosphorus Phosphoric acid Nitrogen	3.06 0.97 0.42	kg PO4--- eq / kg
Global warming (GWP100)	Methane, chlorotrifluoro-, CFC-13 Ethane, hexafluoro-, HFC-116 Methane	$1.4*10^4$ $1.19*10^4$ 23	kg CO2 eq / kg
Ozone layer depletion	Methane, bromotrifluoro-, Halon 1301 Methane, dichlorodifluoro-, CFC-12 Ethane, chloropentafluoro-, CFC-115	12 0.82 0.4	kg CFC-11 eq / kg
Toxicity	2,3,7,8 Tetrachlorodibenzo-p-Dioxin (TCDD) Mercury Cadmium	$1.93*10^9$ $8.2*10^3$ $1.45*10^5$	kg 1,4-DB eq / kg
Photochemical oxidation	1,3,5-trimethyl-Benzene 2-Butene Propene	1.381 1.146 1.123	kg C2H4 eq / kg

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Mid-point categories: RECIPE

Impact calculation

Impact Category	Substance	Factor	Unit
Metal depletion	Gold Iron	$6.99*10^4$ 1	kg Fe eq / kg
Fossil depletion	Oil, crude Gas, oil production Methane	914 0.948 0.855	kg oil eq / m3
Terrestrial acidification	NH3 (Ammonia) SO2 (Sulfur Dioxide) Nitric oxide	2.89 1 0.71	kg SO2 eq / kg
Freshwater eutrophication	Phosphorus	1	kg P eq / kg
Marine eutrophication	Nitrogen Ammonia	1 0.824	kg N eq / kg
Climate Change	Methane, chlorotrifluoro-, CFC-13 Ethane, hexafluoro-, HFC-116 Methane	$1.44*10^4$ $1.22*10^4$ 25	kg CO2 eq / kg
Ozone depletion	Methane, bromotrifluoro-, Halon 1301 Methane, dichlorodifluoro-, CFC-12 Ethane, chloropentafluoro-, CFC-115	12 1 0.44	kg CFC-11 eq / kg
Toxicity	2,3,7,8 Tetrachlorodibenzo-p-Dioxin (TCDD) Mercury Cadmium	$1.01*10^8$ $5.18*10^5$ $4.52*10^4$	kg 1,4-DB eq / kg
Photochemical oxidation	1,3,5-trimethyl-Benzene 2-Butene Propene	2.33 1.94 1.9	kg NMVOC / kg
Ionising Radiation	Carbon-14	10	kg U235 eq / kBq

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Impact calculation

End-point categories: Eco99

Impact Category	Substance	Factor	Unit
Natural Resource Depletion	Copper Zinc Aluminium	36.7 4.09 2.38	MJ surplus
Carcinogens	Dioxin (water) Chromium VI (water) Dioxin (soil) Chromium VI (soil) Dioxin (air) Chromium VI (air)	$2.02*10^{3}$ $3.43*10^{-1}$ 7.06 0.271 179 1.75	DALY
Eutrophication & acidification	SO2 (Sulfur Dioxide) Nitric dioxide NO NOx	1.041 5.713 8.789 5.713	PDF
Climate Change	CO_2 Methane Methane, trichlorofluoro-, CFC-11	$2.1*10^{-7}$ $4.4*10^{-6}$ $2.2*10^{-4}$	DALY
Resp. organics/inorganics	Particles<2.5μm Particles<10μm	$7*10^{-4}$ $3.75*10^{-4}$	DALY
Ecotoxicity	Dioxin (water) Mercure (water) Mercure (soil) Dioxin (air)	$1.87*10^{5}$ $1.92*10^{2}$ $1.68*10^{3}$ $1.32*10^{5}$	PDF
Ozone Layer	CFC-11 CFC-12 Methane, bromochlorodifluoro-, Halon 1211 Methane, bromotrifluoro-, Halon 1301	$1.05*10^{-3}$ $8.63*10^{-4}$ $5.37*10^{-3}$ $1.26*10^{-2}$	DALY

DALY:
Disability adjusted Life years

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Impact calculation

Single point: Ecological scarcity

Impact Category	Substance	Factor	Unit
Natural resources	Water, unspecified natural origin, KW	$4.7*10^{6}$	UBP / m3
Energy resources	Gas Oil, crude	133 151	UBP/m3 UBP/kg
Emission into ground water	Nitrate	$2.71*10^{4}$	UBP / kg
Emission into top soil	Cadmium Zinc Lead	$3.1*10^{8}$ $2.8*10^{6}$ $3.1*10^{7}$	UBP / kg
Deposited waste	Volume occupied, final repository for radioactive waste TOC, Total Organic Carbon	$1.8*10^{10}$ $6.28*10^{4}$	UBP/m3 UBP/kg
Emission into air	2,3,7,8 Tetrachlorodibenzo-p-Dioxin (TCDD) Cd (Cadmium) Hg (Mercury)	$5.7*10^{13}$ $4.6*10^{8}$ $2.1*10^{8}$	UBP / kg
Emission into surface water	Iodine-129 Curium alpha Americium-241	$9.3*10^{4}$ $5.3*10^{4}$ $2.9*10^{4}$	UBP / kBq

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Impact calculation

Différent calculation methods

Environmental pression (CML / EDIP / NF P 01-010)
Environmental dammages (Eco99 / ecological footprint)

Différent time horizon

GWP - Global warming potential

The different greenhouse gases, which are emitted in almost every production process, contribute to a certain extent to global warming. Their individual Global warming potential is expressed as kg CO_2 – equivalent.
The more kg CO_2 – eq. a gas contains, the more it fosters global warming.

Three time perspectives are included: 20, 100 and 500 years.
(Assessment methods: IPCC 2001, CML 2001, EDIP, EDIP 2003)

	IPCC			CML 2001		
	20	100	500	20	100	500
CO_2	1	1	1	1	1	1
CH_4	62	23	7	56	21	6.5
N_2O	275	296	156	280	310	170
HFC 23	9400	12000	10000	9100	11700	9800
HALON-1301	7900	6900	2700	6200	5600	2200

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LCA

A Method

Life Cycle Analysis (LCA)

Part I : Theory

Part II: Challenges

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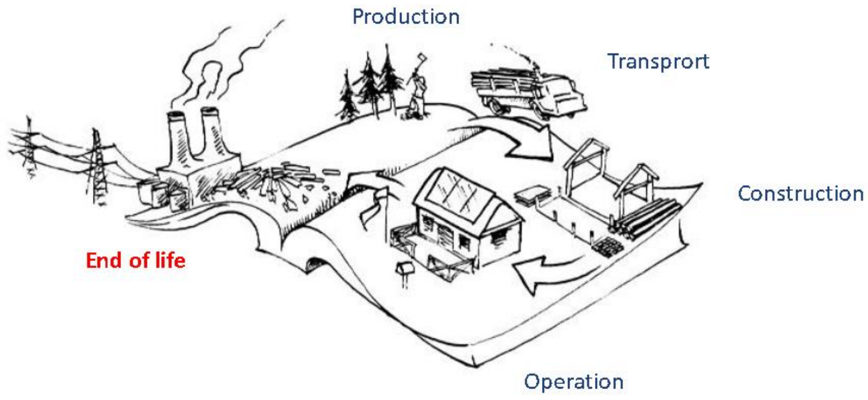
Discussion on end of life



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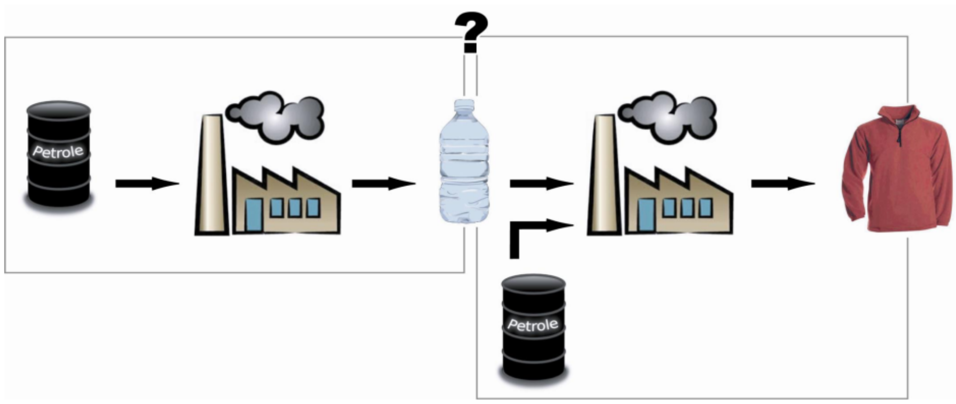
Discussion on end of life

What is the impact of a recycled product ?



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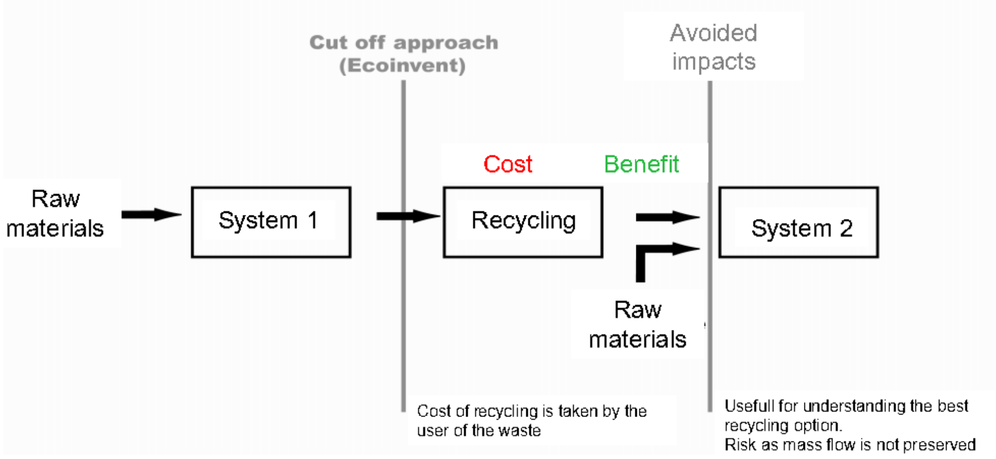
Discussion on end of life

Share costs and benefits between systems



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Discussion on end of life

The functional unit (FU) is defined as the internal roof construction necessary to support a 90-m^2 roof for an industrial hall—a typical area supported by one glulam beam or one steel frame. A simple and typical construction for an industrial hall was chosen: a single, sloping roof with a 1:10 inclination and an aluminium roof cover. We assume a full service-life to be 50 years for both constructions.

Table 2 Description of the EoL scenarios

Abbreviation	Energy source in demolition	Fuel in EoL transportation	Means of disposal	Method for handling the allocation problems related to EoL processes	Attr. (A)/ Cons. (C)
Glulam beam scenarios					
IncCut	Diesel	Average	Incineration	Cut-off	A
IncSub	Diesel	Average	Incineration	Substitution of combustion of natural gas	C
GreenIncCut	Wind	RME	Incineration	Cut-off	A
GreenIncSub	Wind	RME	Incineration	Substitution of combustion of municipal biowaste	C
ReCut	Diesel	Average	Recycling	Cut-off	A
ReSub	Diesel	Average	Recycling	Substitution of today's average European production of debarked round wood	C
GreenReCut	Wind	RME	Recycling	Cut-off	A
GreenReSub	Wind	RME	Recycling	Substitution of today's average European production of debarked round wood[a]	C
NoEoL	All impacts of EOL processes are excluded				
Steel frame scenarios					
ReCut	Diesel	Average	Recycling	Cut-off	A
ReSub	Diesel	Average	Recycling	Substitution of today's average European production of low-alloyed steel	C
GreenReCut	Wind	RME	Recycling	Cut-off	A
GreenReSub	Wind	RME	Recycling	Substitution of today's average production of recycled un- and low-alloyed steel	C
NoEoL	All impacts of EoL processes are excluded				

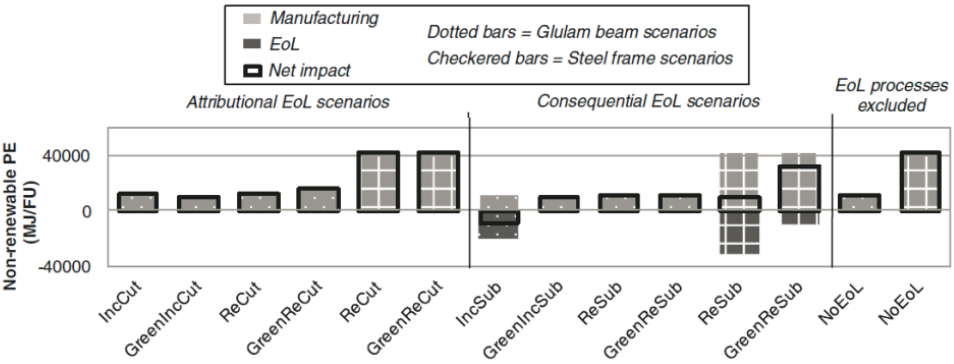
Sandin et al. 2014. Life cycle assessment of construction materials:
The influence of assumptions in end-of-life modelling. The International Journal of Life Cycle Assessment, 19, 723-731

Steel exemple

Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling

Gustav Sandin · Greg M. Peters · Magdalena Svanström

International Journal of Life Cycle Analysis (Springer)



How do we split impact between a product and a co-product?

Article 5

By-products

1. A substance or object, resulting from a production process, the primary aim of which is not the production of that item, may be regarded as not being waste referred to in point (1) of Article 3 but as being a by-product only if the following conditions are met:

(a) further use of the substance or object is certain;

(b) the substance or object can be used directly without any further processing other than normal industrial practice;

(c) the substance or object is produced as an integral part of a production process; and

(d) further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

Official Journal of the European Union L 312/11

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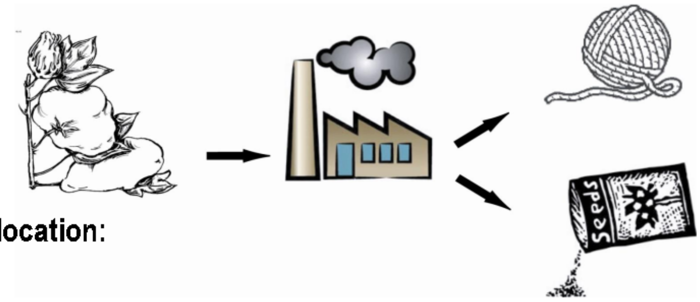
Discussion on end of life

How do we split impact between a product and a co-product?



1) Avoid allocation:

Separation

Séparation of multi-fonctional systems into mono-fonctional ones.

Or System expansion approach

Include both products in the functional unit.

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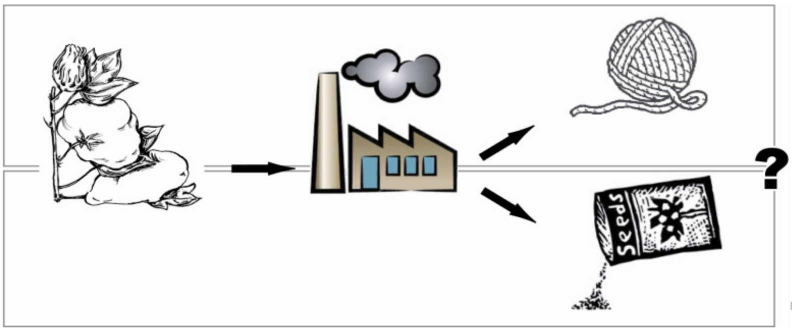
Discussion on end of life

2) If allocation cannot be avoided:

Imputation method
Split flows depending on the relative responsability of both products…

Mass attribution
Energetic allocation, chemical allocation, etc… (linked with physical values)
Or linked with non physical values: money.



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Discussion on end of life

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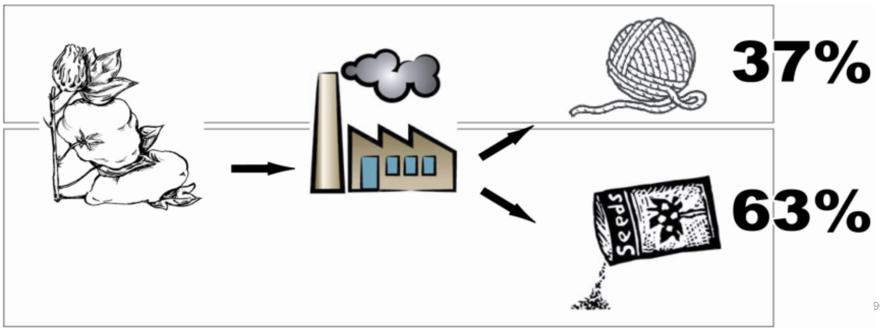

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Discussion on end of life

2) If allocation cannot be avoided:

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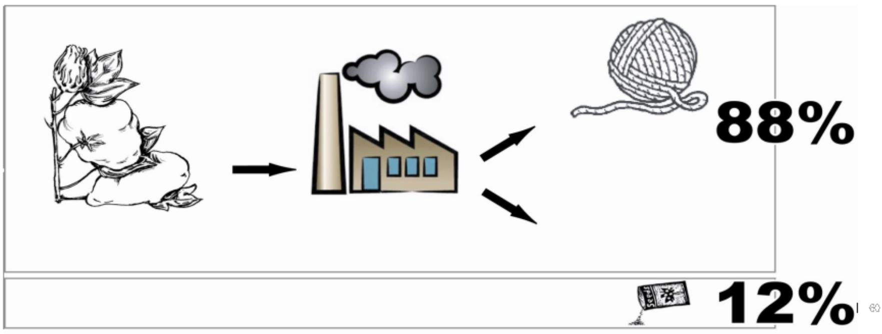
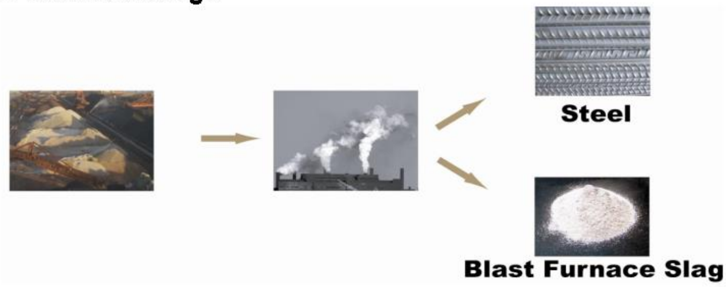
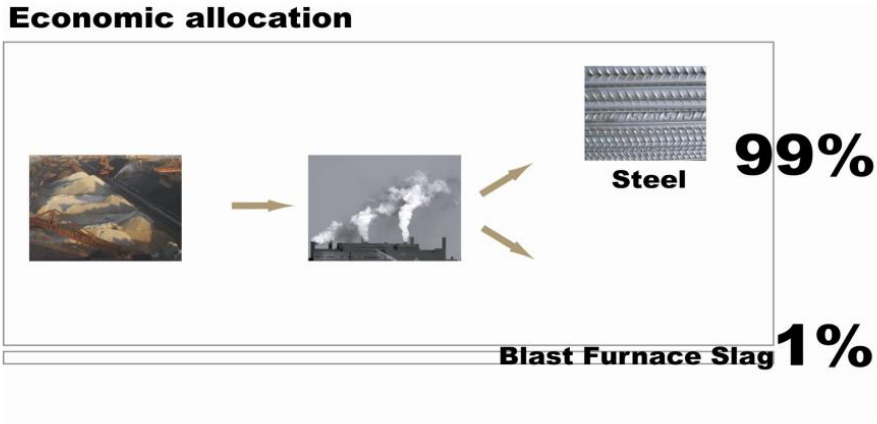


Exemple with steel and slags



Exemple with steel and slags



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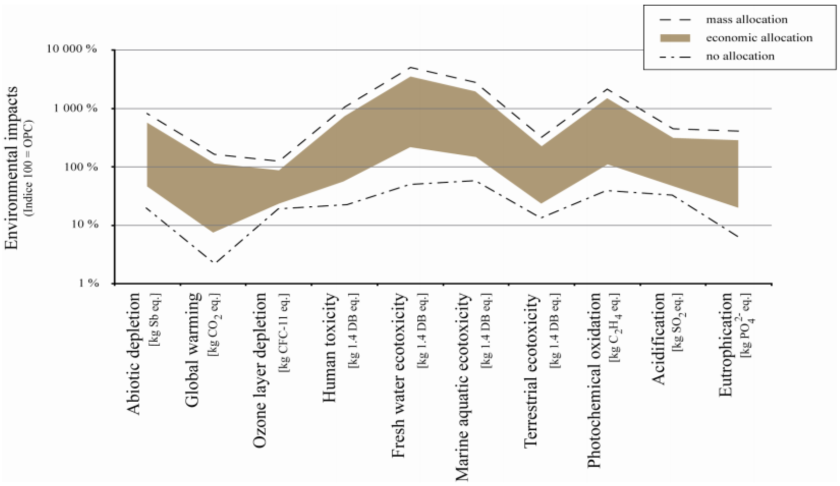
Discussion on end of life



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Discussion industrial variabilities

Ex: Cement production

- **Compare direct emission from different cement plants**
- **European Database on emissions from industries: EPER**

Cement plantProduction [t/yr]	1 500 000	600 000	800 000	600 000	380 000	775 000	240 000	1 100 000	410 000	384 000	900 000	810 000	2 000 000	1 000 000
Air emissions [kg/yr]														
Chlorine (Cl)		666	110		57	64	631		$6.39\ 10^3$	$5.03\ 10^3$	662		$5.2\ 10^3$	$2.01\ 10^3$
Hydrochloric acid (HCl)	$1.60\ 10^4$												$1.0\ 10^4$	
Fluorine and inorganic compounds	183		1								152			140
benzene (C_6H_6)				$2.0\ 10^3$							$2.98\ 10^3$			
Non-Methane Volatile Organic Compounds (NMVOC)								$4.39\ 10^4$	$3.47\ 10^4$	$3.50\ 10^4$	$5.22\ 10^4$	$4.60\ 10^4$	$3.07\ 10^4$	
Carbon dioxide (CO_2)	$1.02\ 10^6$	$3.12\ 10^5$	$5.64\ 10^5$	$4.50\ 10^5$	$2.91\ 10^5$	$5.95\ 10^5$		$8.36\ 10^5$	$3.12\ 10^5$	$3.38\ 10^5$	$4.57\ 10^5$		$9.35\ 10^5$	$6.93\ 10^5$
Mercury and derivates (Hg)	110	11	16			11		65		11		14	40	
Nitrogen oxides (NOx) (eq. NO_2)	$1.54\ 10^6$	$6.38\ 10^5$	$8.34\ 10^5$	$5.84\ 10^5$	$4.23\ 10^5$	$1.20\ 10^6$	$4.14\ 10^5$	$9.84\ 10^5$	$4.53\ 10^5$	$6.50\ 10^5$	$7.85\ 10^5$	$1.17\ 10^6$	$2.23\ 10^6$	$1.38\ 10^6$
Sulphur oxides (SOx) (eq. SO_2)				$1.01\ 10^6$						$2.69\ 10^5$	$9.95\ 10^5$	$1.65\ 10^5$	$1.66\ 10^6$	$3.93\ 10^5$
Nitrous oxide (N_2O)					$1.29\ 10^4$								$1.02\ 10^4$	
Ammonia (NH_3)													$1.44\ 10^6$	
Particulates					$1.85\ 10^5$									
Copper and derivates (Cu)		172												
Manganese and derivates (Mn)		233												
Nickel and derivates (Ni)	67	97							67					
Zinc and derivates (Zn)	$2.75\ 10^3$	202												268
Antimony (Sb)										1.4			3	
Tin (Sn)										4.5			13	
Cobalt (Co)										5.2				
cadnium (Cd)	25		22	28		13								25
Arsenic (As)						25								
Chromium (Cr)													127	
Lead (Pb)													304	324

EPER Database

- Detail per indistrial site
- Mendatory
- Transparent

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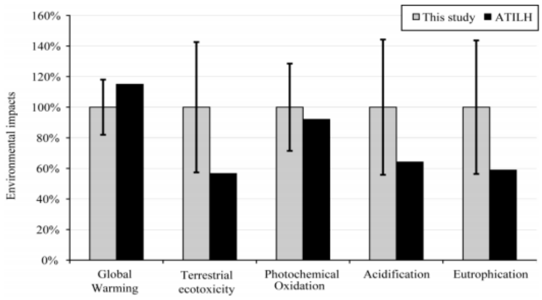
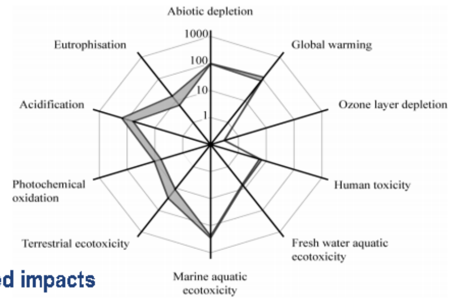
Discussion industrial variabilities

Ex: Cement production
- Compare direct emission from different cement plants





Normalised impacts

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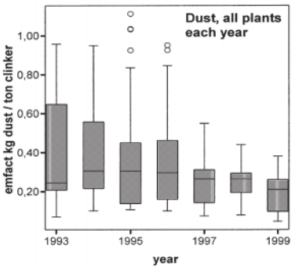
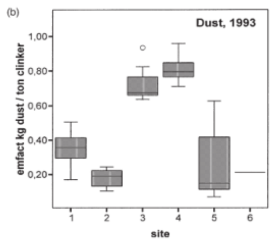
Discussion industrial variabilities

Ex: Cement production
Compare dust emissions

B. von Bahr et al. / Journal of Cleaner Production 11 (2003) 713–725



6 cement plants
Every year



Each cement plant
In 1993

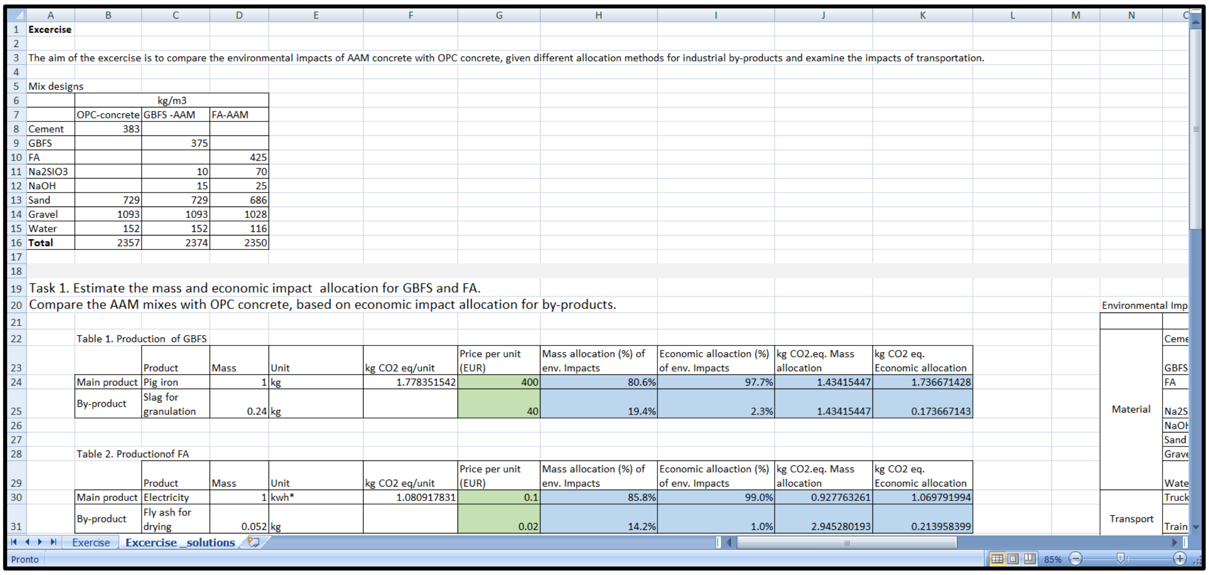
7. Practical exercise on modelling LCA

Guillaume Habert

To obtain first hands-on experience with LCA modelling, an exercise is provided. The exercise looks into the global warming potential (GWP) per 1 m³ of concrete, comparing ordinary Portland cement (OPC) based concrete with alkali-activated materials (AAM) based concrete.

A video recording with further explanation is provided here (15 minutes to watch).

The GWP calculation is performed in an exemplary and simplified spreadsheet, assuming some tentative inventory data on the constituent materials. Terminology refers to that of AAM concrete for which further reference is made to the DuRSAAM eBook 'Introduction to AAM'.



Excercise

The aim of the excercise is to compare the environmental impacts of AAM concrete with OPC concrete, given different allocation methods for industrial by-products and examine the impacts of transportation.

Mix designs

	kg/m3		
	OPC-concrete	GBFS -AAM	FA-AAM
Cement	383		
GBFS		375	
FA			425
Na2SIO3		10	70
NaOH		15	25
Sand	729	729	686
Gravel	1093	1093	1028
Water	152	152	116
Total	2357	2374	2350

Task 1. Estimate the mass and economic impact allocation for GBFS and FA.
Compare the AAM mixes with OPC concrete, based on economic impact allocation for by-products.

Table 1. Production of GBFS

	Product	Mass	Unit	kg CO2 eq/unit	Price per unit (EUR)	Mass allocation (%) of env. Impacts	Economic alloaction (%) of env. Impacts	kg CO2.eq. Mass allocation	kg CO2 eq. Economic allocation
Main product	Pig iron	1	kg	1.778351542	400	80.6%	97.7%	1.43415447	1.736671428
By-product	Slag for granulation	0.24	kg		40	19.4%	2.3%	1.43415447	0.173667143

Table 2. Productionof FA

	Product	Mass	Unit	kg CO2 eq/unit	Price per unit (EUR)	Mass allocation (%) of env. Impacts	Economic alloaction (%) of env. Impacts	kg CO2.eq. Mass allocation	kg CO2 eq. Economic allocation
Main product	Electricity	1	kwh*	1.080917831	0.1	85.8%	99.0%	0.927763261	1.069791994
By-product	Fly ash for drying	0.052	kg		0.02	14.2%	1.0%	2.945280193	0.213958399

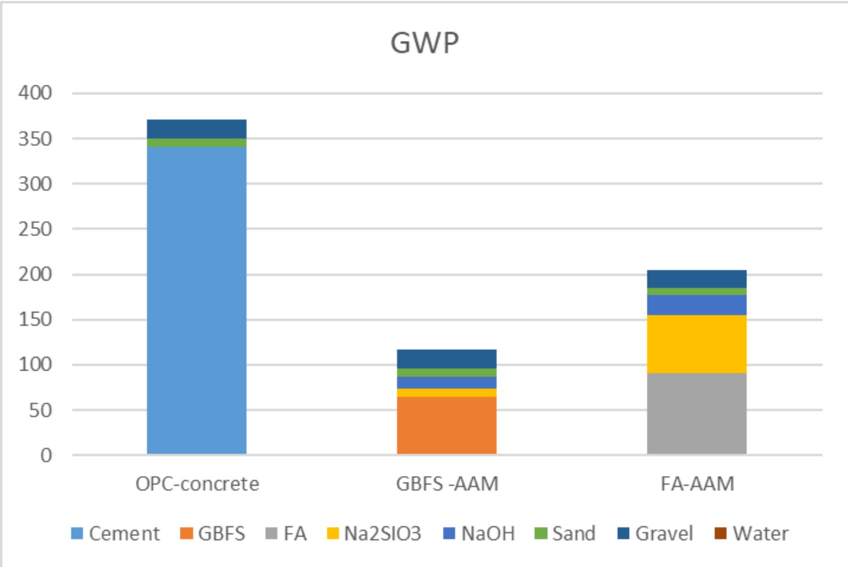
A link to the spreadsheet is provided here.

The spreadsheet contains the following subsequent parts:

- Mix design. This part lists the mix proportions of the 3 concrete compositions which are compared.
- Task 1. In this part the GWP is calculated, accounting for the use of by-products in the concrete mix design by means of an economic impact allocation. For the latter, the mass and unit price of the by-product versus the main product (the latter generating the by-product as a side stream) are of importance. Depending on the entered numbers for these parameters different GWP results are obtained, and the influence of the economic impact allocation can be noted.
- Task 2. In this part the GWP is compared with respect to Task 1, assuming that the prize of FA would increase by a factor 3. It once more illustrated the impact of prize setting on the GWP considering economic allocation.
- Task 3. In this part the GWP is considered when looking closer into transport distances of the by-products. Transport distances have a major impact on GWP and it can be

calculated which transport distances are acceptable for the by-products, so not to exceed the impact of the reference concrete.

Outputs of the GWP calculation are visualised in graphs, which are shown at the right-hand side of that respective part of the spreadsheet. The unit of the resulting GWP is kg CO2.eq per m^3 of concrete. An example output (numbers are indicative) is illustrated below.



8. Introduction to circular economy

Birgitte Holt Andersen

In this chapter an introduction is given on what circular economy is and why it is a popular topic these days. An explanation is given into the shift from a linear to a more circular economy, the policy framework which can be associated to circular economy and the importance of it for the construction sector.

A video recording with further explanation is provided [here](#) (27 minutes to watch).

Introduction to me and CWare

I am an economist, PhD in Corporate Strategy, worked at Joint Research Center/Space Institute, Gallileo Programme, Chief Project Manager in COWI, now CEO and partner in CWare.

CWare is a research and consultancy start-up specialised in circular-economy, economic and environmental feasibility assessments and market strategic exploitation. We are currently involved in H2020 projects on Geopolymer cement using local industrial waste streams, URBCON and one on urban resilience.

www.cware.eu

https://www.linkedin.com/in/birgitte-holt-andersen-5640835/

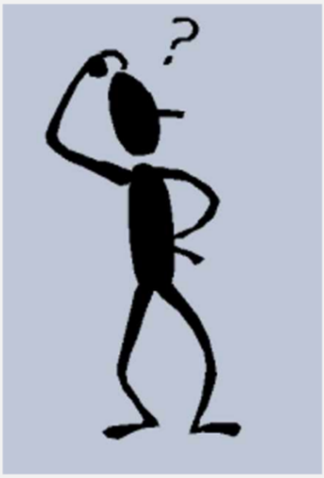
Official Programme

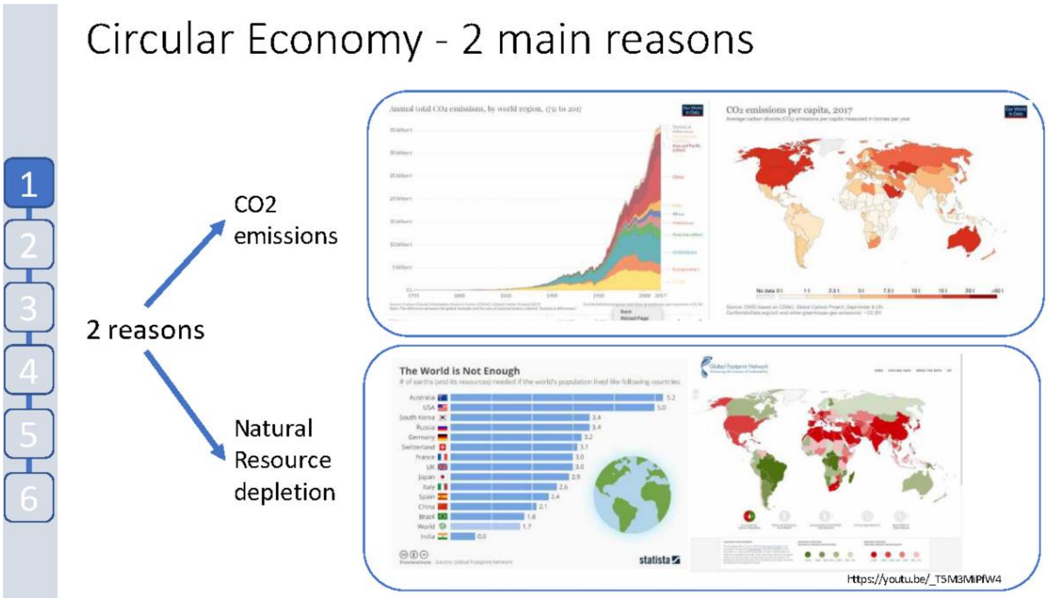
Date:	Thursday, 17 September 2020
9:00 – 9:20	Session 7 *Birgitte Holt Andersen, PhD,* CWare Introduction to Circular Economy – what is Circular Economy and why is it a popular topic these day?
9:20 – 9:30	Polling (short quiz)
9:30 – 9:45	Q&A – discussion session
9:45 – 10:00	Break

The main Subjects of session 7

1. Why are we talking about Circular Economy
2. From Linear to Circular Economy
3. Ellen MacArthur Framework
4. Circular Economy in Policy
5. Relevance of Circular Economy in the Construction Industry
6. Discussion Points

WHY CIRCULAR ECONOMY?




Circular Economy - 2 main reasons
1
2
3
4
5
6
2 reasons
CO2 emissions
Natural Resource depletion
The World is Not Enough
statista
Https://youtu.be/_T5M3MIPfW4


Types of Natural Resources
1
2
3
4
5
6
1. Renewable resources:
Renewable resources are those that are constantly available (like water) or can be reasonably replaced or recovered, like vegetative lands. Animals are also renewable because with a bit of care, they can reproduce offspring's to replace adult animals.
If renewable resources come from living things, (such as trees and animals) they can be called organic renewable resources.
If renewable resources come from non-living things, (such as water, sun and wind) they can be called inorganic renewable resources.
2. Non-renewable resources
Non-renewable resources are those that cannot easily be replaced once they are destroyed. Examples include fossil fuels. Minerals are also non-renewable because even though they form naturally in a process called the rock cycle, it can take thousands of years, making it non-renewable. Non-renewable resources can be called inorganic resources if they come from non-living things. Examples include include, minerals, wind, land, soil and rocks.
Some non-renewable resources come from living things — such as fossil fuels. They can be called organic non-renewable resources.
Animal Resources
Crude Oil
Water Resources
Land Resources
Forest Resources
Precious Metals, Minerals, Rocks
Wind Power and Solar Energy
Natural Gas

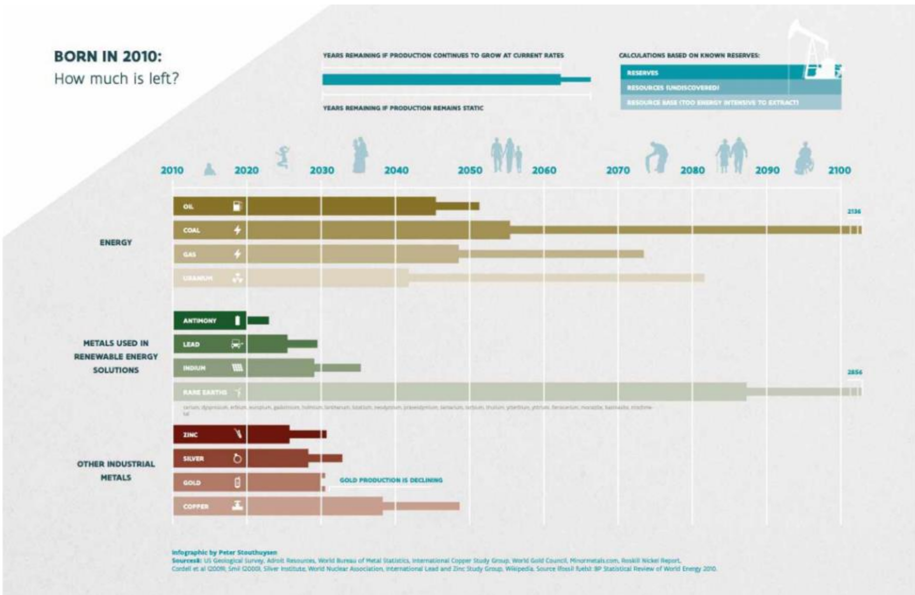
Natural resource depletion

Resources are exhausted when they are used quicker than they can regenerate themselves.

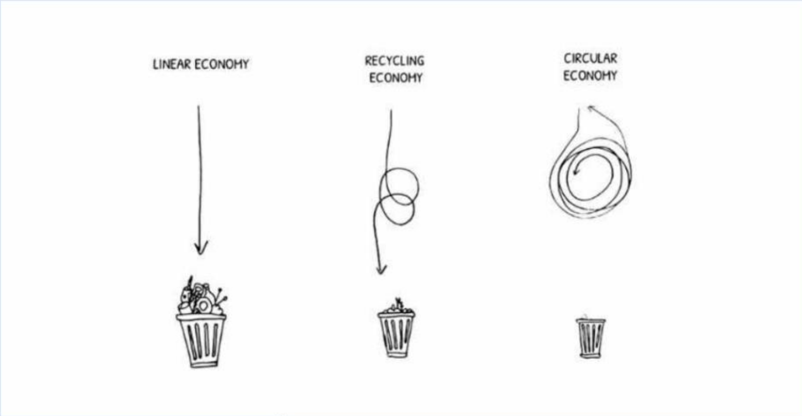
The resources under most threat of depletion are: Water, coal, oil, natural gas, fauna&flora (fish), rare metals, aggregates, sand..

What causes depletion: Population increase, contamination, high utilisations of resources, land-use changes.

Effect on human health: Poverty, atmospheric changes, loss of biodiversity.

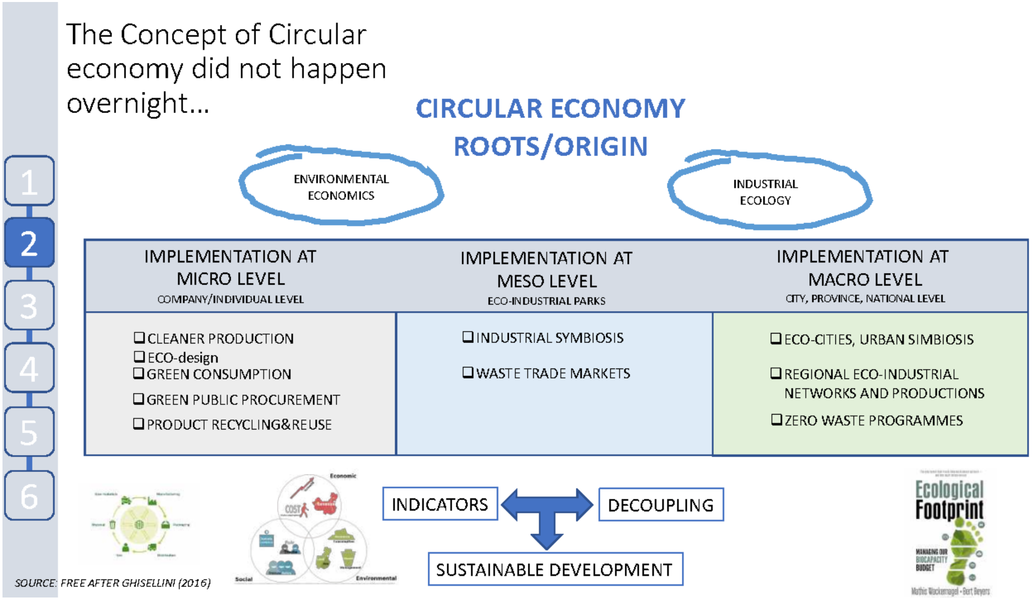


FROM LINEAR TO CIRCULAR ECONOMY



So what is Circular Economy?

Is it a new buzzword, a policy framework, a new economic cure and what does it mean for the individual, the company, the city ,the country and the planet?


The Concept of Circular economy did not happen overnight…
CIRCULAR ECONOMY ROOTS/ORIGIN
ENVIRONMENTAL ECONOMICS
INDUSTRIAL ECOLOGY
IMPLEMENTATION AT MICRO LEVEL
COMPANY/INDIVIDUAL LEVEL
IMPLEMENTATION AT MESO LEVEL
ECO-INDUSTRIAL PARKS
IMPLEMENTATION AT MACRO LEVEL
CITY, PROVINCE, NATIONAL LEVEL
CLEANER PRODUCTION
ECO-design
GREEN CONSUMPTION
GREEN PUBLIC PROCUREMENT
PRODUCT RECYCLING&REUSE
INDUSTRIAL SYMBIOSIS
WASTE TRADE MARKETS
ECO-CITIES, URBAN SIMBIOSIS
REGIONAL ECO-INDUSTRIAL NETWORKS AND PRODUCTIONS
ZERO WASTE PROGRAMMES
INDICATORS
DECOUPLING
SUSTAINABLE DEVELOPMENT
Ecological Footprint
SOURCE: FREE AFTER GHISELLINI (2016)
1
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3
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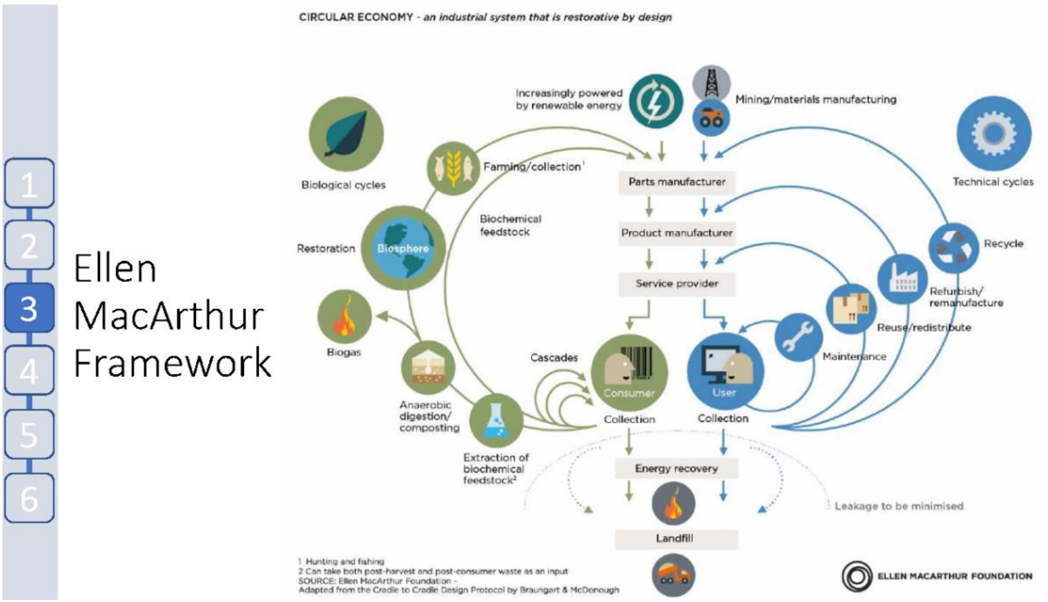
6


Ellen MacArthur Framework
CIRCULAR ECONOMY - an industrial system that is restorative by design
Increasingly powered by renewable energy
Mining/materials manufacturing
Biological cycles
Farming/collection
Parts manufacturer
Technical cycles
Biochemical feedstock
Product manufacturer
Restoration
Biosphere
Recycle
Service provider
Refurbish/remanufacture
Reuse/redistribute
Biogas
Cascades
Maintenance
Consumer
User
Anaerobic digestion/composting
Collection
Collection
Extraction of biochemical feedstock
Energy recovery
Leakage to be minimised
Landfill
1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
SOURCE: Ellen MacArthur Foundation - Adapted from the Cradle to Cradle Design Protocol by Braungart & McDonough
ELLEN MACARTHUR FOUNDATION
1
2
3
4
5
6

CE DEFINITION

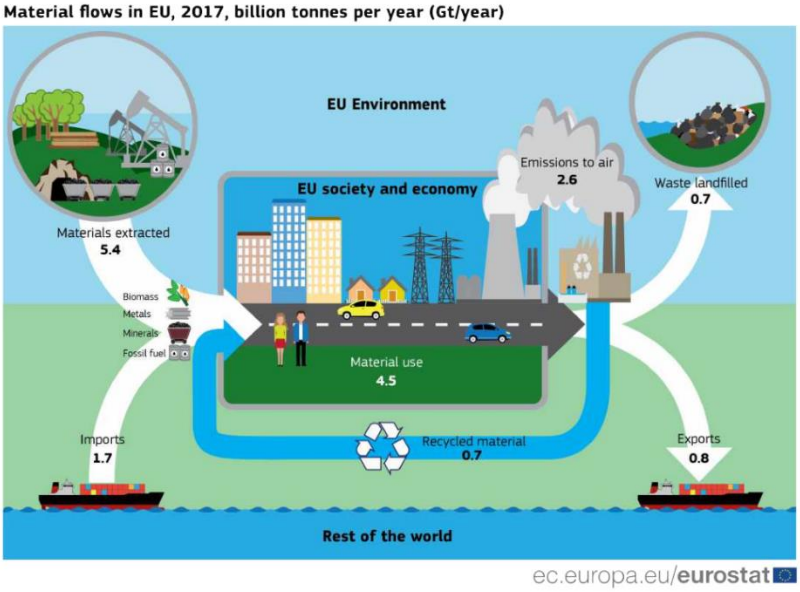
What is a circular economy?
Looking beyond the current take-make-waste extractive industrial model, a circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital. It is based on three principles:

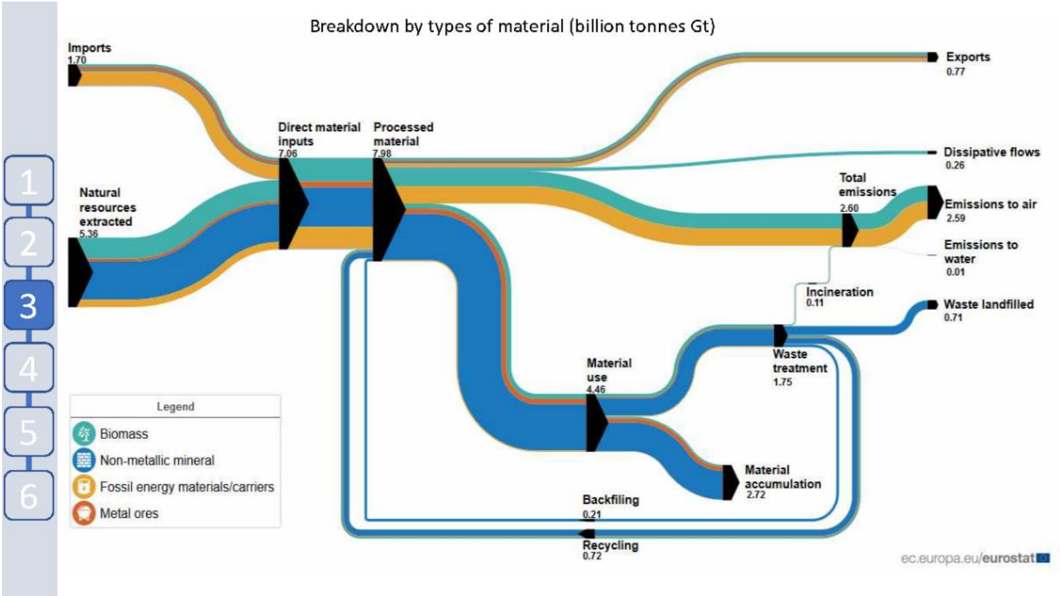
•Design out waste and pollution
•Keep products and materials in use
•Regenerate natural systems

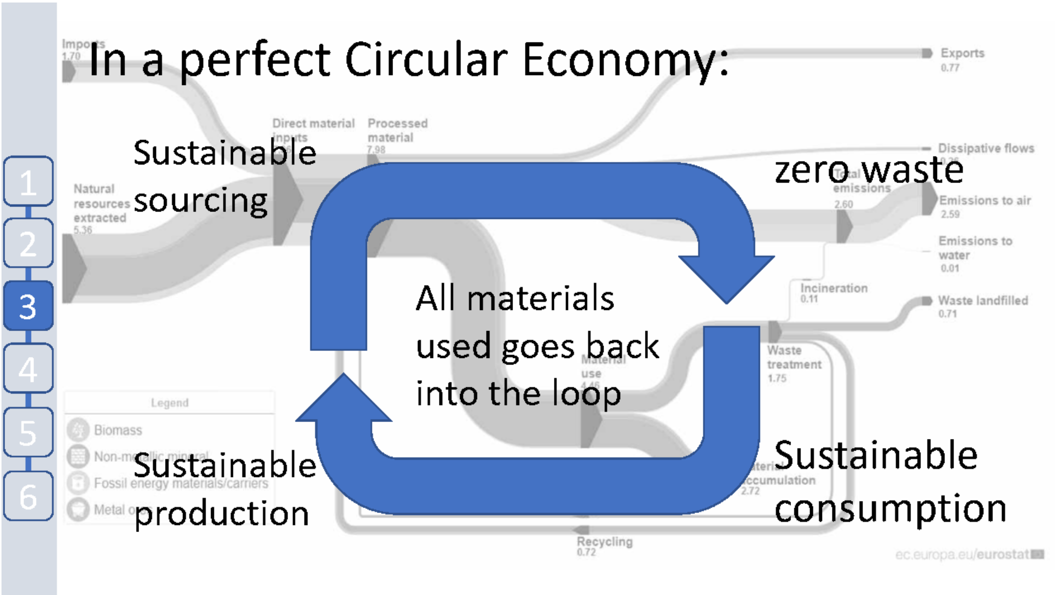
Ellen MacArthur Foundation

This is where we are now

Material flows in EU, 2017, billion tonnes per year (Gt/year)




1
2
3
4
5
6
Breakdown by types of material (billion tonnes Gt)
Imports
1.70
Natural resources extracted
5.36
Direct material inputs
7.06
Processed material
7.98
Exports
0.77
Dissipative flows
0.26
Total emissions
2.60
Emissions to air
2.59
Emissions to water
0.01
Incineration
0.11
Waste landfilled
0.71
Waste treatment
1.75
Material use
4.46
Material accumulation
2.72
Backfilling
0.21
Recycling
0.72
Legend
Biomass
Non-metallic mineral
Fossil energy materials/carriers
Metal ores
ec.europa.eu/eurostat


1
2
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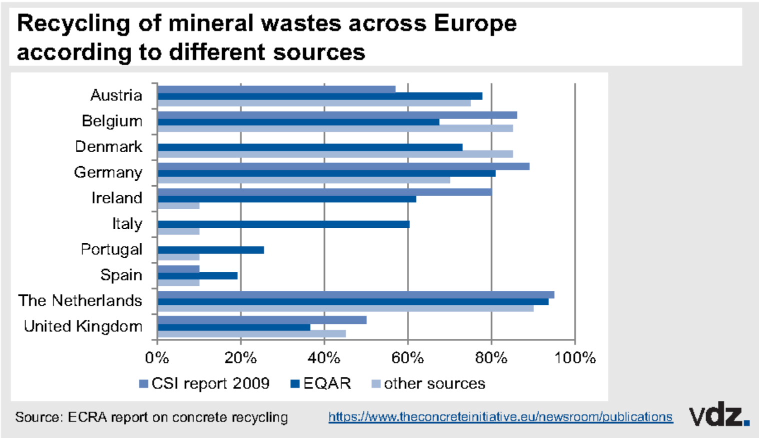
6
In a perfect Circular Economy:
Sustainable sourcing
zero waste
All materials used goes back into the loop
Sustainable production
Sustainable consumption

Recycling rates in EU



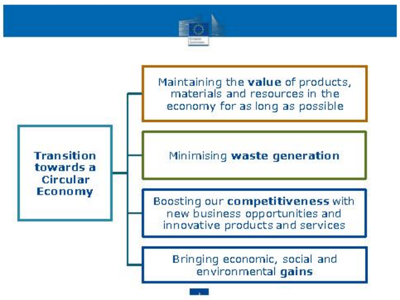
Circular Economy as a political instrument

EU POLICIES

NATIONAL POLICIES

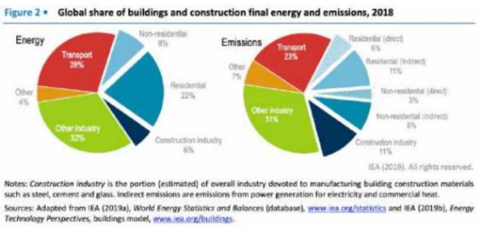
REGIONAL POLICIES

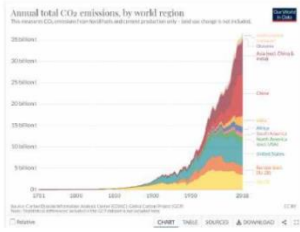
CITY POLICIES



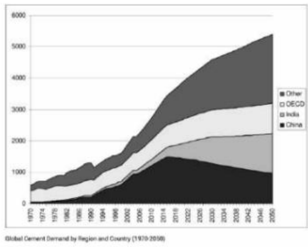
https://www.oecd.org/env/outreach/Presentation%20by%20Patrick%20Wegerdt%20EC.pdf

Relevance of Circular Economy in the Construction Industry

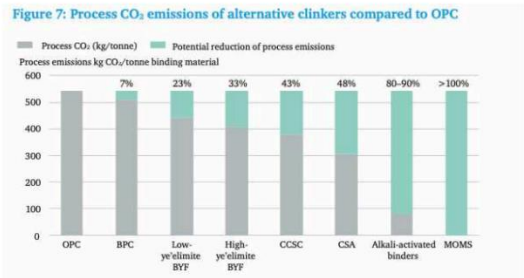




Each year, more than 4 billion tonnes of cement are produced, accounting for around 8 per cent of global CO_2 emissions



Relevance of Circular Economy in the Construction Industry



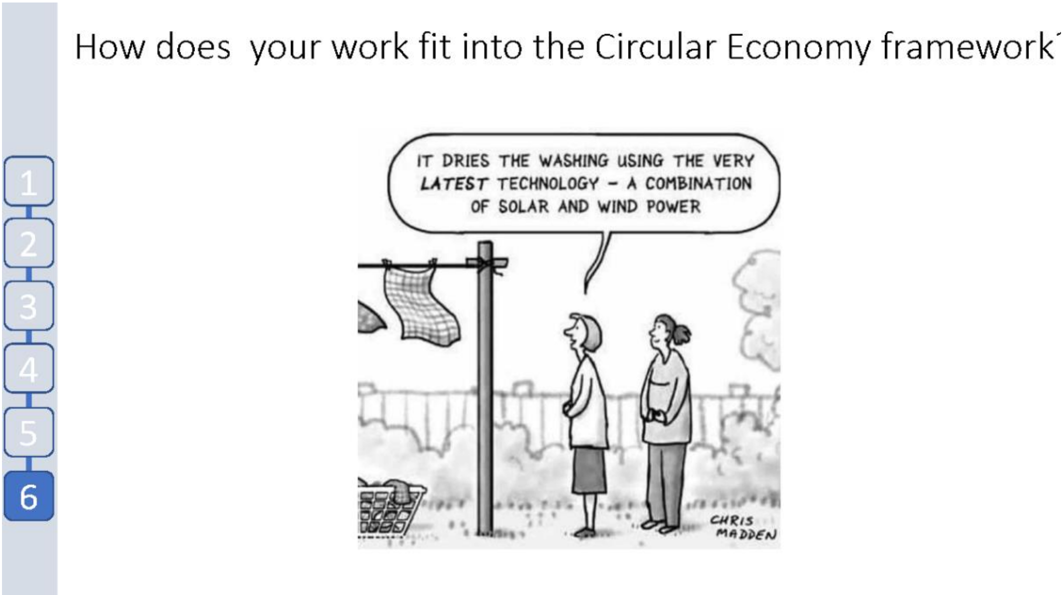
Source: Data for clinker phase compositions (i.e. share of clinker compound in each type) for OPC, BPC, low- and high-ye'elimite BYF, CCSC and MOMS as well as process CO_2 emissions for clinker compounds from Gartner and Sui (2017), 'Alternative cement clinkers'. Data for clinker phase composition for CSA from Quillin, K. (2010), 'Low-CO2 Cements based on Calcium Sulfoaluminate', presentation, https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&cad=rja&uact=8&ved=0ahUKEwiuvZWS0ubYAhVCLMAKHfFIC70QFgg8MAQ&url=https%3A%2F%2Fwww.soci.org%2F-%2Fmedia%2FFiles%2FConference-Downloads%2F2010%2FLow-Carbon-Cements-Nov-10%2FSulphoaluminate_Cements_Keith_Quillin_R.ashx%3Fla%3Den&usg=AOvVaw0kPdXplmBcLMdGMnqzanlV (accessed 20 Jan. 2018).

Note: BPC stands for belite-rich Portland clinker, BYF stands for belite ye'elimite-ferrite and is also sometimes referred to as BCSA (or belite sulphoaluminate), CCSC stands for carbonatable calcium silicate clinker(s), CSA stands for calcium sulphoaluminate clinker, MOMS stands for magnesium oxides derived from magnesium silicates.

1. CO2 reduction

2. Level of Circularity


1
2
3
4
5
6
QUESTIONS?
DISCUSSION
POINTS
EMERYS
CORNWALL, UK
KAOLIN PRODUCTION


How does your work fit into the Circular Economy framework
1
2
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5
6
IT DRIES THE WASHING USING THE VERY LATEST TECHNOLOGY – A COMBINATION OF SOLAR AND WIND POWER
CHRIS MADDEN

9. Circular economic modelling

Birgitte Holt Andersen

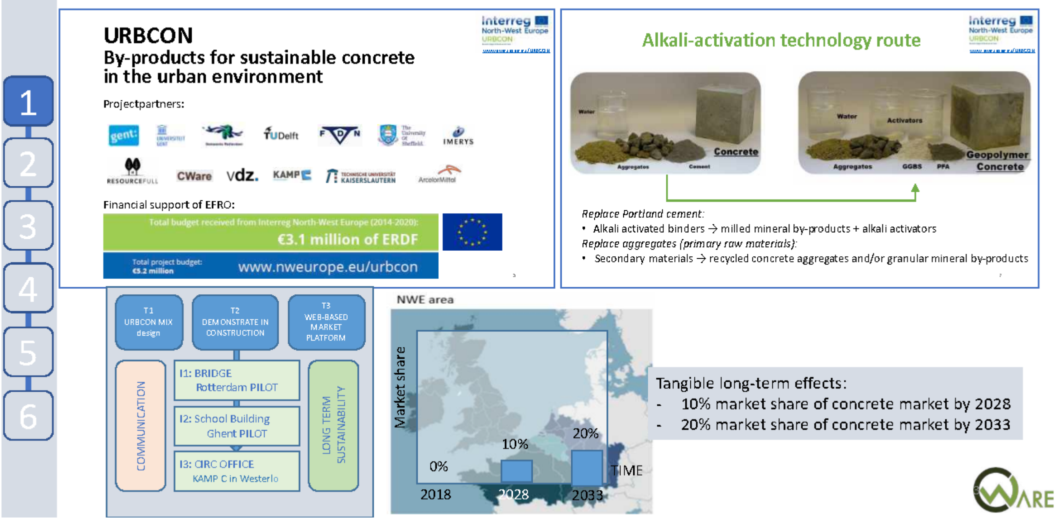
In this chapter circular economic modelling is discussed, addressing the main barriers and challenges throughout the value circle to move from a linear to a circular economy. The main elements of the model are listed, as well as some results in which this is applied for 2 European projects (URBCON and WOOL2LOOP).

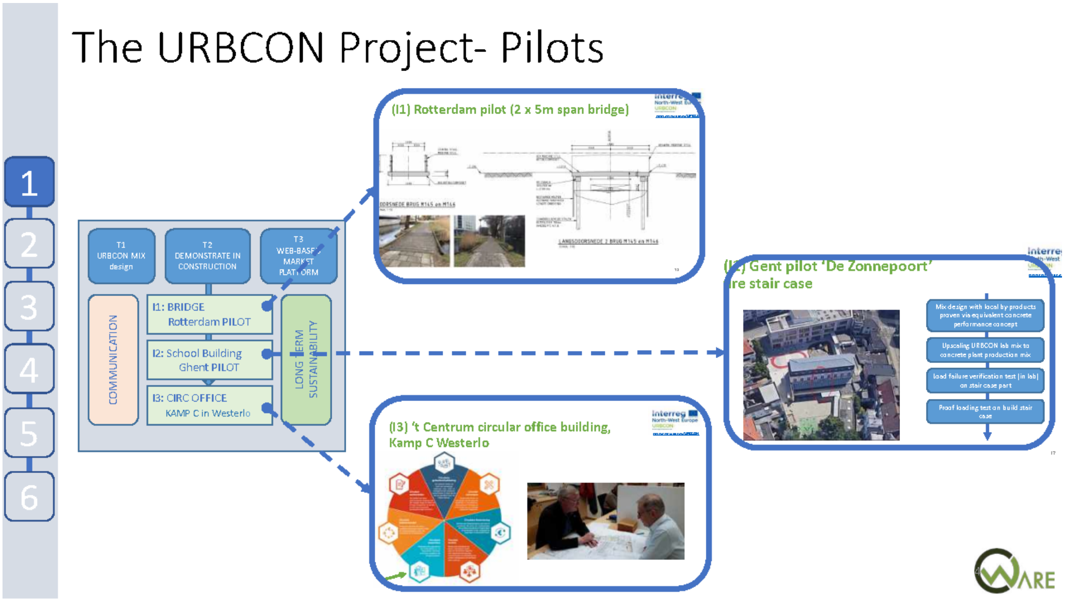
A video recording with further explanation is provided [here] (31 minutes to watch).

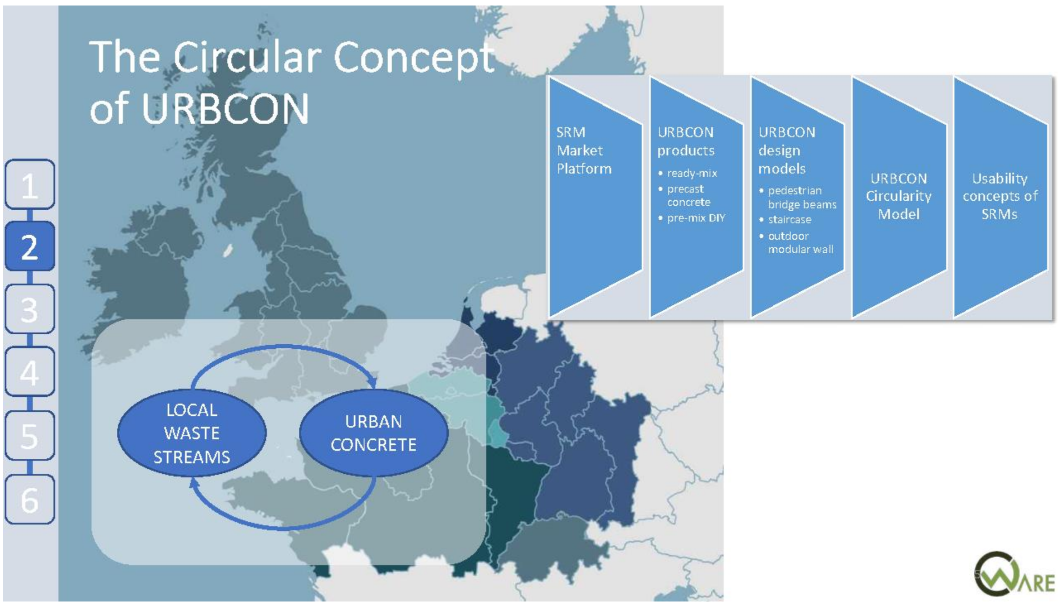
The main Subjects of session 8

1. Short intro to URBCON
2. The Circular Concept of URBCON
3. The elements of our Circular Economic Model
4. Some results from URBCON and WOOL2LOOP
5. Market strategic considerations
6. Discussion Points

The URBCON Project- objectives and scope




The URBCON Project- Pilots
(I1) Rotterdam pilot (2 x 5m span bridge)
T1 URBCON MIX design
T2 DEMONSTRATE IN CONSTRUCTION
COMMUNICATION
I1: BRIDGE Rotterdam PILOT
I2: School Building Ghent PILOT
I3: CIRC OFFICE KAMP C in Westerlo
LONG TERM SUSTAINABILITY
(I3) 't Centrum circular office building, Kamp C Westerlo
1
2
3
4
5
6


The Circular Concept of URBCON
SRM Market Platform
URBCON products
• ready-mix
• precast concrete
• pre-mix DIY
URBCON design models
• pedestrian bridge beams
• staircase
• outdoor modular wall
URBCON Circularity Model
Usability concepts of SRMs
LOCAL WASTE STREAMS
URBAN CONCRETE
1
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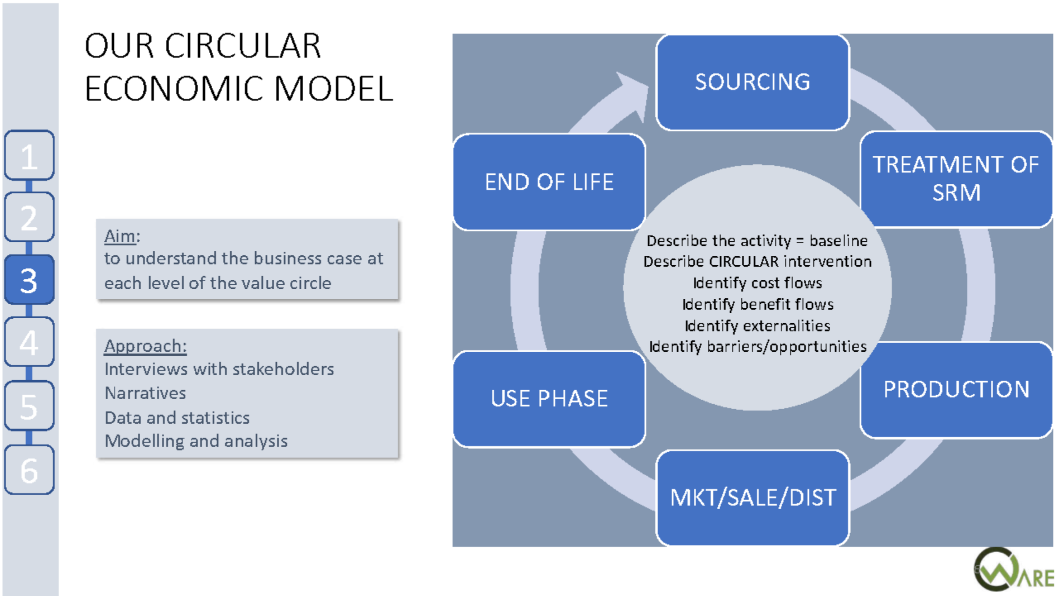
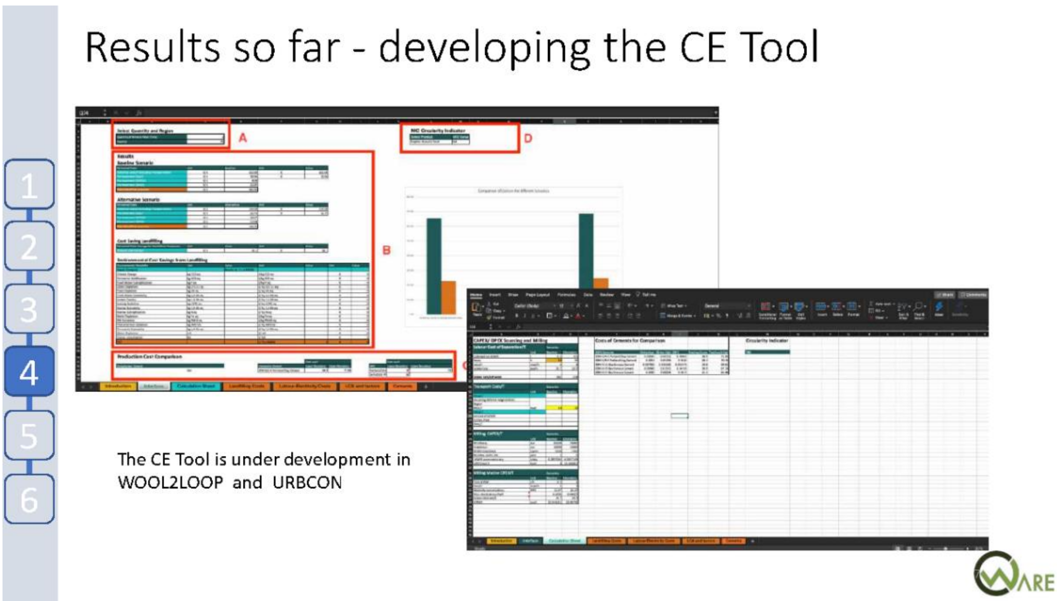
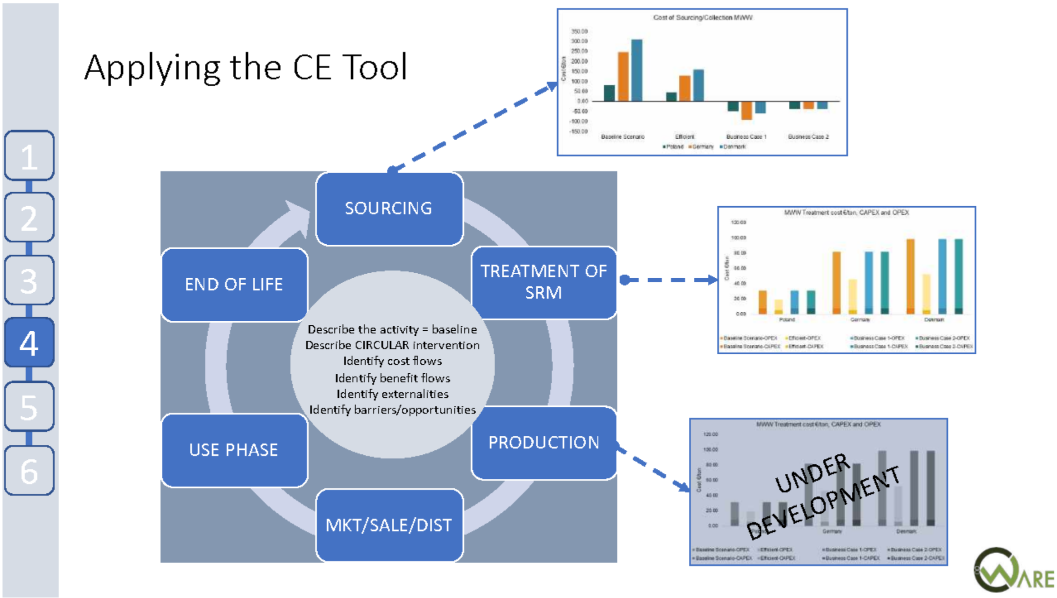
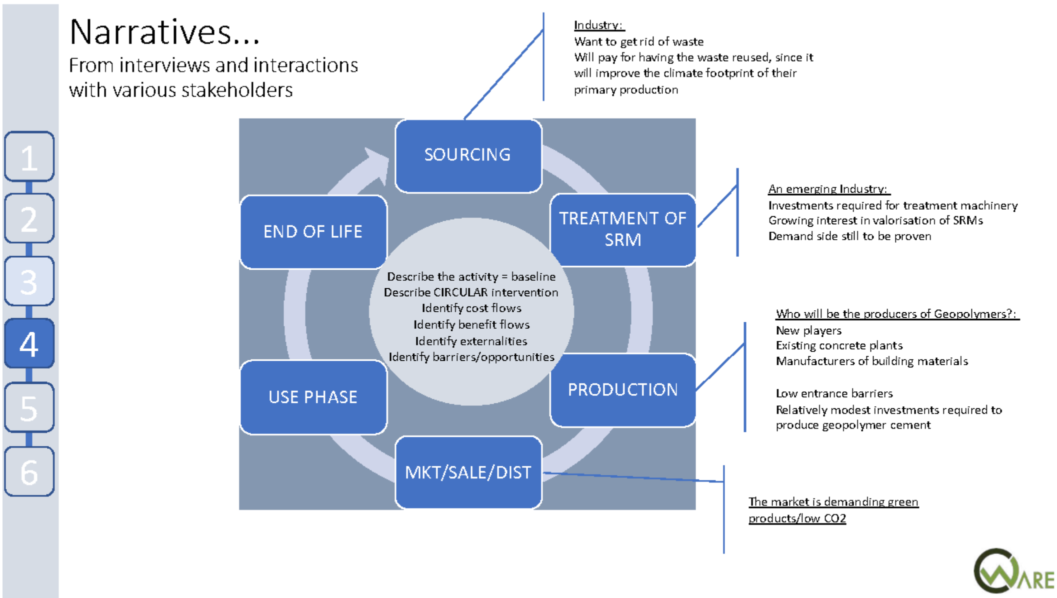

OUR CIRCULAR
ECONOMIC MODEL
1
2
3
4
5
6
Aim:
to understand the business case at
each level of the value circle
Approach:
Interviews with stakeholders
Narratives
Data and statistics
Modelling and analysis
SOURCING
TREATMENT OF
SRM
PRODUCTION
MKT/SALE/DIST
USE PHASE
END OF LIFE
Describe the activity = baseline
Describe CIRCULAR intervention
Identify cost flows
Identify benefit flows
Identify externalities
Identify barriers/opportunities
WARE


Results so far - developing the CE Tool
1
2
3
4
5
6
A
B
D
The CE Tool is under development in
WOOL2LOOP and URBCON
WARE

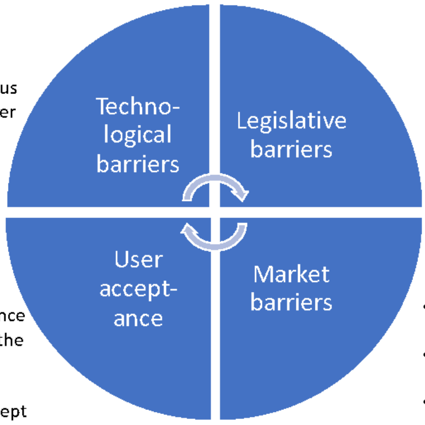

Applying the CE Tool
1
2
3
4
5
6
SOURCING
END OF LIFE
TREATMENT OF SRM
Describe the activity = baseline
Describe CIRCULAR intervention
Identify cost flows
Identify benefit flows
Identify externalities
Identify barriers/opportunities
USE PHASE
PRODUCTION
MKT/SALE/DIST
UNDER DEVELOPMENT
WARE


Narratives...
From interviews and interactions with various stakeholders
1
2
3
4
5
6
Industry:
Want to get rid of waste
Will pay for having the waste reused, since it will improve the climate footprint of their primary production
SOURCING
END OF LIFE
TREATMENT OF SRM
An emerging Industry:
Investments required for treatment machinery
Growing interest in valorisation of SRMs
Demand side still to be proven
Describe the activity = baseline
Describe CIRCULAR intervention
Identify cost flows
Identify benefit flows
Identify externalities
Identify barriers/opportunities
USE PHASE
PRODUCTION
Who will be the producers of Geopolymers?:
New players
Existing concrete plants
Manufacturers of building materials
Low entrance barriers
Relatively modest investments required to produce geopolymer cement
MKT/SALE/DIST
The market is demanding green products/low CO2
WARE

Main barriers in turning circular - the general picture

- Long term performance data
- OPC is a homogenous product, Geopolymer is not

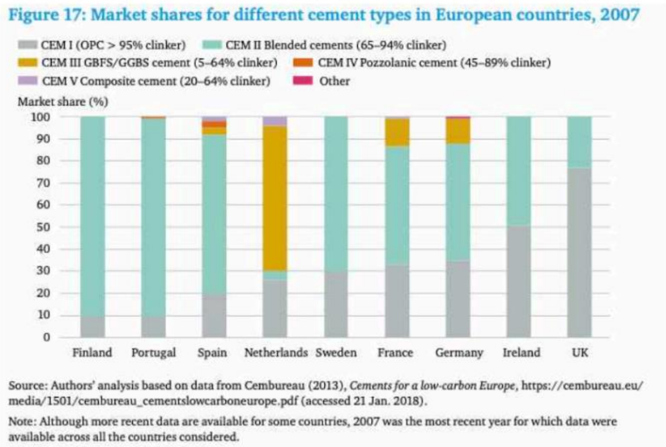
- Building codes
- Regulatory standards
- Hazardous waste considerations



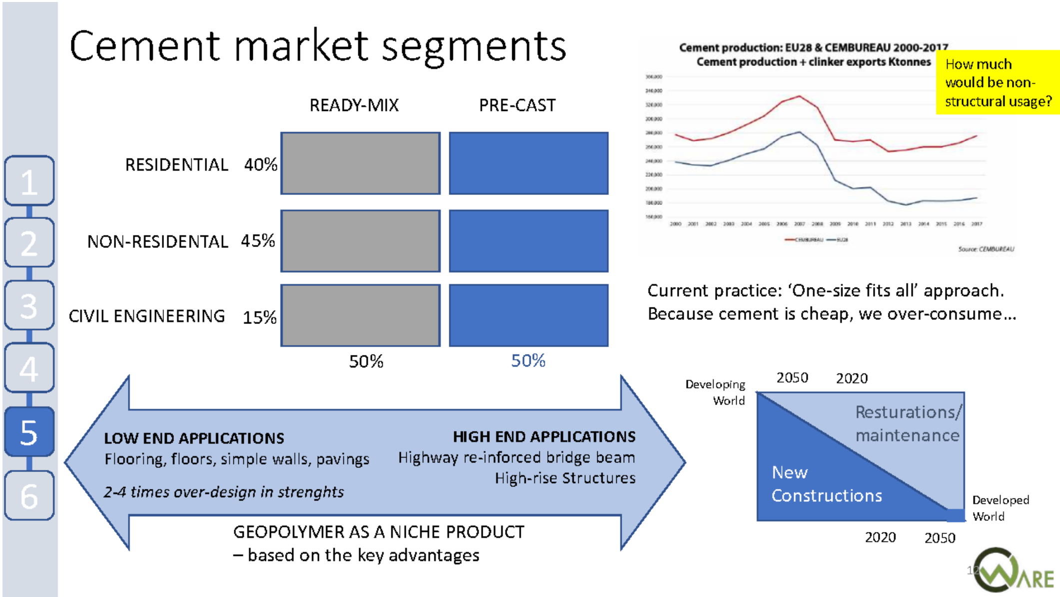
- Consumer and stakeholder reluctance
- Risks associated to the products
- Lack of reference cases/proof of concept

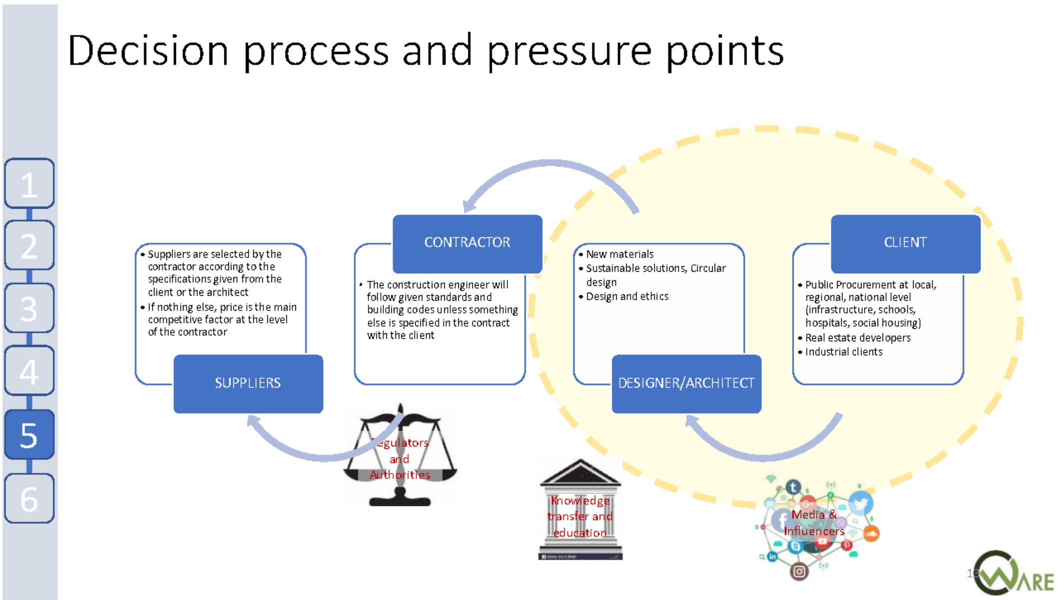
- Market prices of OPC relatively low
- Price on virgin materials still low
- Procurement procedures favor OPC

The competitive reality of geopolymer cement



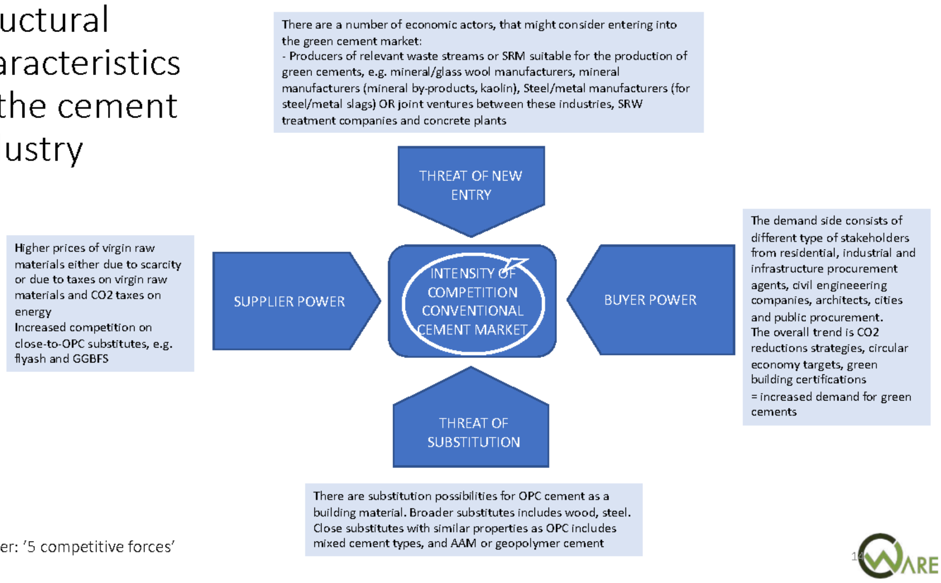
- Some countries are more change-ready than others
- NB: Old data (2007)


Cement market segments
READY-MIX
PRE-CAST
RESIDENTIAL 40%
NON-RESIDENTAL 45%
CIVIL ENGINEERING 15%
50%
50%
LOW END APPLICATIONS
Flooring, floors, simple walls, pavings
2-4 times over-design in strenghts
HIGH END APPLICATIONS
Highway re-inforced bridge beam
High-rise Structures
GEOPOLYMER AS A NICHE PRODUCT
– based on the key advantages
Cement production: EU28 & CEMBUREAU 2000-2017
Cement production + clinker exports Ktonnes
How much would be non-structural usage?
Current practice: 'One-size fits all' approach.
Because cement is cheap, we over-consume…
Developing World
2050
2020
Resturations/ maintenance
New Constructions
Developed World
2020
2050


Decision process and pressure points
CONTRACTOR
CLIENT
• Suppliers are selected by the contractor according to the specifications given from the client or the architect
• If nothing else, price is the main competitive factor at the level of the contractor
• The construction engineer will follow given standards and building codes unless something else is specified in the contract with the client
• New materials
• Sustainable solutions, Circular design
• Design and ethics
• Public Procurement at local, regional, national level (infrastructure, schools, hospitals, social housing)
• Real estate developers
• Industrial clients
SUPPLIERS
DESIGNER/ARCHITECT
Regulators and Authorities
Knowledge transfer and education
Media & Influencers

.

Structural characteristics of the cement industry



Porter: '5 competitive forces'

Discussion Points

- How to launch geopolymer cement into the market?
- How to orchestrate the value chain to ensure uptake of geopolymer cement and to overcome the identified barriers?
- What are the main challenges in implementing circular concepts like the URBCON concept, and geopolymer cement?

10. Securing future supply of secondary raw materials

Birgitte Holt Andersen

Secondary raw materials (SRMs) play an important role in some circular economy concepts, such as using by-products for AAM concrete (or geopolymer concrete), as researched in the DuRSAAM project. The material flows associated to the use of SRM are of importance and should be inline with the market dynamics, e.g. will there be enough suitable SRMs to feed the production of geopolymer cement in the future?

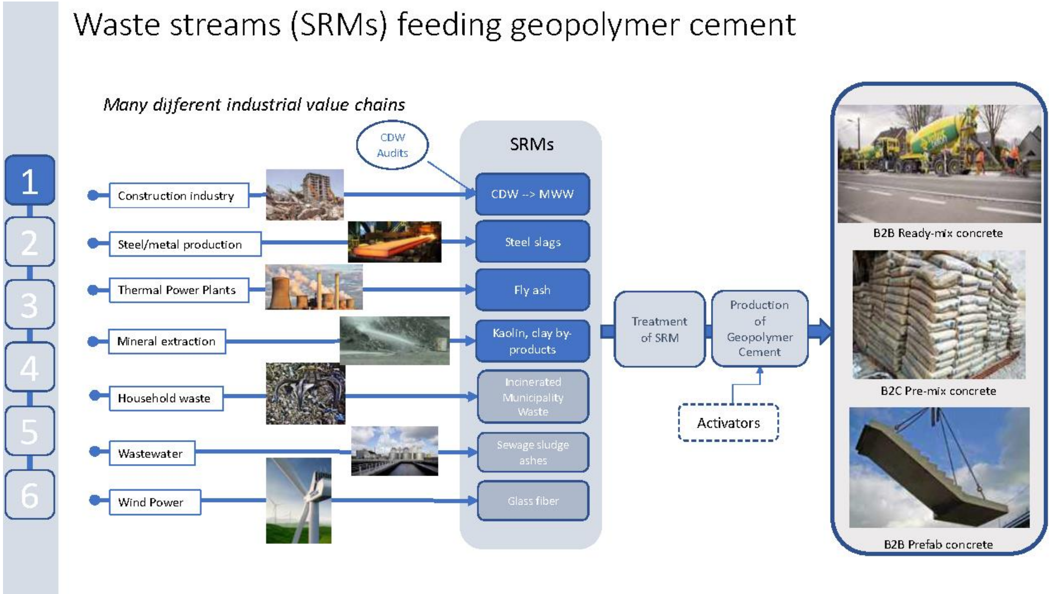
A video recording with further explanation is provided here (23 minutes to watch).

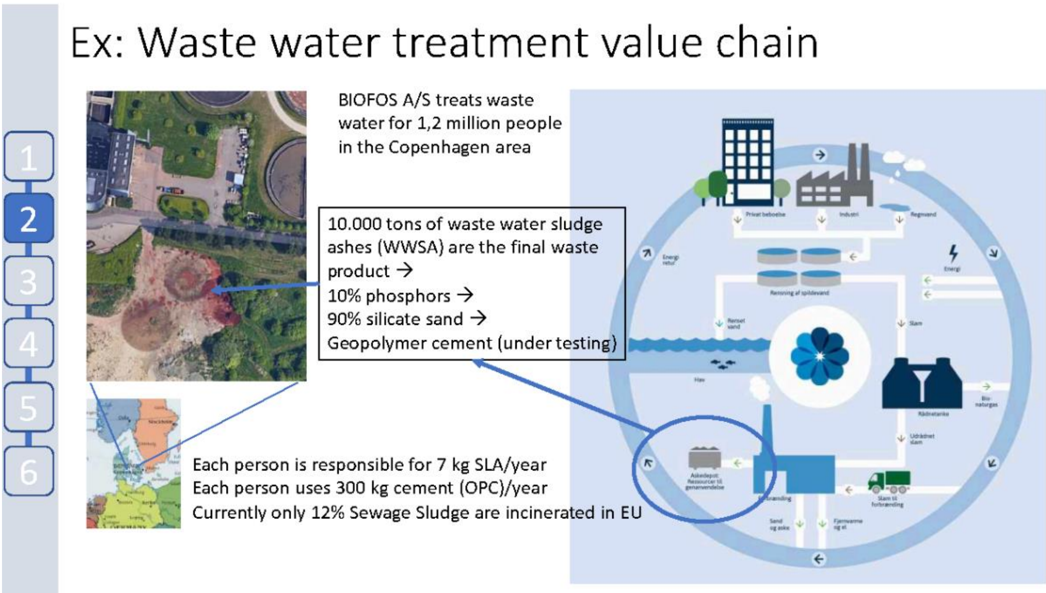
OFFICIAL PROGRAMME

11:00 – 11:20	Session 9 *Birgitte Holt Andersen, PhD, ApHER* Securing future supply of secondary raw materials (SRM) – will there be enough suitable SRMs to feed the production of geopolymer cement in the future?
11:20 – 11:30	Polling (short quiz)
11:30 – 11:45	Q&A session - discussion
11:45 – 12:00	Closing session

The main Subjects of session 9

1. Overview of SRMs suited for geopolymer cement production
2. Overview of availability: amounts and characteristics
3. Forecasting availability
4. What will determine the prices of the SRMs?
5. Potential SRMs??
6. Presentation of assignments and Discussion Points

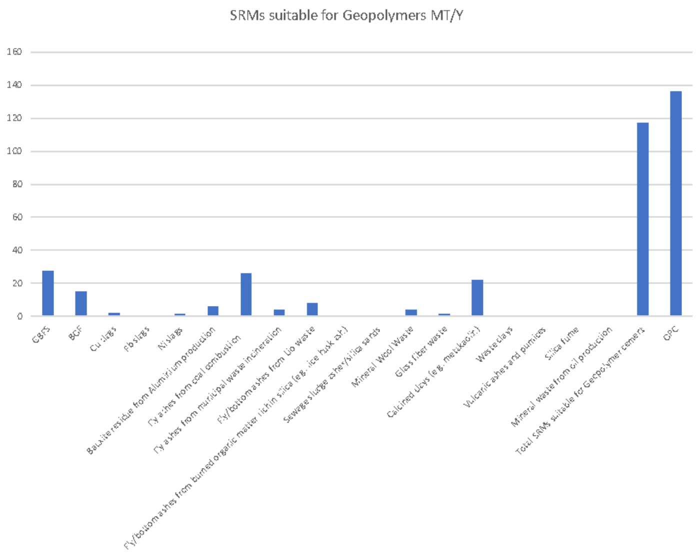

Waste streams (SRMs) feeding geopolymer cement
Many different industrial value chains
CDW Audits
SRMs
1
2
3
4
5
6
Construction industry
Steel/metal production
Thermal Power Plants
Mineral extraction
Household waste
Wastewater
Wind Power
CDW --> MWW
Steel slags
Fly ash
Kaolin, clay by-products
Incinerated Municipality Waste
Sewage sludge ashes
Glass fiber
Treatment of SRM
Production of Geopolymer Cement
Activators
B2B Ready-mix concrete
B2C Pre-mix concrete
B2B Prefab concrete


Ex: Waste water treatment value chain
1
2
3
4
5
6
BIOFOS A/S treats waste water for 1,2 million people in the Copenhagen area
10.000 tons of waste water sludge ashes (WWSA) are the final waste product →
10% phosphors →
90% silicate sand →
Geopolymer cement (under testing)
Each person is responsible for 7 kg SLA/year
Each person uses 300 kg cement (OPC)/year
Currently only 12% Sewage Sludge are incinerated in EU

1
2
3
4
5
6

Are there enough SRMs available?

- Stocks and flows of SRM
- Competing use
- Regional perspective/regional sourcing



1
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4
5
6

FORECASTING AVAILABILITY OF SRMs

STOCKS/FLOWS

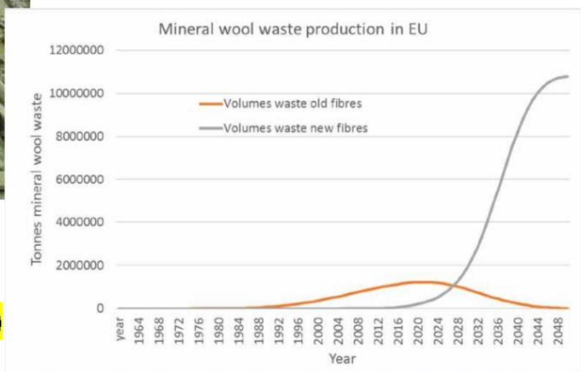


Figure 6: Expected mineral wool waste volumes (old and new fibres) - including shorter renovation cycles from 2018 on

Example
Mineral Wool Waste (MWW)

FORECASTING AVAILABILITY OF SRMs

Example
Wind mill wings (MWW)
Glassfiber

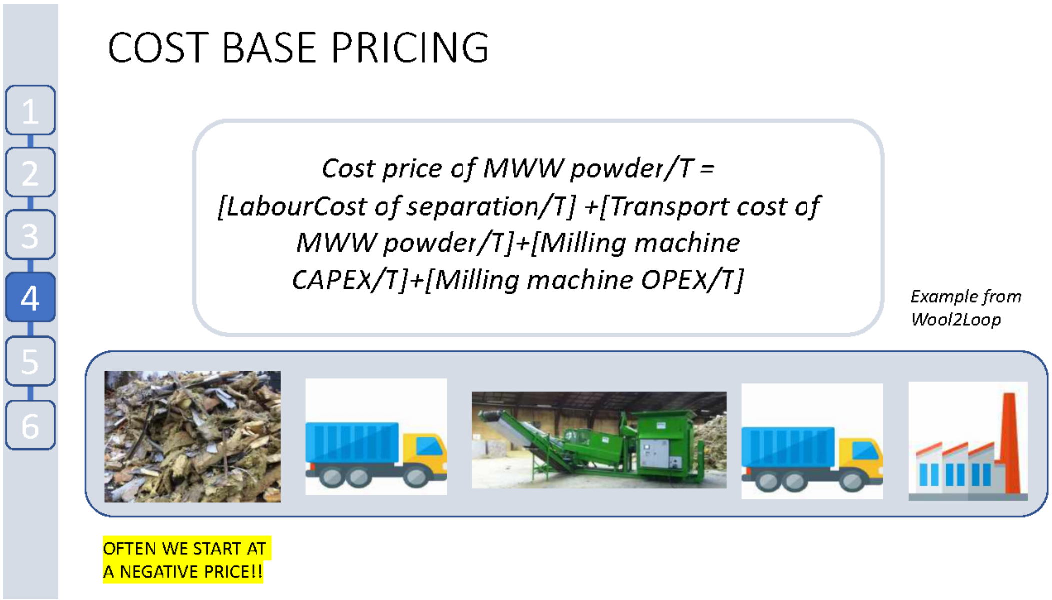
Different sources to estimate flows:

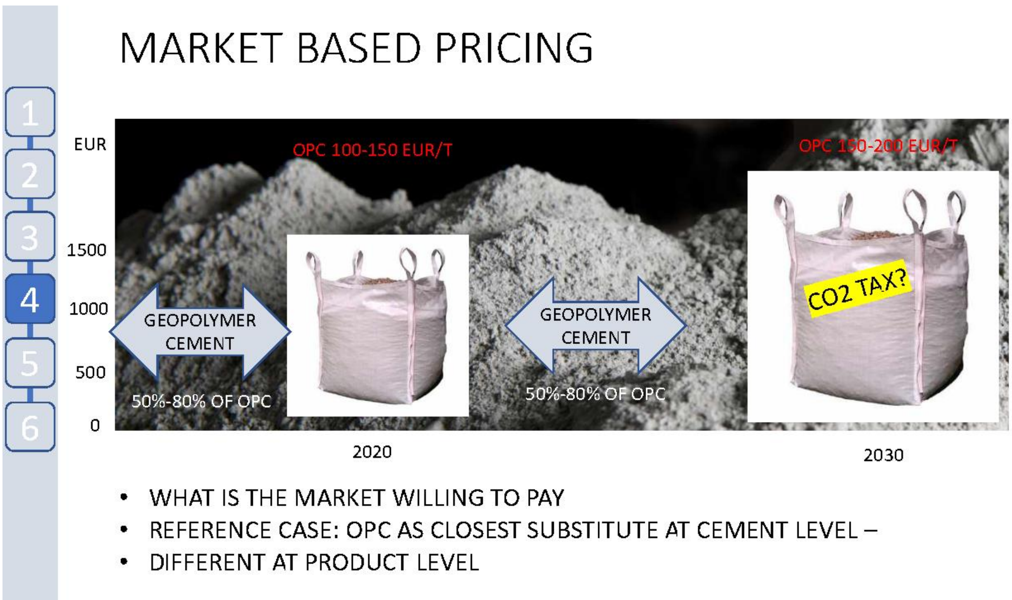
- Number of wings to be scrapped each year
- Number of leisure vessels to be scrapped each year
- Yearly production of glass fiber

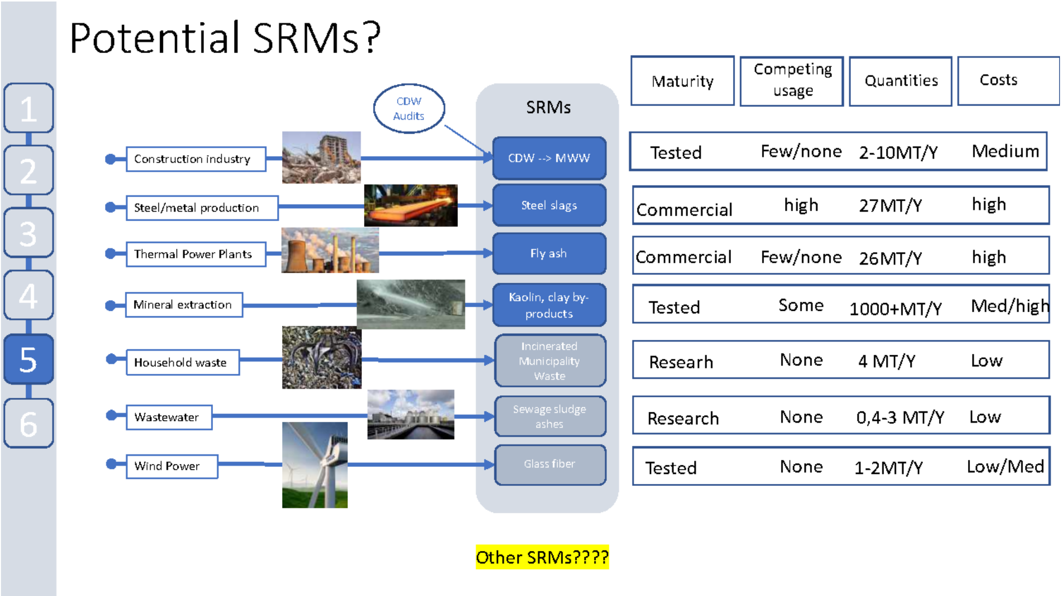
What will determine the price of the SRM?

In principle two ways of pricing a product:

- Cost base pricing
- Market based pricing


COST BASE PRICING
1
2
3
4
5
6
Cost price of MWW powder/T = [LabourCost of separation/T] +[Transport cost of MWW powder/T]+[Milling machine CAPEX/T]+[Milling machine OPEX/T]
Example from Wool2Loop
OFTEN WE START AT A NEGATIVE PRICE!!


MARKET BASED PRICING
1
2
3
4
5
6
EUR
1500
1000
500
0
OPC 100-150 EUR/T
OPC 150-200 EUR/T
GEOPOLYMER CEMENT
50%-80% OF OPC
GEOPOLYMER CEMENT
50%-80% OF OPC
CO2 TAX?
2020
2030
• WHAT IS THE MARKET WILLING TO PAY
• REFERENCE CASE: OPC AS CLOSEST SUBSTITUTE AT CEMENT LEVEL –
• DIFFERENT AT PRODUCT LEVEL


Potential SRMs?
1
2
3
4
5
6
CDW Audits
SRMs
Construction industry
Steel/metal production
Thermal Power Plants
Mineral extraction
Household waste
Wastewater
Wind Power
CDW --> MWW
Steel slags
Fly ash
Kaolin, clay by-products
Incinerated Municipality Waste
Sewage sludge ashes
Glass fiber
Maturity
Competing usage
Quantities
Costs
Tested Few/none 2-10MT/Y Medium
Commercial high 27MT/Y high
Commercial Few/none 26MT/Y high
Tested Some 1000+MT/Y Med/high
Researh None 4 MT/Y Low
Research None 0,4-3 MT/Y Low
Tested None 1-2MT/Y Low/Med
Other SRMs????


1
2
3
4
5
6
QUESTIONS
DISCUSSION
POINTS
EMERYS
CORNWALL, UK
KAOLIN PRODUCTION

DISCUSSION POINT 1: SECONDARY RAW MATERIALS

- Mention the SRMs you have worked with or you believe has the best potential for producing geopolymer cement
- Identify availability of SRMs (suitable for geopolymer) in your country or region and try to identify sourcing possiblities and quantities available

DISCUSSION POINT 2: Pricing the geopolymer cement

- Explain how you would price your developed geopolymer cement?
- Your considerations for calculating a price
- What are the customers willing to pay?
- What are your key selling points?
- Prepare a sales pitch - 2 minutes oral presentation

About the teachers

Geert De Schutter – Ghent University

Geert De Schutter is full professor Concrete Technology and ERC Advanced Grant holder at Ghent University. He is head of the Department of Structural Engineering and Building Materials, technical director of the Magnel-Vandepitte Laboratory and former RILEM Director of Development. He is fellow of RILEM and ACI, and recipient of several national and international awards. His research is situated in the following domains: concrete technology, hydration and microstructure development, properties of hardening concrete, durability of cementitious materials, self-compacting concrete, rheology of cementitious materials... He is author of a few text books, including “Damage to Concrete Structures”.

Guillaume Habert – ETH Zurich

Guillaume Habert holds the Chair of Sustainable Construction and is associate professor at the ETH Zürich. His work focused on the development of sustainable concrete. He has lectured on sustainable construction and has taught in various engineering and architectural schools. In 2015, he was awarded the RILEM Robert L’Hermite medal for his pioneering work on LCA of concrete and recycling processes.

Birgitte Holt Andersen - Cware

Birgitte Holt Andersen is heading the research and consultancy activities at CWARE and is involved in a number of research projects concerning Circular Economy, resource efficiency, resilience and sustainability of Cities. Birgitte also acts as an expert adviser to the European Commission on specific programmes of the H2020 RTD framework Programme. Birgitte is an experienced economist/PhD working in both research, industry and for the European Commission. Birgitte’s main interests are circular economic modelling, emerging industries and exploitation of innovative products/services/business concepts that can help our societies in becoming more sustainable.

Stijn Matthys – Ghent University

Stijn Matthys is full professor on renovation of civil structures at Ghent University, Magnel Laboratory for Concrete Research, furthermore he is manager of the Ghent University DuraBUILDmaterials knowledge cluster. His expertise relates to structural renovation of civil structures, fibre reinforced polymer (FRP) reinforcement, structural behaviour of concrete structures, damage diagnostics and monitoring, and technologies for durable building materials and techniques.

Marijana Serdar – University of Zagreb

Marijana Serdar works as Assistant Professor at the Department of Materials. Her main field of research interest is design, testing and application of more durable and sustainable construction materials and development of design approaches for more durable structures. In 2015 she received annual award for young scientist "Vera Johanides " from Croatian Academy of Engineering. Currently, she is managing 2 and participating in 1 project in the field of alternative binders for concrete, and is managing 1 project on development of autonomous system for assessment of structures. She is mentoring PhD students in a newly formed LATOM laboratory.

About DuRSAAM

DuRSAAM is a collaborative PhD framework creating a critical mass of experts skilled in innovative alkali-activated material (AAM) concrete, as a key enabling technology for a sustainable and resilient built environment. AAM technology presents a new generation of materials, ideally conceived to respond to the need for more efficient, durable, eco-friendly and reliable construction, and utilizing by-product resources as raw materials. Modern concrete will be produced with low carbon footprint (CO2 emissions reduced by 80%), lower energy consumption and reduced use of primary resources (>1.5 t raw materials are quarried per t Portland cement clinker; this will be reduced by >60%), and with an addressable market for AAM binders of 5 B€/yr. DuRSAAM answers unmet industry demands, to facilitate emerging AAM technology for continued market entry and to unlock its potential in society.

The consortium brings together 7 academic and 15 non-academic partners, to excel in the scientific development and exploitation of AAM concrete, advancing design, modelling and practice beyond the state-of-the-art. It holds a unique focus on: (1) today's concerns of users and engineers that the durability and sustainability of AAM concrete is yet insufficiently quantified; and (2) provision of an AAM technology for rehabilitation of structures to meet the growing demand for renovation, to be developed in parallel with AAM for new concrete structures.

DuRSAAM runs from 2018 till 2023 and delivers world-leading training in this multidisciplinary field through 13 PhDs in interrelated aspects of AAM concrete, fibre reinforced high-performance concrete, and textile-reinforced mortar, as well as sustainability assessment. The outcomes will be instrumental in delivering a sustainable future in Europe's construction industry, which is increasingly driven by the growing demand for durable yet cost-effective solutions, driving a greater focus on reliable and comprehensive eco-efficient material technologies such as AAM.

The PhD Training Network on Durable, Reliable and Sustainable Structures with Alkali-Activated Materials

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 813596 DuRSAAM.