# Regelsæt for specifikation og dokumentation af krav til $CO_2$-belastning

Teknisk rapport, 2019

Grøn omstilling af cement- og betonproduktion

## Titel

Regelsæt for specifikation og dokumentation af krav til $CO_2$-belastning

**Projekt**

Grøn omstilling af cement- og betonproduktion

## Arbejdspakke

I1: Fremtidens krav til grønne betonkonstruktioner

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## Om Innovationskonsortiet

Innovationskonsortiets overordnede mål er at udvikle løsninger, som er med til at skabe et grundlag for fortsat grøn omstilling af cement- og betonproduktion i Danmark. Projektet gennemføres i perioden fra marts 2014 til marts 2018 og er medfinansieret af InnovationsFonden. Projektets hjemmeside er www.gronbeton.dk. Deltagerne i innovationskonsortiet er:

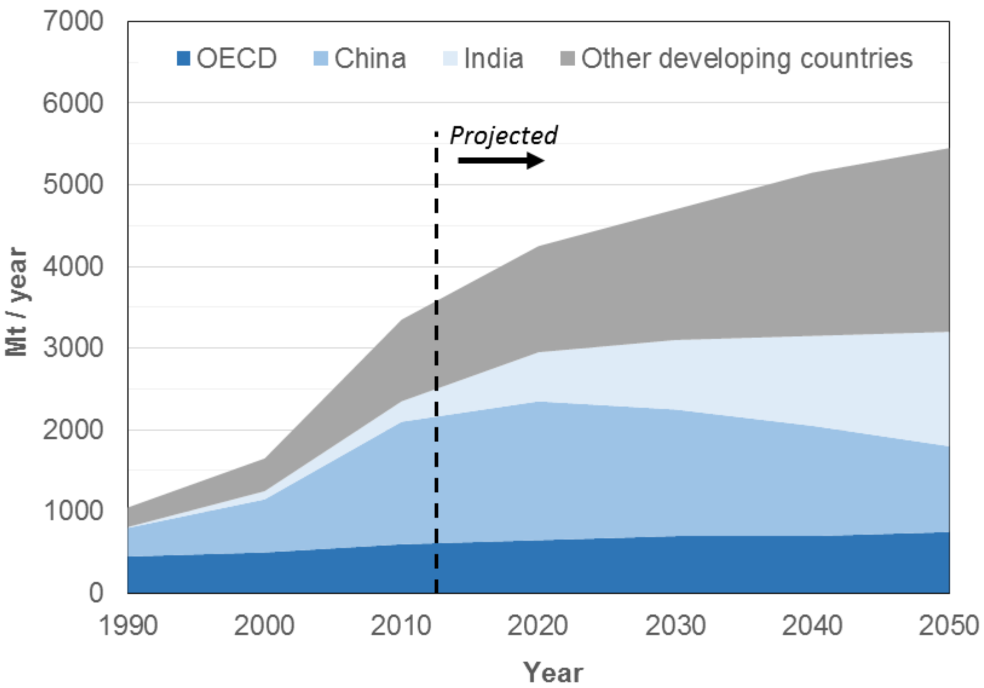
| | | |
|---|---|---|
| Aalborg Portland A/S | Vejdirektoratet | Banedanmark |
| Femern A/S | Rambøll Danmark A/S | Sweco A/S |
| MT Højgaard A/S | Unicon A/S | Dansk Beton, Fabriksbetonforeningen |
| Energistyrelsen | Københavns Erhvervsakademi | |
| Erhvervsakademiet Lillebælt | Via University College | Erhvervsakademi Sjælland |
| DTU Byg | Teknologisk Institut (projektleder) | Center for Betonuddannelse |

## Indhold

# 1. Introduktion

Innovationskonsortiet ”Grøn omstilling af cement og betonproduktion” er et dansk forsknings- og udviklingsprojekt fra 2014 til 2018, som er støttet af Innovationsfonden. Projektet samler en stor del af værdikæden og har som hovedformål at reducere miljøaftrykket fra beton ved at undersøge konsekvenserne af at anvende nye alternative cement- og bindersystemer til at reducere emissionen af drivhusgasser, primært kuldioxid $CO_2$, men også gasser som methan (CH4), carbonmonooxid (CO), dinitrogenmonooxid (N2O), svovlhexafluorid (SF6) og ethan (C2H6). Resultaterne omsættes til praktisk anvendelige teknologier til brug i betonindustrien gennem demonstrationsprojekter. Dette for blandt andet at imødekomme, at flyveaske fra kulfyrede kraftvarmeværker bliver en knap ressource og at det globale behov for beton er stærkt stigende.

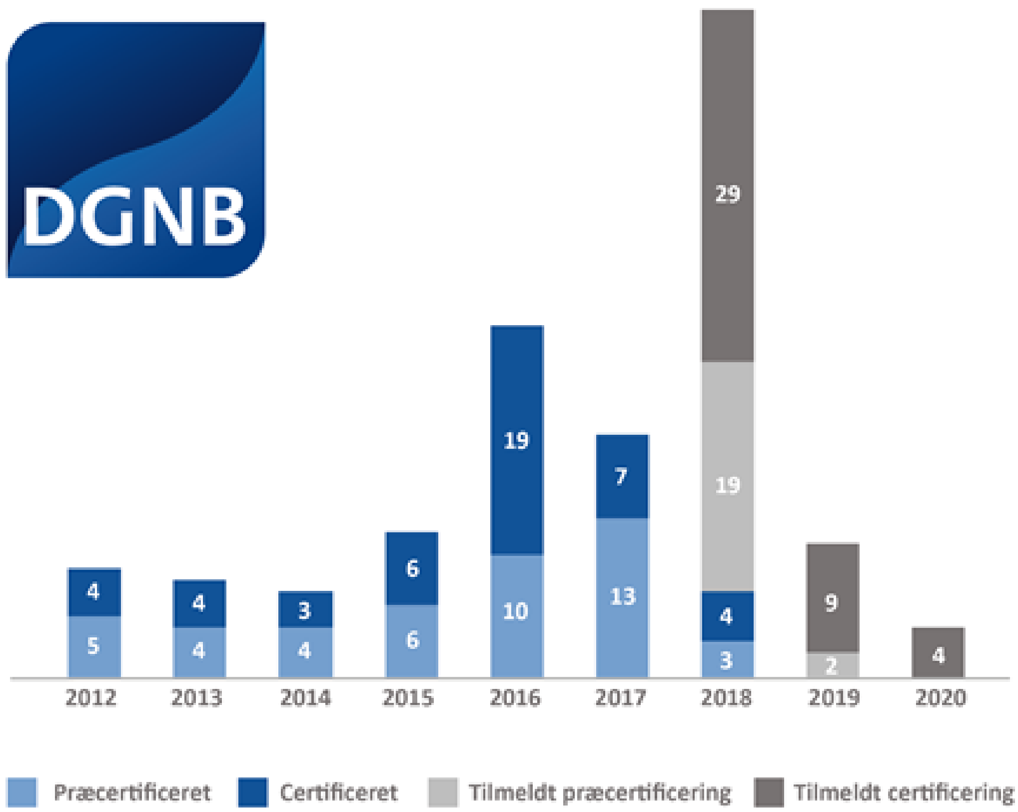
Figur 1-1 viser et bud på fremskrivning i den globale produktion af cement frem mod år 2050. Data fra Impadi et al. [1] opdeler fremskrivningen i forskellige regioner. Denne fremskrivning forudsiger, at behovet for cement vil stige med ca. 60 % fra 2010 til 2050. Behovet for cement bliver særlig stort i udviklingslandene, hvor stigende befolkningstal og urbanisering har skabt et stort behov for boliger og infrastruktur. Tilsvarende fremskrivninger, der netop er udgivet i IEA’s rapport fra 2018 “Technology Roadmap Low-Carbon Transition in the Cement Industry” [3], forudsiger en global stigning i behovet for beton på mellem 12 og 23 % fra 2014 til 2050. Det skal dog nævnes, at disse stigninger kun forventes at ske i udviklingslandene. Der forventes således kun en marginal stigning i OECD landene, herunder EU og Danmark, hvilket også fremgår af Fig. 1-1.




*Figur 1-1. Estimat for verdens Portland cementproduktion frem mod år 2050. Fremskrivning opdelt på forskellige regioner [1].*

Udover udvikling af ny betonteknologi, har projektet som formål at undersøge mulighederne for at implementere og kvantificere betons miljøaftryk i byggeri- og anlægssektoren. Grøn omstilling af cement- og betonproduktionen er i dag især styret af økonomi (udbud og efterspørgsel) og de til en hver tid gældende krav og regler for byggeriet. Der er en klar forventning om, at byggeri- og anlægssektoren vil blive pålagt øgede krav i form af reducerede miljøpåvirkninger og øget bæredygtighed. Blandt andet er det på tale at indføre frivillige bæredygtighedsklasser i bygningsreglementet [4] i lighed med hvad der tidligere er gennemført med lavenergiklasser.

Indenfor byggeriet af især domiciler, institutioner og hoteller mv. er der stigende efterspørgsel efter bæredygtigheds-certificeringer af bygninger. I Danmark er det non-profit organisationen Green Building Council Denmark, som administrerer bæredygtighedscertificering af bygninger i henhold til DGNB standarden. Et stigende antal byggerier tier er tilmeldt denne ordning siden starten i 2012.




*Figur 1-2. Antallet af DGNB certificerede byggerier [5].*

Som et led i DGNB certificeringsprocessen vurderes byggeriets samlede miljøpåvirkning i form af en LCA – for opførelsen og for driften af byggeriet. Bilag 2 giver en overordnet gennemgang af DGNB systemet med fokus på de områder, hvor beton spiller en markant rolle, jf. afsnit 4.5.

På anlægsområdet findes der ikke tilsvarende ordninger og der er p.t., hverken tradition eller motivation for at indføre miljørelaterede krav til infrastrukturprojekter. Der er dog tidligere foregået et fælles-nordisk arbejde med at udarbejde retningslinjer og værktøjer for LCA af anlægskonstruktioner og infrastrukturløsninger[1]. Dette koncept er dog aldrig blevet implementeret i Danmark.

Der er eksempler på større anlægsprojekter i Danmark hvor krav til $CO_2$ fodaftrykket, eller lignende er indført i grundlaget for entreprisen bl.a. kan nævnes udbuddet til den nye metro i København, hvor metroselskabet stillede krav om[2], at betonens $CO_2$ fodaftryk ikke måtte overstige 400 kg/$m^3$. Til sammenligning angiver Metroselskabet, at udledningen var ca. 700 kg/$m^3$ ved etablering af den eksisterede metro i 1990'erne. Udfordringen med denne type krav kan være, at det bl.a. ikke er entydigt, hvordan man dokumenterer overensstemmelse med kravet, eller hvilke livscyklusfaser der skal medtages. Dette kan skabe ulige konkurrencevilkår og grobund for tvister.

Nærværende rapport er fremstillet som et forsøg på at skabe overblik på dette område og opstille nogle scenarier for håndtering, dokumentation og formulering af miljøkrav.

## 2. Formål og målgruppe

Formålet med rapporten er at:

- Beskrive forskellige scenarier for opstilling og håndtering af miljøkrav til anlægsprojekter, herunder både projektering, udbud og udførelse.
- Danne grundlag for en anerkendt metode til at implementere miljørelaterede krav for betonbygværker i forbindelse med anlægsprojekter.
- Analysere betons aftryk i DGNB systemet og vurdere om der er anledning til at foreslå justeringer i den måde beton indregnes i DGNB pointskalaen.

Rapporten omfatter dermed ikke byggeriet, hvor der allerede er mange initiativer i gang til kvantificering af bæredygtighed, herunder DGNB-systemet. Ligeledes er byggemodning og vejprojekter ikke inkluderet i nærværende rapport.

Rapportens målgruppe er primært aktørerne i betonbranchen, herunder producenter og entreprenører, der er ansvarlige for at implementere og dokumentere kravene. Dertil kommer kravstillerne (rådgivere og bygherrer), som er ansvarlige for at definere kravene og opstille rammebetingelserne.

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[1] ETSI, Bridge Life Cycle Optimisation, 2004-2012. Dansk deltagelse fra Vejdirektoratet og Cowi.

[2] Metro Cityringen i København. https://www.m.dk/#!/om+metroen/metrobyggeriet/saadan+bygger+vi+metro/metrobyggeri+og+miljoe

## 3. Bæredygtighed

Begrebet bæredygtighed har eksisteret i mange år og i 1987 blev bæredygtig udvikling sat på dagsordenen med den såkaldte Brundtland rapport. Siden er der i FN regi udviklet såkaldte verdensmål for bæredygtig udvikling3 omfattende miljømæssig bæredygtighed samt økonomisk og social bæredygtighed. Nærværende rapport omfatter kun krav og mål for den miljømæssige bæredygtighed.

Livscyklusanalyse (LCA) er et redskab til at sammenligne forskellige løsningers miljømæssige påvirkninger. Bilag 1 til rapporten giver en grundig indføring i de vigtigste begreber og grundlaget for LCA samt de standarder og metoder, der ligger til grund for LCA.

### 3.1 Definitioner

Nedenfor er der givet nogle vigtige definitioner indenfor LCA:

- Deklareret enhed = en veldefineret kvantificering af et byggemateriale eller -produkt. For eksempel en kubikmeter beton af en given kvalitet, et ton cement, en mursten, et ton armering, etc.

- Funktionel enhed = en veldefineret enhed, der beskriver en funktion, som kan udfyldes i en given årrække. Fx definerer [6] sin funktionelle enhed som en meter vej/sti hævet over terræn i en given reference levetid.

- EPD = Environmental Product Declaration = Miljøvaredeklaration.
  Et dokument for en deklareret enhed af et givet materiale, byggevare eller produkt. fx 1 m2 præfabrikeret betonelement, 1 $m^3$ fabriksbeton, eller 1 ton stål.
  En EPD er oftest gennemført som en cradle-to-gate deklaration, hvor opførelsen, brugsfasen og end-of-life fasen ikke er medtaget. Ofte har producenten desuden inkluderet transportenergi svarende til en gennemsnitstransportafstand til kunden. EN 15804 [7] indeholder definitioner på de faser, som skal anvendes, når man udformer en EPD.

- LCA faser. En LCA opdeles i en række faser, der modsvarer dem som er benyttet i EPD. Faserne A1-A3 omfatter råmaterialer og oparbejdning af disse svarende til cradle-to-gate. Faserne A4-A5 omfatter transport til byggepladsen og opførelsen. Faserne B1-B7 omfatter brugsfasen indeholdende bl.a. vedligehold, reparationer og energiforbrug til drift. Faserne C1-C4 dækker end-of-life, herunder nedbrydning og bortskaffelse. Fasen D1 dækker evt. genanvendelse.

- RSL = Reference Service Life. Forventer levetid under normale brugsbetingelser.

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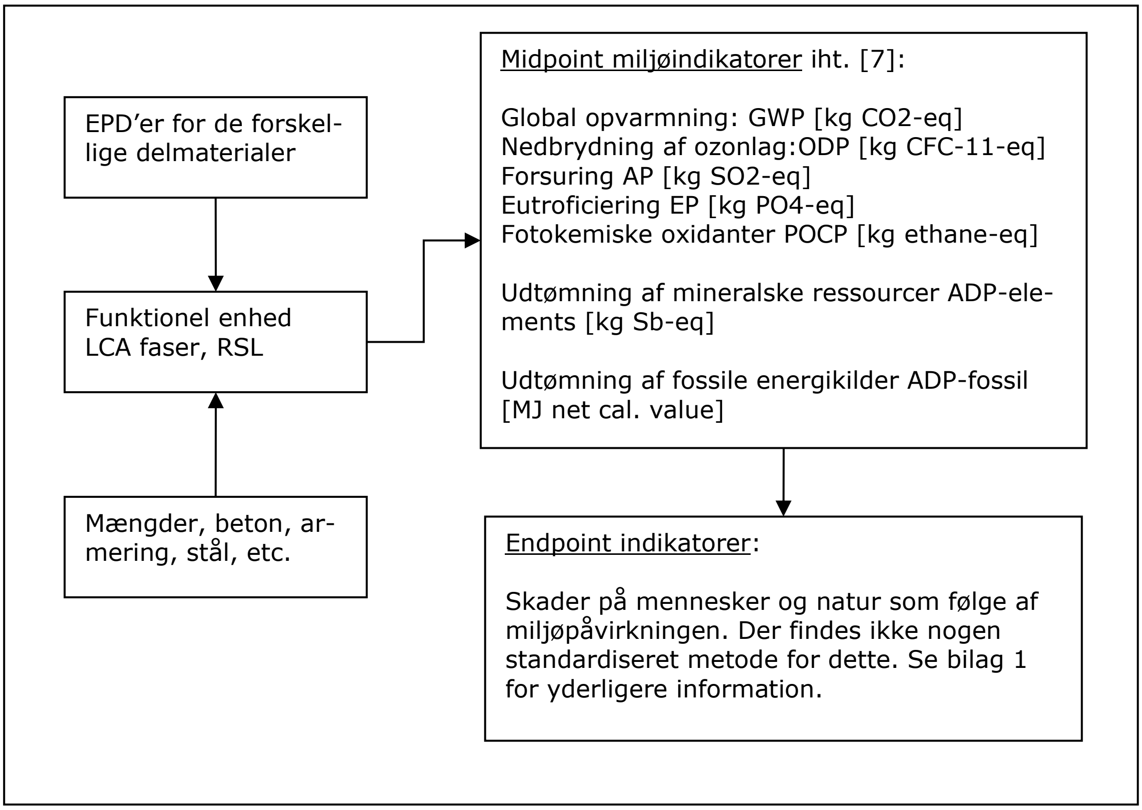
[3] http://mst.dk/virksomhed-myndighed/groen-strategi/baeredygtig-udvikling/hvad-er-baeredygtig-udvikling/

## 3.2 Livscyklusanalyse

Bilag 1 til rapporten indeholder eksempler på Livscyklusanalyser (LCA) baseret på cement og beton. Der beskrives vigtigheden af afgrænsning indenfor de forskellige processer og delmaterialer. Desuden beskrives udfordringen med at allokere miljøpåvirkninger mellem de forskellige delmaterialer, der indgår i en proces. Dette er især et issue, når produktionen indeholder restprodukter fra andre produktioner – fx slagge fra stålproduktion eller flyveaske fra energiproduktion.

Figur 3-1 viser de grundlæggende elementer i en LCA (baseret på Bilag 1). De 7 midpoint indikatorer, som er defineret i [7] er ikke en udtømmende liste. Der findes LCA værktøjer, hvor andre indikatorer såsom partikelforurening, giftighed overfor mennesker og natur, radioaktiv stråling, vandforbrug, arealanvendelse mv. indgår i midpoint indikatorerne. Dette betyder selvklart, at en direkte sammenligning mellem forskellige LCA værktøjer er meget vanskelig, jf. Bilag 1.




*Figur 3-1. Illustration af LCA.*

Når de enkelte miljøindikatorer er kvantificeret vha. input fra EPD'er for de enkelte delmaterialer og delkomponenter kan disse samles i såkaldte endpoint indikatorer, som beskriver skaderne på økosystemet og på menneskers sundhed. Dette kan lette sammenligninger mellem forskellige løsninger, da endpoint indikatorerne samler miljøpåvirkningen på færre tal. Der findes dog ikke nogen enighed omkring, hvordan de enkelte miljøindikatorer bidrager til endpoint indikatorerne, hvilket betyder at dette er forskelligt fra system til system sådan som det er illustreret i bilag 1.

En anden metode til at gøre sammenligning mellem forskellige løsninger nemmere er at normalisere miljøindikatorerne mht. et fast mål. Dette kan fx være samlet europæiske emissioner for et givet reference-år, eller omregnet til personækvivalenter. Et eksempel på dette kan ses i [8], hvor en normalisering af de 6 midpoint indikatorer (GWP, ODP, AP, EP, POCP og ADP) er foretaget mht. totale emissioner i Europa i 1995. Derefter er indikatorerne vægtet indbyrdes og summeret, således at et enkelt miljøpåvirkningstal opnås til sammenligning.

Der kan på tilsvarende vis foretages en kapitalisering, hvor de enkelte miljøindikatorer prissættes, hvorefter sammenligning er direkte muligt og de enkelte indikatores relative betydning bliver synlig.

Problemet er bare at der ikke er enighed om hvilken kapitalisering, der er korrekt at anvende - i den sidste ende er dette naturligvis et politisk valg. Reference [9] indeholder et hollandsk system, hvor midpoint indikatorer er kapitaliseret og der opereres med en miljøomkostning i Euro pr. deklareret enhed. Dette system er nærmere beskrevet i afsnit 4.2.

## 3.3 Miljøvaredeklarationer for byggevarer

Som nævnt ovenfor (se også Bilag 1) indgår miljøvaredeklarationer (EPD) som et vigtigt input til en LCA. For byggevarer er de grundlæggende regler for udarbejdelse af EPD defineret i den europæiske standard [7]. Standarden refererer videre til diverse bagvedliggende CEN og ISO standarder, der udgør en fælles ramme for udarbejdelse af miljøvaredeklarationer for byggevarer, eller –processer.

De enkelte produktgrupper vil udarbejde en såkaldt PCR, der definerer de specifikke EPD regler for det pågældende materiale eller produkt. En PCR kan være udgivet i CEN regi og have status af en standard ligesom det er tilfældet for fabriksbeton og betonelementer [10], eller cement [11]. Der kan også være tale om PCR udgivet af en brancheorganisation, eller i regi af det internationale fællesskab EPD International, eller det britiske BRE.

For at give eksempler på miljødata, som kan trækkes ud af en EPD er der i det følgende vist forskellige miljødata for cement, beton og armering. Der er anvendt følgende grundlag for disse miljødata:

- Databasen EcoInvent benyttet bl.a. af ETSI værktøjet
- Databasen ESUCO, som tidligere blev benyttet bl.a. af DGNB systemet[4].
- Diverse EPD'er offentligt tilgængelige på fx EPD International hjemmesiden, samt på andre hjemmesider såsom EPD Danmark og EPD Norge.

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[4] DGNB benytter p.t. den tyske database www.oekobaudat.de via software værktøjet LCAByg.

Man bør dog være opmærksom på, at en meningsfuld sammenligning af EPD'er kræver, at materialerne har samme ydeevne. For beton kan det være i form af fx bearbejdelighed, afbindingstid, styrke og holdbarhed. Krav til betonens konsistens har typisk stor indvirkning på mængden af pasta og dermed mængden af cement fx kræver en SCC beton mere pasta end en sætmålsbeton. Krav til styrkeudvikling har ligeledes stor betydning for valg af cementtype og cementindhold.

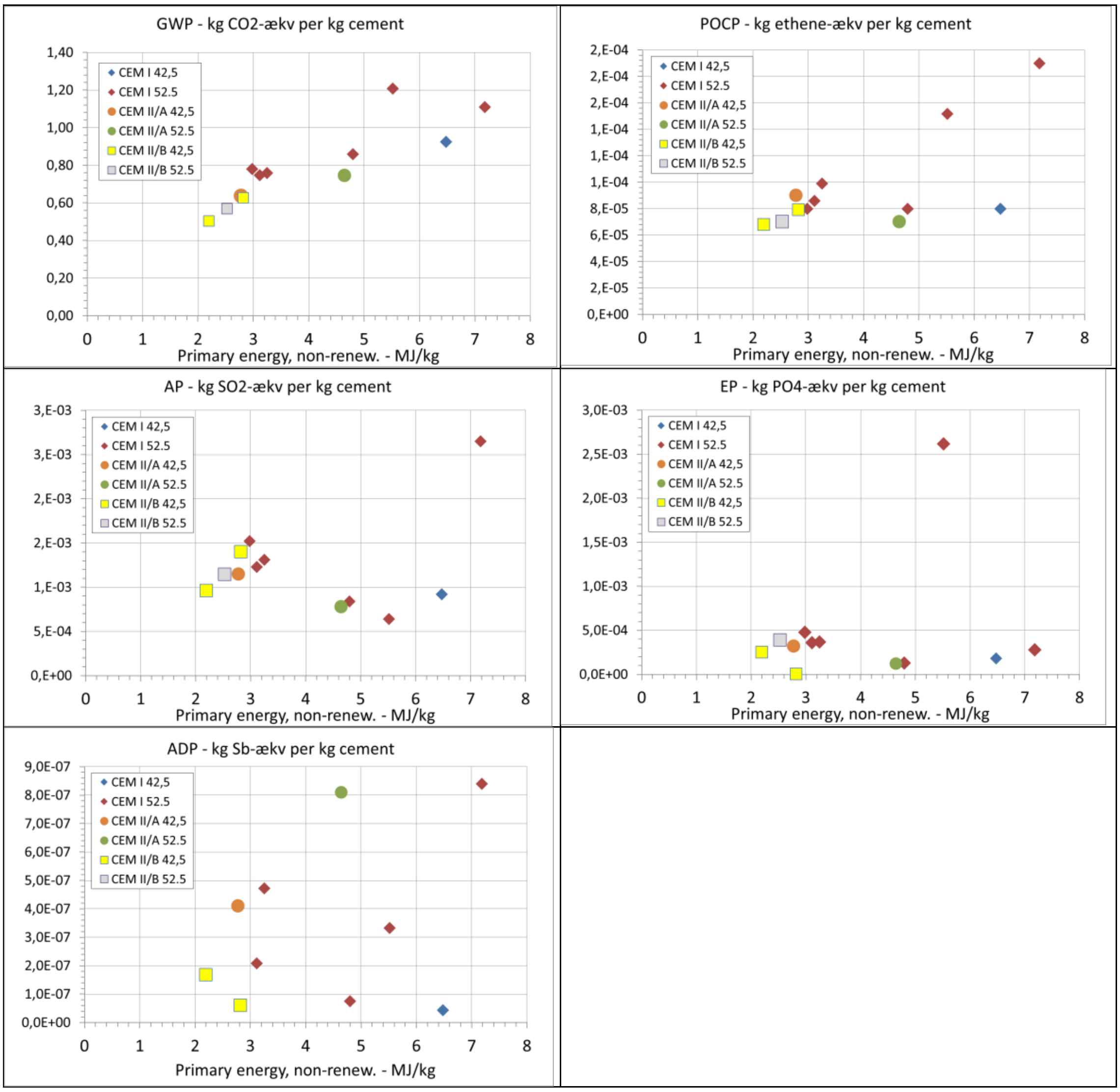
Krav til holdbarhed er typisk reguleret gennem EN 206, nationale annekser og krav, der foreskriver krav til betonsammensætningen (fx minimum cementindhold, styrkeklasse og maksimum v/c-tal) samt tilladelige cementtyper i forhold til eksponeringsklasse og konstruktionstype. Det kan gøre en sammenligning af EPD'er på tværs af lande vanskelig, da der kan være forskellige nationale regler og krav til betonsammensætning og valg af delmaterialer. Derudover kan der være forskel på designmæssige krav, fx krav til dæklagstykkelse, som kan have indflydelse på kravene til betonen.

### 3.3.1 Cement

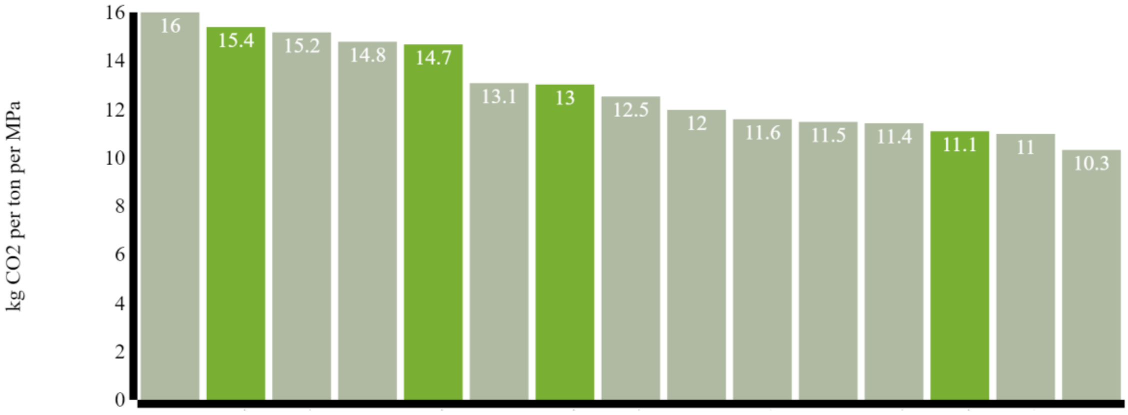
Figur 3-2 viser midpoint indikatorer for forskellige cementer for at give et indtryk af størrelsesordenen for de forskellige miljøindikatorer. Den deklarerede enhed er 1 kg cement. De enkelte miljøindikatorer er vist som funktion af ikke-fornybar energibehov, som er opgivet for den enkelte deklarerede enhed. De anvendte data er baseret på EPD'er, der er offentligt tilgængelige på EPD-Norges hjemmeside. De enkelte datapunkter er kategoriseret efter overordnet cementtype (dvs. CEM I, CEM II/A og CEM II/B) og deklareret styrkeklasse (42,5 eller 52,5 MPa).

Variationen er generelt ganske høj på de fire indikatorer ODP, AP, EP og POCP, mens GWP indikatoren ligger i et relativt smalt bånd direkte afhængigt af den forbrugte mængde ikke fornybar energi.

Cements $CO_2$ aftryk har stor indflydelse på betons $CO_2$ aftryk, typisk udgør cementens $CO_2$ aftryk op mod 90 % af den samlede $CO_2$ aftryk for beton. Men som indikeret ovenfor, så er en direkte sammenligning af cementers miljøindikatorer ikke nødvendigvis retvisende for, hvilket miljøaftryk betoner med forskellige cementer opnår. Ydeevnen af cementen har stor indflydelse på den mængde cement, som er nødvendig for at en beton opfylder de specificerede egenskaber. Fx har styrken af cementen indflydelse på, hvor meget man kan optimere sin pastasammensætning for at betonen lever op til den specificerede styrkeklasse. Ved sammenligning af forskellige cementers $CO_2$ aftryk kan det derfor være mere retvisende, at sammenligne forskellige cementers $CO_2$ aftryk ved at normalisere med ydeevnen. Som et eksempel på dette viser Figur 3-3 forskellige cementers $CO_2$ aftryk er normaliseret med den målte styrke efter 28 modenhedsdøgn. En lignende klassificering er benyttet af andre undersøgelser for beton [24], hvor betonens $CO_2$ normaliseres pr. $m^3$ pr. faktisk trykstyrke MPa.




*Figur 3-2. Cement. Data for midpoint indikatorer taget fra forskellige EPD'er offentligt tilgængeligt på EPD-Norges hjemmeside. Deklareret enhed er 1 kg cement. cradle to gate, fase A1-A3.*




*Figur 3-3. $CO_2$ aftryk for forskellige cementtyper normaliseret med trykstyrken[5]. De grønne søjler repræsenterer danske cementer fra Aalborg Portland. De øvrige er cementer fra Norge og Sverige [12].*

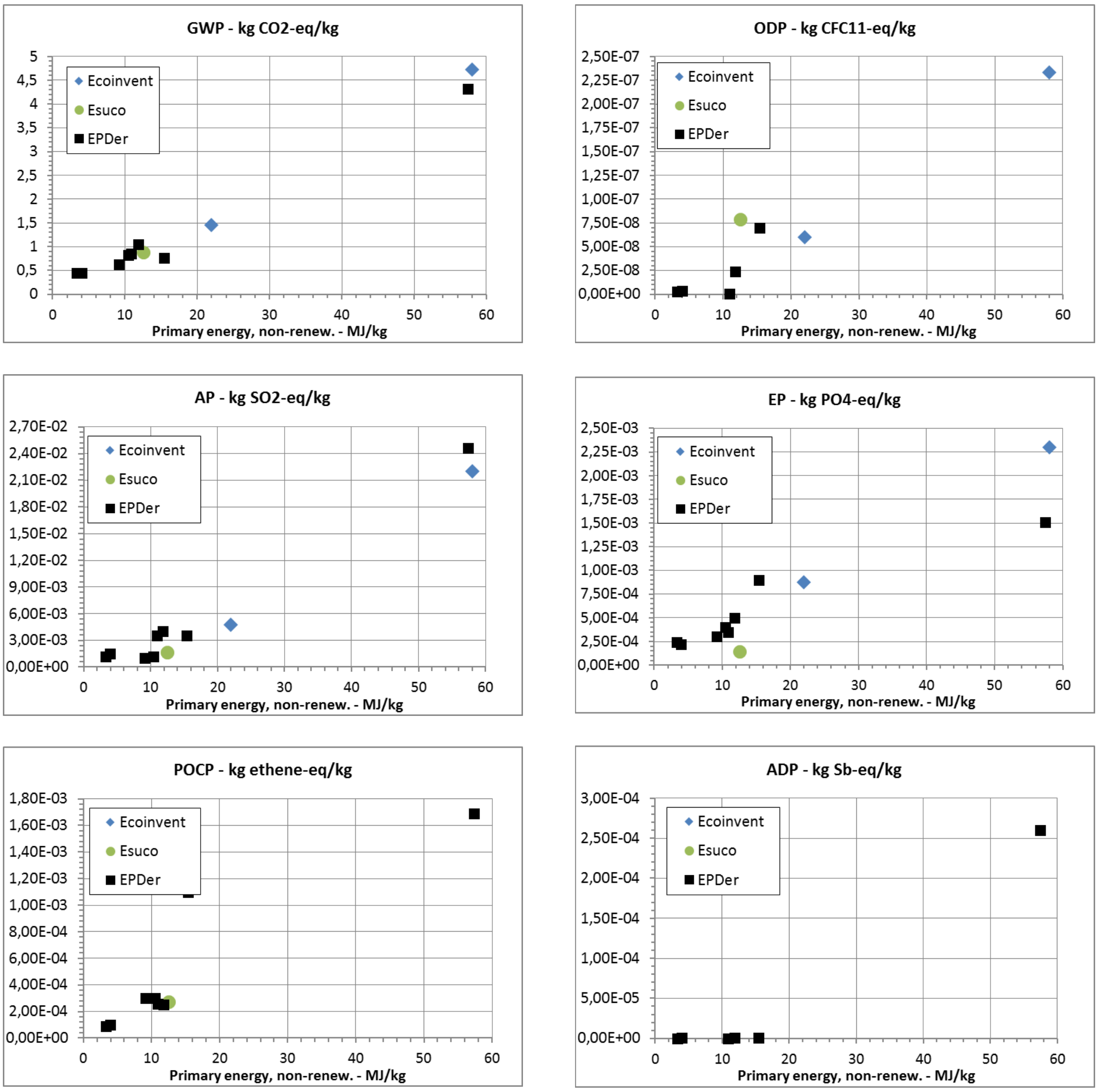
### 3.3.2 Armering

Data for armeringsstål taget fra Esuco og EcoInvent databaser er indikeret i Figur 3-4. De øvrige datapunkter stammer fra specifikke EPD'er fra det britiske CARES og fra EPD International.

Datapunkter er afbilledet som en funktion af ikke-fornybar energibehov, som er opgivet for den enkelte deklarerede enhed. De største energibehov på næsten 60 MJ pr. kg armeringsstål er gældende for rustfri armering. De laveste værdier for 4-5 MJ/kg er gældende for Celsa, som producerer armering i Norge vha. en meget stor andel af hydro-elektricitet.

På trods af nogen variation er der en klar sammenhæng mellem den forbrugte energi og de forskellige midpoint indikatorer. Dog er ADP (udtømning af mineralske ressourcer) kun målbar for rustfri stålarmering, da dette kræver forskellige knappe grundstoffer såsom krom og molybdæn at producere.

[5] Trykstyrker målt på 40 mm mørtelterninger.



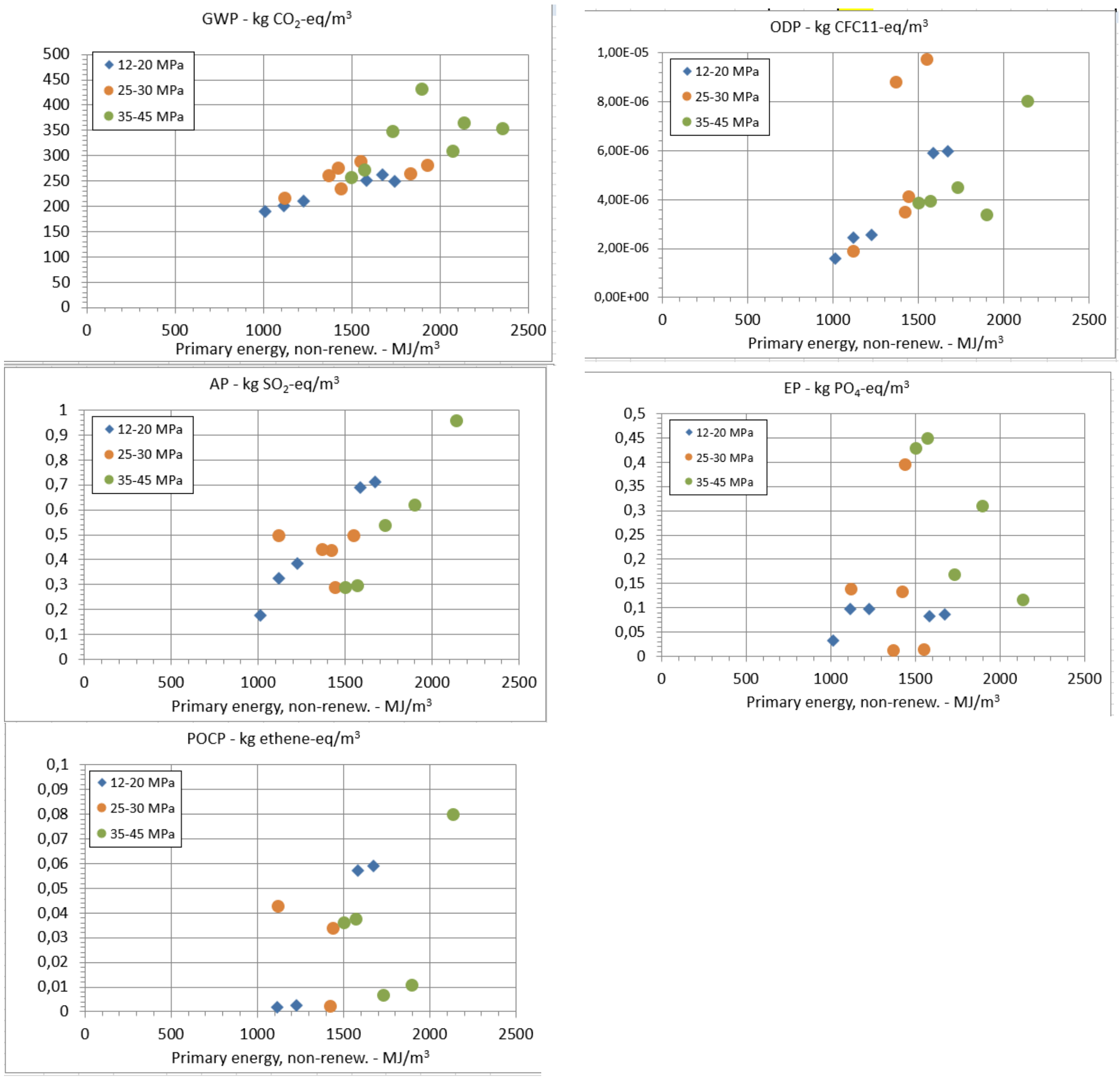

*Figur 3-4. Armeringsstål. Data for midpoint indikatorer taget fra forskellige EPD'er og databaser. Deklareret enhed er 1 kg armeringsstål, fase A1-A4.*

### 3.3.3 Fabriksbeton

Figur 3-5 indeholder tilsvarende miljødata for deklareret enhed 1 m$^3$ fabriksbeton. ADP indikatoren er dog udeladt, da den generelt viser forsvindende værdier for beton. Der indgår datapunkter fra EPD'er fra Danmark og Norge samt datapunkter fra EcoInvent og Esuco databaserne. De danske EPD'er er branchedata fra Dansk Byggeri Fabriksbetonforeningens hjemmeside, som svarer til de 4 gængse miljøklasser P20, M30, A35 og E40. Norske data er taget fra tilgængelige EPD'er baseret på norsk flyveaskecement.

Variationen er generelt ganske høj på de fire indikatorer ODP, AP, EP og POCP, mens GWP indikatoren ligger i et relativt veldefineret bånd direkte afhængigt af den forbrugte mængde ikke fornybar energi.

Tilsvarende data kan findes for andre materialer såsom asfaltbelægning, fugtmembran, etc. Det er dog udenfor afgrænsningen af nærværende rapport at gå yderligere i detaljer med dette.




*Figur 3-5. Fabriksbeton. Data for midpoint indikatorer taget fra forskellige EPD'er og databaser. Deklareret enhed er 1 m³ beton leveret på byggeplads, fase A1-A4.*

# 4. Implementering af betons miljøpåvirkning i design

## 4.1 Generelt

Det må forventes at miljøpåvirkningen vil komme til at indgå i højere grad i designprocessen for betonkonstruktioner i fremtiden, end det har været tilfældet hidtil. De seneste 20 år har der været stor fokus på betons miljøpåvirkning – specielt en nedbringning af $CO_2$ fodaftrykket – vha. optimeret betonsammensætning og en generel effektivisering af cementproduktionen[6]. Samtidig er der opstået en vis efterspørgsel efter miljøvaredeklarationer, som indgår i livscyklusanalyser. Der er ligeledes set en forøgelse i antallet af tekniske rapporter og guidelines - udgivet af de forskellige landes brancheorganisationer – som beskriver muligheder og redskaber. Et eksempel herpå er den britiske vejledning udgivet af The Concrete Centre [13], der beskriver de forskellige delmaterialers rolle for betons bæredygtighed samt angiver gennemsnitsværdier for $CO_2$ fodaftrykket i Storbritannien.

Specielt indenfor byggeriet findes der en lang række mærkningsordninger og certificeringer af bygninger. Disse omfatter LEED[7], BREEAM[8], DGNB[9]. Sidstnævnte anvendes især i Danmark og bestyres i Green Building Council Denmark, jf. afsnit 4.5. BREEAM indeholder desuden en ordning for anlægsprojekter (infrastruktur) under betegnelsen CEEQUAL.

Der er desuden udgivet en PCR [10] for betonprodukter, som vil ensrette miljøvaredeklarationer for såvel fabriksbeton som præfabrikerede elementer. Miljøvaredeklarationerne (EPD'er) danner grundlag for udarbejdelse af en LCA (Fig. 3-1). I visse tilfælde kender man ikke den præcise oprindelse af et givet delprodukt – fx armeringsjern – og der er behov for at benytte generiske og anerkendte databaser over miljøindikatorer. Disse kan fx være udarbejdet af en brancheorganisation, eller en forskningsgruppe tilknyttet et universitet.

I det følgende er der beskrevet tre scenarier som kan tænkes indført:

- Miljøkrav medtages i tilbudsprocessen, hvor entreprenøren skal prissætte miljøpåvirkningen. Entreprisen tildeles efter en kombineret vægtning af den direkte entreprenørudgift og den indirekte miljøpåvirkningsomkostning.

- Miljøkrav er indarbejdet i udbudsmaterialet og entreprenøren skal opfylde kravene under arbejdets gennemførelse. Opfyldelse af kravene reguleres vha. bod og bonus.

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[6] Se fx www.groenbeton.dk

[7] Amerikansk ordning: Leadership in Energy and Environmental Design. www.usgbc.org/LEED

[8] Britisk ordning: Building Research Establishment Environmental Assessment Method, der anvendes over hele verden. www.breeam.com

[9] Tysk bæredygtighedscertificeringsordning: Deutsche Gesellschaft für Nachhaltiges Bauen.

- Indførelse af klassesystem for miljøpåvirkning fra beton og armering. Tanken er at klasserne kan specificeres på lige fod med styrke- og holdbarhedsklasser.

For alle scenarier gælder at der normalt vil være størst effekt af miljøkrav, hvis der er tale om totalentreprise, hvor entreprenøren har en vis fleksibilitet i forhold til en given løsning. For hovedentrepriser er detailprojektet oftest optimeret således at der er færre muligheder for miljømæssige gevinster.

Det første scenarie er beskrevet nærmere i afsnit 4.2, hvor en hollandsk model er brugt som eksempel. Det andet scenarie er beskrevet nærmere i afsnit 4.3, hvor ETSI er brugt som eksempel. Det tredje scenarie er beskrevet i afsnit 4.4 med udgangspunkt i et norsk system med $CO_2$-klasser.

Fælles for alle scenarier er, at miljøkrav skal udformes således at følgende kriterier er opfyldt:

- Entydig funktionel enhed.
  PCR for broer [2] deklarerer for eksempel en funktionel enhed for en bro som en løbende meter bro pr. reference levetid. Her er der mulighed for at sammenligne forskellige broløsninger, hvor brodesign og valg af materialer er i spil.
  For beton og armering, hvor brodesignet og de tekniske krav allerede er specificeret er den funktionelle enhed oftest givet som $m^3$ eller tons.

- Entydig afgrænsning af de indgående materialer, herunder cut-off regler.

- Hvilke(n) (midpoint) miljøindikator(er) skal indgå?

- Hvilken vægtning mellem indikatorerne skal anvendes og hvordan skal disse normeres?

## 4.2 Den hollandske model

I den hollandske model sker der en kapitalisering af miljøindikatorerne således at der kan udvælges en løsning baseret dels på en tilbudt pris og dels på en miljømæssig omkostning [9]. Figur 4-1 illustrerer denne model.

Entreprenøren skal allerede i tilbudsfasen tilbyde at gennemføre projektet i henhold til en af fem klasser for $CO_2$ fodaftryk under udførelsen. For hver klasse man går op får man en rabat på sin tilbudte pris.

Entreprenøren skal ligeledes gennemføre en LCA, hvor miljøindikatorerne beregnes igennem hele livscyklus og der foretages en omregning til projektets samlede miljøomkostning. Der findes et fælles beregningsværktøj (DuboCalc), som skal anvendes til denne LCA. I DuboCalc's beregning indgår 6 midpoint indikatorer (GWP, ODP, AP, EP, POCP and ADP) samt toksicitet overfor mennesker og natur.

Efterfølgende skal der foretages en uafhængig dokumentation af om det udførte arbejde lever op til den tilbudte LCA. Hvis dette ikke er tilfældet, idømmes entreprenøren en bod.

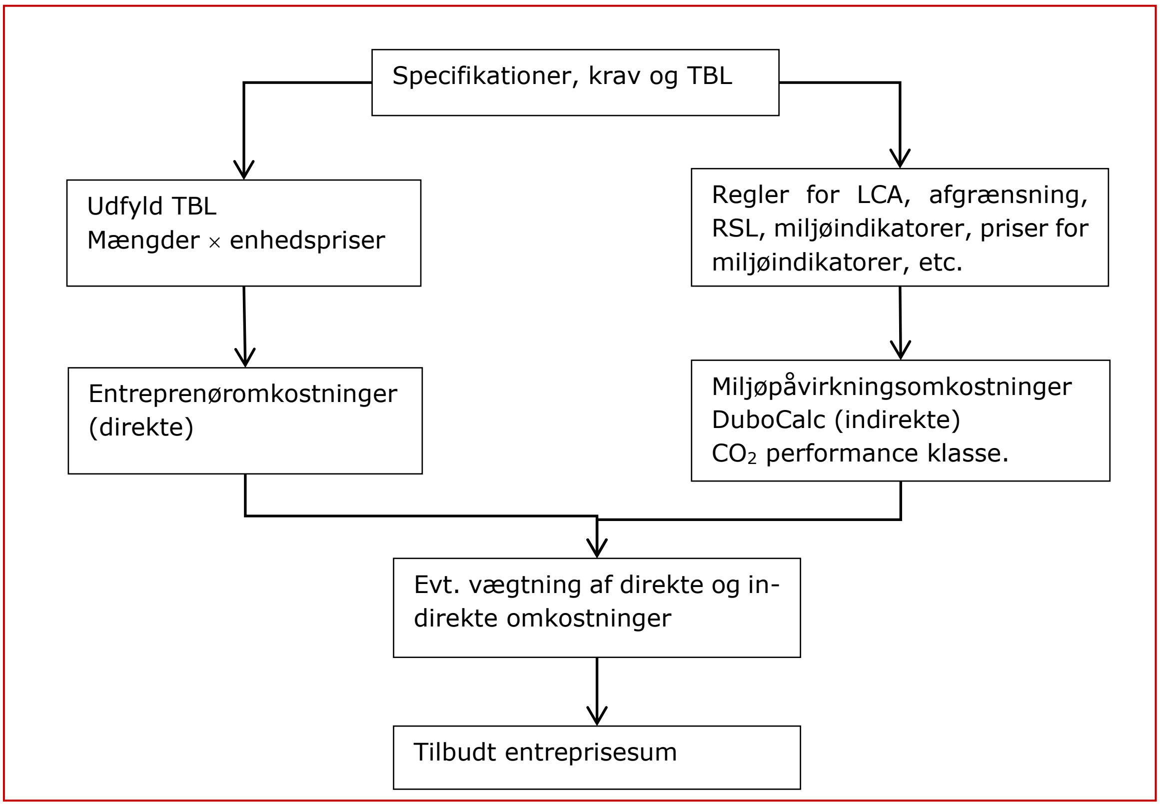
Bygherre har i sit udbudsmateriale fastlagt de overordnede rammer såsom krav til levetid, vægtning af miljøomkostning og tildelingskriterier samt bodsbestemmelser for entreprenøren såfremt han ikke opnår den lovede $CO_2$ performance klasse og miljøomkostning.

De anvendte kapitaliseringsrater for de normale miljøindikatorer er følgende i DuboCalc:

- GWP: 0,05 € / kg $CO_2$-eq
- ODP: 30,0 € / kg CFC-11-eq
- AP: 4,0 € / kg SO2-eq
- EP: 9,0 € / kg PO4-eq
- POCP: 2,0 € / kg eth-eq
- ADP: 0,16 € / kg Sb-eq

Ovennævnte rater stammer tilbage fra 2000 og må formodes at kunne trænge til en opdatering.

Der er ikke medtaget toksicitet i det følgende pga. mangel på data fra de tilgængelige EPD'er.




*Figur 4-1. Illustration af hollandsk model, hvor direkte entrepriseomkostninger og indirekte miljøomkostninger indgår i tildeling af kontrakt.*

Tabel 1 indeholder et eksempel på en beregning baseret på de hollandske tal og mængder for demobroen Lindholtvej ved Holstebro. Der er anvendt midpoint indikatorer taget fra Fabriksbetonforeningens generelle EPD-værdier[10] baseret på branchens gennemsnit for de to betontyper A35 og E40. Armeringsdata er taget fra armeringsproducenten Celsa's miljøvaredeklaration, der er tilgængelig på deres hjemmeside.

De to nederste linjer i tabel 1 viser det totale aftryk fra armering og beton fordelt på de 6 midpoint-indikatorer og efterfølgende multipliceret med hver enkelt indikators kapitaliseringsrate. Det fremgår tydeligt at GWP er den altdominerende faktor i dette regnskab.

*Tabel 1: Eksempel for demobro Lindholtvej. Der er anvendt kapitaliseringsrater taget fra DuboCalc.*

| **Midpoint indikator** | **GWP** | **ODP** | **AP** | **EP** | **POCP** | **ADP** |
|---|---|---|---|---|---|---|
| Enhed X | kg $CO_2$-eq | kg CFC-11-eq | kg $SO_2$-eq | kg $PO_4$-eq | kg eth-eq | kg Sb-eq |
| € / X | 0,05 | 30 | 4 | 9 | 2 | 0,16 |
| Armeringsstål | 48 tons armeringsstål | | | | | |
| Aftryk, X / tons | 450 | 3,7E-6 | 1,5 | 0,22 | 0,10 | 2,8E-4 |
| I alt, X | 21.600 | 1,8E-4 | 72,0 | 10,6 | 4,8 | 0,013 |
| Beton | Beton A35 i underbygning, 42 $m^3$ | | | | | |
| Aftryk, X / $m^3$ | 348 | 4,5E-6 | 0,54 | 0,017 | 0,0068 | 4,9E-5 |
| I alt, X | 14.616 | 1,9E-4 | 22,7 | 0,71 | 0,28 | 0,002 |
| Beton | Beton E40 i brodæk, 256 $m^3$ | | | | | |
| Aftryk, X / $m^3$ | 432 | 3,4E-6 | 0,62 | 0,031 | 0,011 | 6,0E-5 |
| I alt, X | 110.592 | 8,7E-4 | 158,7 | 7,9 | 2,8 | 0,015 |
| | Armering og beton, i alt | | | | | |
| Aftryk i alt, X | 146.808 | 12,4E-4 | 253,4 | 19,2 | 7,9 | 0,03 |
| Kapitalisering, € | 7.340 | ≈0 | 1.014 | 173 | 16 | ≈0 |

Den kapitaliserede miljøpåvirkning (fra armering og beton) beløber sig til ca. 64.000 DKK ud af en samlet entreprisesum[11] på ca. 5 mio. DKK. Hvis man forestiller sig at entreprenøren kan reducere GWP med ca. en tredjedel ved at vælge grønne betoner i stedet for de konventionelle så vil "miljø"-besparelsen ligge i størrelsesordenen 20.000 DKK. Alt i alt en relativ lille motivation for at vælge grønt.

### Vurdering

Den hollandske model har den fordel, at den indeholder et fælles beregningsværktøj med foruddefinerede materialer og parametre som alle skal anvende. Desuden indeholder det et krav om en vis grad af uvildig kontrol og opfølgning. Af ulemper ved systemet kan nævnes, at det baserer sig på en vægtning og kapitalisering, som dels kan diskuteres og som dels har en tendens til at blive relativt hurtigt forældet. Kapitaliseringsfaktorerne er i høj grad arbitrære, ikke videnskabelige og specifikke valg taget i Holland. For eksempel

[10] Kan findes på http://www.danskbeton.dk/fabriksbeton/produkter/miljoevaredeklarationer/

[11] Inklusiv jordarbejder, autoværn mv.

benytter StepWise2006[12] en rate på 0,083 € i stedet for 0.05 € pr. kg $CO_2$-eq. Alt andet lige stiger incitamentet til at reducere miljøbelastninger ved valg af høje kapitaliseringsrater. Det kræver altså nøje overvejelser at fastlægge kapitaliseringsraterne for at sikre at et sådant redskab skal have nogen reel motivation og effekt på miljøpåvirkningen fra et givet projekt.

## 4.3 ETSI – Optimering af livscyklus for brokonstruktioner

ETSI projektet blev startet tilbage i 2004 i samarbejde mellem de finske, norske og svenske vejdirektorater samt tekniske universiteter fra de tre lande. Danmark gik ind i projektet med Vejdirektoratet og Cowi senere i forløbet med fokus på livscyklus optimering af brokonstruktioner. Der blev bl.a. udviklet LCA og LCC regnearks-værktøjer baseret på tilgængelige databaser.

ETSI værktøjerne medtager en lang række materialer som er normale for brokonstruktioner, herunder beton, armering, fugtisolering, asfalt, stål mv. Hele livscyklus er medtaget fra opførelse hen over drift og vedligehold til nedrivnings-/genanvendelsesfasen. Ydermere indeholder ETSI et modul, som kan medtage miljøpåvirkningen fra trafikale omlægninger og kødannelser i forbindelse med reparationsarbejder eller nyanlæg, der medfører forsinkelser og gener for trafikken. Der blev også udarbejdet et modul for den æstetiske effekt af en brokonstruktion på landskabet og den visuelle kvalitet af bro og omgivelser. Disse moduler er ikke set i andre lignende værktøjer.

I Norge arbejder Statens Vegvesen fortsat med LCA værktøjer, der er videreudviklet og opdateret i forhold til ETSI. Blandt andet benyttes værktøjerne til at beslutte linjeføringer for større vej- og infrastruktur-projekter. Eller til at vælge blandt forskellige løsningsalternativer baseret på forskellige materialevalg mv. I Danmark er der ikke gjort anvendelse af ETSI.

Efter afslutningen på ETSI i 2012 er der publiceret en del forskellige artikler og studier baseret på arbejdet – et eksempel på dette ses i [8] og [14].

LCA værktøjet i ETSI indeholder næsten de samme midpoint indikatorer for miljø, som blev beskrevet i den hollandske DuboCalc model. Dog er POCP og ADP ikke medtaget i ETSI værktøjet. Systemet baserer sig på EcoInvent databasen og ReCiPe metoden for midpoint indikatorer. For flere detaljer omkring disse forskellige metoder se Bilag 1. Figur 4-2 indeholder en skematisk oversigt over, hvordan ETSI LCA-værktøjet fungerer.

[12] https://lca-net.com/services-and-solutions/impact-assessment-option-full-monetarisation/

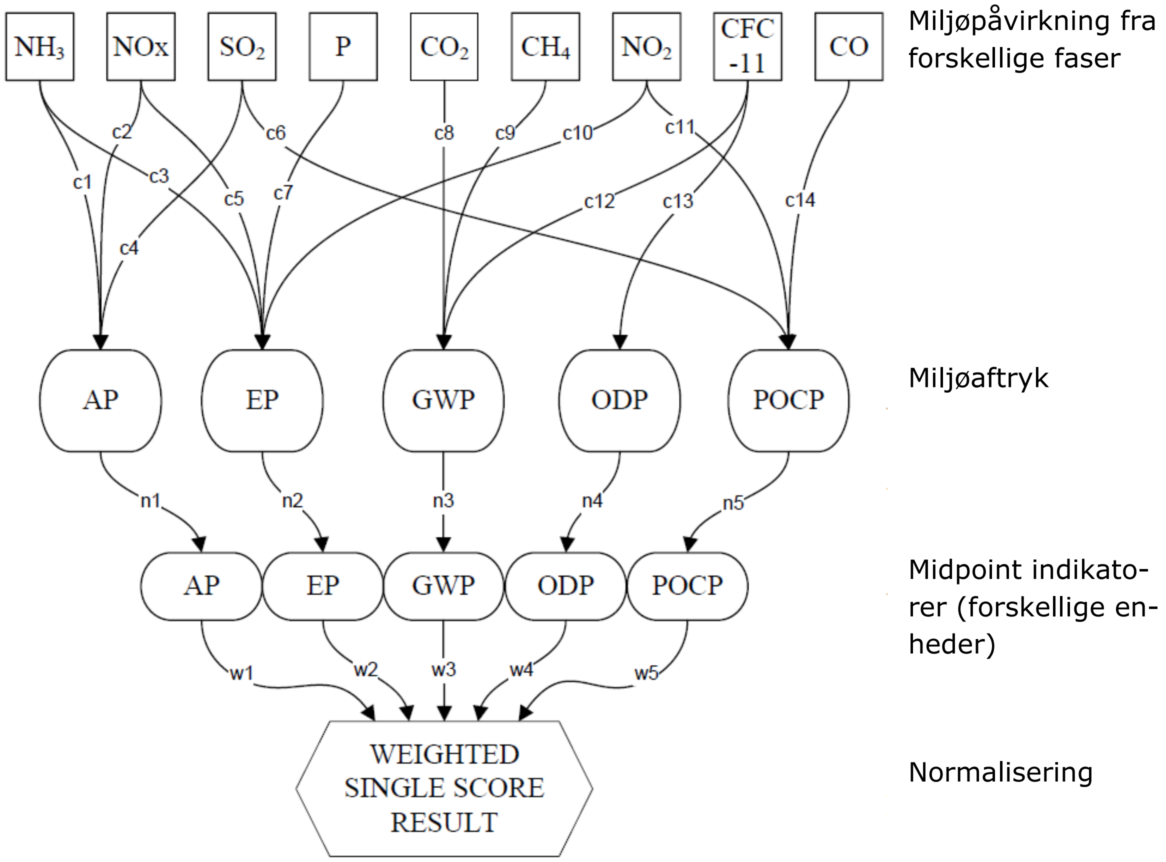
*Tabel 2: Eksempel for demobro Lindholtvej med materialedata fra ETSI værktøj. Der er kun medtaget påvirkninger fra konstruktionsmaterialer.*

| **Midpoint indikator** | **GWP** | **ODP** | **AP** | **EP** | **FD** | **Eco Toksicitet** |
|---|---|---|---|---|---|---|
| Enhed X | kg CO2-eq | kg CFC-11-eq | kg SO2-eq | kg PO4-eq | kg olie-eq | CTUe |
| Armering | 48 tons armeringsstål | | | | | |
| Aftryk, X / tons | 1.450 | 6,0E-5 | 4,74 | 0,87 | 481 | 0,75 |
| I alt, X | 69.600 | 2,9E-3 | 228,0 | 41,8 | 23.100 | 36,0 |
| Beton | Beton A35 i underbygning, 42 $m^3$ | | | | | |
| Aftryk, X / $m^3$ | 289 | 9,8E-6 | 0,50 | 0,016 | 29,3 | 0,26 |
| I alt, X | 12.100 | 4,1E-4 | 20,9 | 0,66 | 1.200 | 10,9 |
| Beton | Beton E40 i brodæk, 256 $m^3$ | | | | | |
| Aftryk, X / $m^3$ | 289 | 9,8E-6 | 0,50 | 0,016 | 29,3 | 0,26 |
| I alt, X | 73.900 | 2,5E-3 | 128,0 | 4,1 | 7.500 | 66,6 |
| | Armering og beton, i alt | | | | | |
| Aftryk i alt, X | 155.600 | 5,8E-3 | 376,9 | 46,6 | 31.800 | 113,5 |
| Normaliseret aftryk | 13,9 | 0,26 | 10,9 | 112 | 19,1 | - |

Noter til tabel: FD = fossil depletion (udtømning af fossile ressourcer) målt i kg olie ækvivalenter. CTU = Comparative toxicity unit.

Tabel 2 indeholder en beregning af demobroen med ETSI værktøjet, som i 2012 var tilgængeligt på hjemmesiden, hvor kun materialerne under opførelsesfasen er medtaget. Kun indikatoren for Eco toksicitet er medtaget her, da denne er størrelsesordner højere end human toksicitet. Normalisering af de forskellige midpoint indikatorer sker i forhold til værdier fra ReCiPe metoden per capita i EU [9]. ETSI indeholder dog ingen normaliseringstal i forhold til toksicitet. Hvis de normaliserede tal nederst i tabel 2 anvendes til at udpege den mest alvorlige indikator så er det EP, der vinder. I henhold til Petersen et al. [15], så er der behov for at videreudvikle ETSI til danske forhold herunder miljøinputparametre, beregningsmodeller, udvidelse af drift og vedligeholdelsesdelen og implementering af Vejdirektoratets trafikmodel. Vedrørende materialerne, så skal det udvikles til at indarbejde specifikke danske emissionsfaktorer for de materialer som anvendes i Danmark. Som det fremgår af tabellen, så anvender ETSI identiske miljøaftryk for en beton A35 og E40, hvilket ikke er retvisende i forhold til de normale danske betontyper.

Reference [8] indeholder en sammenligning mellem tre vejbroer (hhv. i stål, armeret beton og limtræ) baseret på ETSI principperne. Der foretages en normalisering og en vægtning, hvor GWP vægter ca. 3 gange så højt som de øvrige midpoint indikatorer. ETSI værktøjet indeholder også en mulighed for vægtning, men der er ikke angivet nogen specifikke forslag til, hvordan denne vægtning skal foretages. Sammenligningen i [8] konkluderer, at de tre vigtigste indikatorer er GWP, ADP og AP. Dette synes underligt i og med, at ADP slet ikke indgår i ETSI LCA-værktøjet. En nærmere undersøgelse af tallene bag sammenligningen i [8] viser dog at ADP bidraget primært kan henføres til produktion af stål, armering asfalt og bitumen. Toksicitet er ikke medtaget i sammenligningen under henvisning til at der hersker stor usikkerhed på input data. Desuden findes der normalt ikke tal for toksicitet i tilgængelige EPD'er, ligesom det heller ikke optræder direkte i standarderne [7, 10].




*Figur 4-2. Illustration af ETSI LCA værktøj. Taget fra projektrapport fra ETSI [9].*

**Vurdering**

ETSI værktøjet baserer sig på et simpelt regnearksbaseret LCA værktøj specielt skræddersyet til anlægsprojekter. ETSI medtager alle livscyklusfaser og specielt effekten fra transport og trafikantgener er et nyskabende element i forhold til andre lignende værktøjer. Dog lider værktøjet af de samme ulemper som tidligere er nævnt i form af generiske data baseret på en (forældet) database og (arbitrære) valg af midpoint indikatorer som kan diskuteres.

Det vurderes at ETSI kan anvendes til at dokumentere en given miljøpåvirkning fra en anlægskonstruktion eller et anlægsprojekt. Problemet er naturligvis at værktøjerne aldrig er blevet udbredt i Danmark, hvilket ville kræve, at Vejdirektoratet og/eller Banedanmark skulle implementere LCA krav – fx i et projekts indledende fase – og klart definerer hvordan disse krav dokumenteres med et fælles LCA værktøj.

I Norge har man videreudviklet ETSI til et system under navnet VegLCA, der bliver mere og mere udbredt på vej og anlægsprojekter. I første omgang primært for at skabe transparens og overblik over et givet projekts miljøfodaftryk, men på sigt et redskab til at stille krav til samme aftryk.

## 4.4 Miljøpåvirkningsklasser

I Norge har man i flere år haft tradition for at have EPD'er tilgængelige for specifikke betontyper og producenter. Der ligger p.t. således 25 EPD'er gældende for færdigbeton på den norske portal EPD-Norge samt adskillige EPD'er for forskellige typer af betonelementer. I 2015 udgav den norske betonforening en publikation [16], der klassificerer færdigbeton i forskellige $CO_2$ klasser baseret på GWP indikatoren. For hver anvendt styrkeklasse (holdbarhedsklasse) er der defineret et referenceniveau, som angiver det normale $CO_2$ fodaftryk beregnet ved producentens port (cradle to gate), samt tre $CO_2$-klasser svarende til:

A. GWP pr. $m^3$ beton må højst ligge på 55-60 % af referencen.
B. GWP pr. $m^3$ beton må højst ligge på 70-75 % af referencen.
C. GWP pr. $m^3$ beton må højst ligge på ca. 85 % af referencen

For at dokumentere sin beton skal producenten kunne fremlægge en EPD – fx en produktspecifik EPD igennem EPD-Norge – der er valideret af en uvildig part. Alternativt kan der foreligge en projektspecifik EPD, der er kan være udarbejdet vha. den norske betonbranches fælles EPD værktøj. Krav til EPD'er kan ses i [16].

Ovenstående klasser A, B og C er afstemt i forhold til tilgængelige råmaterialer og betonrecepter i forskellige egne af Norge. Klasse C er defineret ved, at den kan opnås med ret enkle tiltag på receptniveau hos producenten, mens klasse A kræver specielle tiltag og anvendelse af alternative delmaterialer.

Tanken bag de norske $CO_2$-klasser er at den projekterende kan stille krav til de enkelte konstruktionsdeles $CO_2$-aftryk under hensyntagen til styrke, holdbarhed og funktionalitet.

Det svenske Trafikverket har siden 2016 arbejdet på en strategi, der indeholder en reduktion af $CO_2$ stammende fra opførelse, drift og vedligehold af broer og bygværker [17, 18]. Set i forhold til 2015 niveauet skal udslippet reduceres med 15 % frem til 2020 og 30 % frem til 2025[13]. Trafikverket stiller krav om LCA på store projekter (>50 MSEK). Undersøgelsen i [17] har haft til formål at afdække potentialet for reduktioner i $CO_2$ emissioner

[13] Strategien indeholder desuden visioner omkring en fuldstændig $CO_2$ neutral betonproduktion i 2050 baseret på carbon-capture-storage teknologier

indenfor brokonstruktioner opdelt på forskellige typer af tiltag. Disse tiltag inkluderer anvendelse af alternative delmaterialer, valg af armering med lavt $CO_2$-aftryk og reduceret transportbehov. Resultatet af analysen viser at såvel valg af armering som optimering af betonrecept kan reducere udslippet af $CO_2$ under udførelsesfasen med hver ca. 25 %. En anden undersøgelse for Trafikverket [19] peger desuden på krav til maksimale $CO_2$ udledninger på materialeniveau (armering, cement, beton),som en driver til reduktion af miljøpåvirkningen for at nå ovennævnte mål. Desuden foreslås det at stille specifikke krav til entreprenørens valg af brændstof på byggepladsen specielt i tætbebyggede områder.

**Vurdering**
Udgangspunktet for den norske model har været et ønske om at etablere et enkelt system til at stille krav til betons $CO_2$ belastning [16]. Der er defineret tre $CO_2$ klasser for forskellige styrke- og holdbarhedsklasser, som er gængse i Norge. Disse $CO_2$ klasser er defineret ved en procentvis reduktion i forhold til prædefinerede referencebetoner (branchegennemsnit). Modellen baserer sig på den deklarerede enhed ”1 $m^3$ beton” og $CO_2$ aftrykket skal være dokumenteret med en godkendt EPD. Optimering af konstruktionsdesign, udførelse, drift og vedligehold samt nedbrydning er ikke indeholdt, men er lige så vigtig i forhold til at optimere den samlede bæredygtighed gennem en konstruktions levetid. Således må det antages, at der forud for stillingtagen til valg af $CO_2$ klasser er gennemført en projektering dvs. mængder af beton og tekniske betonkrav er veldefinerede.

Anvendelse af et tilsvarende system i andre lande vil kræve en tilpasning til nationale forhold, herunder hensyntagen til de design- og materialekrav som er gældende i det pågældende land. Desuden kan det overvejes at inkludere yderligere opdeling i fx bearbejdelighedsklasser, da der kan være store nationale forskelle på fordelingen af beton i forskellige bearbejdelighedsklasser, herunder fordeling mellem sætmålsbeton og selvkompakterende beton. Endelig bør det bemærkes, at systemet kun fokuserer på $CO_2$ på produktstadiet og således repræsenterer er et afgrænset hjørne af en samlet LCA vurdering af en konstruktions bæredygtighed.

Den svenske analyse [17] understreger vigtigheden af at optimere betonen således at den kun lige akkurat opfylder de nødvendige krav til styrke og holdbarhed. Desuden er stålarmeringens bidrag til $CO_2$ aftrykket for anlægskonstruktioner illustreret.

Vedrørende valg af delmaterialer i såvel den norske model som i de svenske undersøgelser, peges der bl.a. på anvendelsen af slagge og flyveaske, som effektive midler til at opnå reduceret miljøpåvirkninger fra betonproduktionen. Disse materialer er dog generelt til debat i forhold til beton og bæredygtighed. Mange kulfyrede kraftværker lukker, hvormed tilgængeligheden af flyveaske reduceres markant for helt at blive udfaset på et tidspunkt. Slagge, som stammer fra stålproduktion, er en forholdsvis knap ressource, som ikke kan udbredes globalt. Samtidig er slagge på nuværende tidspunkt friholdt for et $CO_2$ bidrag, hvilket er til debat - bl.a. anfører Buttiens et al. [20], at slagges bidrag til global opvarmning er 550 kg $CO_2$-eq per ton. Tilsvarende har Sayegh et al. [21] anført, at en fordeling af den miljøbelastninger mellem stål og slagge svarende til de respektive massefordelinger vil forhøje betonbelægningers bidrag til global opvarmning med ca. 60 %.

## 4.5 DGNB Certificeringsordning

Det danske system for DGNB certificering er beskrevet i Bilag 2. DGNB benyttes i den danske byggebranche, især indenfor prestigebyggerier (domiciler, kontorer og hoteller), hvor der opereres med tre niveauer. Certificeringen har til formål at benchmarke byggerier i forhold til bygningsreglementet og i forhold til hinanden. Certificeringen er en frivillig ordning som reguleres hver gang bygningsreglementet opdateres. På den måde vil certificeringen hele tiden presse de benyttede teknologier udover hvad der er krævet i henhold til lovgivningen.

Certificeringen måler et byggeri på 5 kvalitetsområder (Miljø, Økonomi, Sociokulturel og funktion, Teknik og Proces). Disse 5 områder er opdelt i 36 forskellige kriterier, som igen er opdelt på et antal underkriterier. Indenfor hvert område har valget af beton som byggemateriale forskellig indflydelse:

- Miljø: 6 kategorier, beton har især indflydelse på kriterier vedr. livscyklusvurdering for miljøpåvirkninger og primærenergi under materialeproduktionen.

- Økonomi: 3 kategorier, beton har stor betydning for alle kriterier, da disse omhandler levetid, holdbarhed, robusthed og fleksibilitet.

- Social: 12 kategorier, beton har kun indflydelse på kriterier vedr. termisk komfort og indendørs luftkvalitet.

- Teknisk: 8 kategorier, beton har direkte indflydelse på et antal kriterier, herunder god brandmodstandsevne, lydisolering og egnet til genanvendelse efter endt brug.

- Proces: 7 kategorier, beton har kun minimal indflydelse på dette område.

DGNB certificeringen omhandler – som det fremgår ovenfor – af langt mere end blot en livscyklusanalyse for de benyttede materialer. I Bilag 2 findes resultatet fra en arbejdsgruppe, som har undersøgt, hvilken indflydelse beton som byggemateriale har på den endelige DGNB score. Et af hovedresultaterne er, at beton generelt udgør en væsentlig del af et byggeris $CO_2$ fodaftryk under opførelsesfasen (ofte mere end 50 % og sommetider op til 75 %). Når driftsperioden medtages, bliver betonens relative andel naturligvis mindre.

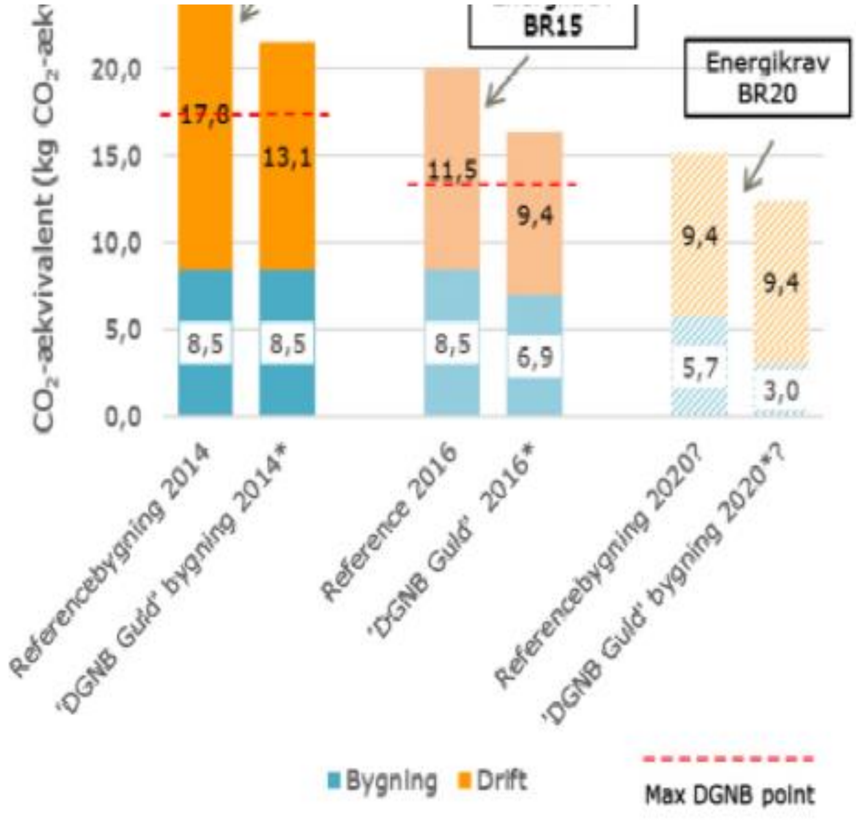
Tabel 3 viser en oversigt over andre lignende studier, hvor betons bidrag til den samlede $CO_2$ aftryk spænder fra 16-38 % under byggeriets opførelse. De højeste andele opnås for tungt byggeri med kælderkonstruktioner, hvor beton normalt er eneste realistiske materialevalg.

*Tabel 3: Data fra litteraturen vedr. betonens bidrag til bygningers samlede $CO_2$ aftryk i opførelsesfasen. Armeringens bidrag er ikke medtaget.*

| Emne, artikel | Forfattere | År | Land | Beton mængder [tons og $m^3$] | $CO_2$ andel fra beton |
|---|---|---|---|---|---|
| An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework | J. Monahan, J.C. Powell | 2011 | United Kingdom | 57 | 36 % |
| Embodied $CO_2$ Emissions in Building Construction Materials of Hellenic Dwellings | Georgios Syngrosa, Constantinos A. Balarasb and Dimitrios G. Koubogiannisa | 2017 | Greece | 722 | 23 % |
| | | 2017 | Greece | 573 | 23 % |
| | | 2017 | Greece | 581 | 29 % |
| | | 2017 | Greece | 371 | 23 % |
| Parcelhus, et-plans med tegl (150 $m^2$) | Beregnet på baggrund af SBi rapport Bygningers indlejrede energi og miljøpåvirkninger [22] Birgisdóttir, H. & Madsen, S.S. (2017) | 2017 | Denmark | 63 45 | 16 % |
| Betonbyggeri, tungt, 3 etager med kælder (1400 $m^2$) | | | | 1193 497 | 25 % |
| Let rækkehusbyggeri i træ (4000 $m^2$) | | | | 1258 638 | 18 % |
| Kontor i lette materialer med huldæk og bjælke/søjlesystem i beton, 4 etager med kælder (4157 $m^2$) | | | | 2856 1190 | 22 % |
| Kontor i lette materialer som ovenfor, men med kælder (12900 $m^2$) | | | | 17345 7227 | 27 % |
| Kontorbyggeri i beton med P-kælder og 6 etager (6200 m2) | | | | 9463 3943 | 38 % |

Det forventes at referenceniveauet for materialeforbrug og $CO_2$ fodaftryk under byggeriets opførelse vil blive sænket for de kommende DGNB byggerier (Figur 4-3) i takt med at kravene i Bygningsreglementet skærpes.

Tidligere kunne DGNB-scoren relativt nemt hæves ved at gennemføre energioptimeringer i form af energisparevinduer, ekstraisolering mv., hvorfor der hidtil ikke har været særligt stort fokus på materialeoptimering i byggefasen. Dette forventes dog at skifte i takt med at energirammen har nået den praktiske nedre grænse. Dette har været udgangspunktet for en SBi analyse [22]. Heri anføres det bl.a. at indenfor de seneste 50 år er energiforbruget til nyopførte bygningers opvarmning, ventilation og køling blevet reduceret med en faktor 9. Derfor retter opmærksomheden sig i højere grad imod bygningens indlejrede ressourcer til byggematerialer. Analysen medtager forskellige bygningstyper og forskellige levetider og konkluderer at der er god ræson i at foretage en offentlig regulering af nye bygningers bæredygtighed – fx igennem fremtidige bygningsreglementer. Det anføres dog samtidig, at de tilgængelige LCA værktøjer og EPD data er for usikre til at indføre egentlig regulering. I stedet anbefales det at arbejde med frivillige bæredygtighedsklasser i første omgang [4, 22].




*Figur 4-3. Illustration af DGNB udviklingen inkl. en forudsigelse for den kommende referenceniveau og sammenholdt med de seneste udgaver af bygningsreglementet. Diagrammet viser $CO_2$ fodaftryk pr. $m^2$ fordelt på byggeriets opførelse og drift af bygningen*

Et skrivebordstudie udført på et allerede udført byggeri på 10.000 $m^2$ (Bilag 2) har vist, at en $CO_2$-reduceret beton ville kunne reducere den indlejrede $CO_2$ på det pågældende byggeri med en mængde på ca. 14.000 kg $CO_2$ svarende til omkring 15 % af den samlede påvirkning. Denne reduktion kan opnås ved at betonens $CO_2$ aftryk nedsættes med 25 til 30 %. I den samlede DGNB score, som består af en masse mindre bidrag, kan indflydelsen af at anvende $CO_2$ reduceret beton virke ret beskeden. Dog grundet den store mængde af beton, der normalt benyttet inden for byggeriet, vil en sådan $CO_2$-reduceret beton kunne øge DGNB scoren med langt mere, end andre normale bæredygtighedstiltag indenfor DGNB kriterierne. Endelig så har betonkonstruktioner typisk en holdbarhed og designlevetid udover de levetidsscenarier, der regnes med i DGNB systemet dvs. potentialet er stort for genanvendelse af råhuskomponenter samt for omformning af bygninger til andre tidssvarende formål fx omformning af bygninger fra boliger til kontorer eller vice versa.

**Vurdering**
DGNB er et udbredt værktøj indenfor byggerisektoren. Systemet har sin store styrke i, at niveauet løftes kontinuerligt i takt med at nye teknologier og nye krav opstår. Ordningen er frivillig, hvorfor denne primært benyttes indenfor prestigebyggerier. Den egner sig dog ikke direkte til anlægskonstruktioner pga. de mange vægtningskriterier, som er skræddersyet til byggeri.

Ordningen forventes i den nærmeste fremtid at skabe stor interesse for mere bæredygtige byggematerialer, da fokus for pointskabelse i høj grad er flyttet fra energireducerende tiltag og over på byggematerialer. Dette vil øge incitamentet til at anvende byggematerialer med reduceret miljøbelastning i forhold til de referencematerialer, der måles op imod. Desuden bidrager det til pointskabelsen at kunne dokumentere miljøbelastningen med godkendte EPD'er. Endelig bør det overvejes om betons lange holdbarhed belønnes tilstrækkeligt i det nuværende DGNB system.

Det vurderes at et lignede system med færre vægtningen ville kunne udarbejdes for anlægsbyggeri også, men dette vil kræve at diverse anlægsbygherre har et klart ønske om at ville bygge grønnere, og vil betale for det.

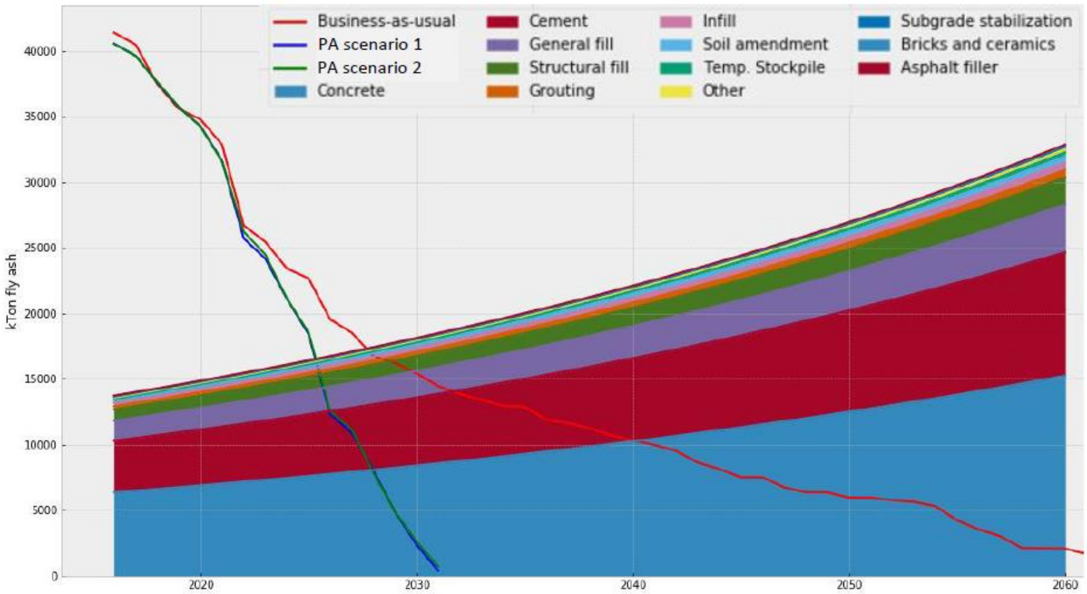
## 5. Sammenfatning

Der er en tendens til at bygherrer og arkitekter efterspørger bæredygtighed i byggeriet. Dette udmønter sig i øget omfang af DGNB certificeringer og generel fokus på implementering af bæredygtighedsklasser i det nye bygningsreglement. Beton spiller en markant rolle specielt for det indlejrede $CO_2$- og energiindhold under byggeriets opførelse. Beton og andre byggematerialer får i fremtiden endnu større betydning for pointskabelsen i DGNB, hvorved incitamentet til at anvende byggematerialer med reduceret miljøaftryk vil være stigende. En af de store fordele ved at bygge i beton er bl.a. den lange holdbarhed, som ofte går langt ud over de levetidsscenarier, der regnes med i DGNB. Potentialet for genanvendelse og transformation af bygninger er derfor stort, og det bør overvejes om dette belønnes nok i det nuværende DGNB system.

Indenfor anlægssektoren i Danmark findes der ikke på samme måde fælles retningslinjer for beregning og dokumentation af bæredygtighed. Her vurderes anvendelsen af LCA beregninger at vinde frem i en nær fremtid, men anvendelsen sådanne beregninger er i øjeblikket hæmmet af manglen på ensartethed i valg af indikatorer og vægtning mellem de enkelte indikatorer. Der findes mange metoder og teorier på markedet, hvilket gør det svært at sammenligne og vurdere. Der er således behov for, at man beskriver hvordan LCA skal anvendes, herunder afgrænsning i forhold til hvilke materialer og processer der skal medtages. I vores nordiske nabolande har man indført fælles regneværktøjer fra myndighedernes side, der skal benyttes af alle, hvilket sikrer at tallene er sammenlignelige og baseret på det samme sæt af forudsætninger. Således anvender de i Norge og Sverige allerede på nuværende tidspunkt LCA på de store anlægsprojekter. Danmark var i perioden 2004-2012 involveret i det fællesnordiske samarbejde ETSI, der havde som mål at udvikle fælles værktøjer til kvantificering af bæredygtigheden for anlægskonstruktioner. Dette arbejde har bl.a. ført til udvikling af VegLCA, der anvendes af Statens Vegvesen i Norge. I Danmark har LCA beregninger ikke for alvor vundet indpas hos Vejdirektoratet og Banedanmark. Der er dog en målsætning om, at det bliver en del af udbudsmaterialet i fremtiden.

Denne rapport beskriver nogle fremgangsmåder, hvor miljøkrav kan medtages allerede i udbudsprocessen og prissættes af entreprenøren, men det er også ret klart, at vægtning og prissætning skal gennemtænkes grundigt for at kunne skabe et motivationsgrundlag for at miljøpåvirkningen kan udsættes for konkurrence. Der er desuden meget begrænset plads til variationer indenfor de nuværende præskriptive materialekrav til beton til anlægsbygværker. Såfremt at der skabes et fælles system for LCA – fx inspireret af DGNB – vil det være muligt at efterspørge/kræve dokumentation for miljøpåvirkninger indenfor de enkelte projekter.

I forhold til en komplet LCA beregning, hvor levetid og alle miljøindikatorer regnes med, har man i Norge implementeret et forslag til miljøkrav til betonkonstruktioner med fokus udelukkende på $CO_2$ i produktionsfasen (fra "cradle to gate"), hvor de har defineret $CO_2$ klasser for forskellige styrke og holdbarhedsklasser. Anvendelse af et tilsvarende system i andre lande vil kræve en tilpasning til nationale forhold, herunder hensyntagen til de design- og materialekrav, som er gældende i det pågældende land. Det kan også overvejes at inkludere yderligere opdeling i fx bearbejdelighedsklasser, da der kan være store nationale forskelle på fordelingen af beton i forskellige bearbejdelighedsklasser.




*Figur 5-1. Fremskrivning af efterspørgslen og tilgængeligheden af flyveaske i perioden fra 2015-2060 [12]. Linjerne viser udbuddet af flyveaske baseret på forskellige udfasningshastigheder af kulfyrede kraftværker i Europa og dækker såvel god som dårlig kvalitet af flyveaske. De farvede bånd angiver efterspørgslen fordelt på anvendelsesområder.*

Desuden er det vigtigt at tage hensyn til de valg af delmaterialer, som tilgængelige i forhold til at reducere $CO_2$ aftrykket. I det norske system motiveres der på nuværende tidspunkt til brug af flyveaske og slagge. Den langsigtede og globale bæredygtighed ved anvendelse af disse materialer er dog til diskussion. Kulfyrede kraftværker bliver langsomt men sikkert udfaset, hvorved flyveaske ikke er tilgængelige for betonproduktion i samme udstrækning som tidligere. Figur 5-1 viser en fremskrivning i behovet for flyveaske til forskellige anvendelser sammenholdt med tilgængeligheden af flyveaske baseret på udfasning af kulfyrede kraftværker. Fremskrivningen baserer sig på ECOBA[14] statistik i 2015, hvorefter en 2 % årlig stigning er forudsat [12].

Slagge er i forvejen en knap ressource og stålproduktion baseret på brug af højovne, hvor slaggen er et restprodukt, kan overgå til andre produktionsformer bl.a. elektriske ovne, som ikke danner et slaggeprodukt. Slagge fra stålproduktion ligger på ca. 8 % af cement-produktionen (2014), hvilket betyder at mængderne er langt fra nok til at gøre en forskel globalt [23, 24]. Ydermere kan der stilles spørgsmålstegn ved hvorvidt slagge fortsat skal opfattes som et $CO_2$ neutralt materiale, når det indgår i beton.

Betonbranchen har gennem mange år arbejdet målrettet på at fremme bæredygtigheden af beton og anvendelsen af beton. Ved udvikling af veldefinerede værktøjer, der favner alle relevante aspekter af bæredygtighed, vil det skabe grundlag for mere præcise og objektive vurderinger af forskellige løsningers bæredygtighed og skabe incitament for anvendelsen af nye løsninger. Som led i udbredelsen af bæredygtige løsninger er der dog et antal områder, hvor betonbranchen kan øge sin synlighed i forhold til bæredygtighed:

- Større promovering af miljøvaredeklarationer – dels fælles som branche og dels individuelle deklarationer fra den enkelte producent.

- Forbedret input til DGNB systemet vedr. de generiske data, som findes i DGNB værktøjerne.

- Fokus på stålarmeringens bidrag og betydning for den samlede miljøpåvirkning.

- Indarbejdelse af vægtning(er) mellem de enkelte miljøindikatorer således at $CO_2$ ikke er den eneste der styrer.

- Vurdering af muligheder for at medtage karbonatiseringens bidrag til $CO_2$ aftrykket. Denne mulighed findes allerede i [10].

- Italesætning af fælles visioner for den danske betonbranche. Gerne med en kvantificering af målbare reduktioner.

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## 7. Bilag 1: *Life Cycle Assessment on Concrete Structures*, Technical report by Romain Sacchi, Aalborg Portland A/S, March 2017.

# LIFE CYCLE ASSESSMENT ON CONCRETE STRUCTURES

28/3/2017

Technical report – Work package I1

This document intends to provide a basic understanding of life cycle assessments performed on concrete structures, with the current methods and rules usually applied in Europe.

# Contents

# TERMINOLOGY

**Biosphere** - It is a living and study area of a wide thermodynamic system open to external influences, which derives most of its energy from sunlight via photosynthesis. The complex mechanisms of auto-maintenance and sustainability of the biosphere sets up each year, into chemical energy, some 500×1018 calories – or nearly 10 times more than what is consumed by all forms of human industry.

**Carbon Footprint Assessment (CF)** - It is considered a subset of Life Cycle Assessment as it focuses solely on a single impact category: Global Warming. Although it observes the same methodology, steps and structure as Life Cycle Assessment, the Carbon Footprint Assessment looks at environmental damages resulting from the release of greenhouse gases throughout the product life cycle. The assessment is compiled in a single score midpoint indicator: a quantity of CO2eq. gases. It may be used as a basis for comparison with other product systems.

**Carcinogenic compound** - It is a compound causing, aggravating or sensitizing the onset of cancer. This can be due to a simple or complex chemical, to occupational exposure, or risk factors related to lifestyle or physical and biological agents.

**Closing the Loop** - Term first coined in the Industrial Ecology literature, referring to the technological linking operated between the disposal of a product and its production by means of reusing, recycling or recovering the materials. The Industrial Ecology field considers such system as a mature and closed one, that has a high level of integration within its environment, where the notion of waste disappears and the reversibility of processes allows a complete disassembling, reuse and recover of products and their associated co-products.

**Combined Heat-Power plant (CHP)** - It usually refers to the use of a steampowered plant to simultaneously generate both electricity and useful heat. All thermal power plants emit a certain amount of heat during power generation. Usually, the heat is lost in the environment and turns into a less useful form, increasing the inefficiency of the process. To fully utilize this energy before it becomes too "difficult to use", a CHP plant captures some of the heat produced by the steam process and transforms it into useful and distributable forms, such as heat injected in the district heating system, or electricity released in the national grid.

**Cradle-to-Gate** – Spatial scope used for the life cycle assessment of a product that encompasses the material and energy flows at the very early stage of its supply chain, down to, but not including, the point where the product becomes available for distribution to customers. It is often the scope used in business-to-business environmental product declarations (EPD).

**Cradle-to-Grave** - Refers to the life cycle of a product (see Product Life Cycle). It designates the very beginning of the conceptual phase of a product, via its full manufacture at the factory plant, to its use and disposal: the cradle, where the product is "born" by extracting raw materials and capturing energy, down to the grave, where the product is disposed by end-users and treated by waste treatment facilities.

**Disability-Adjusted Life Year (DALY)** – DALYs are a central concept among endpoint indicator methods. It is a unit that tries to describe damages inflicted upon human recipients. It quantifies damage by measuring the *number of years* of healthy life lost, following the exposure of the recipient to emissions of various sorts. A similar concept, Quality-Adjusted Life Year (QALY), is also used in endpoint indicator methods like StepWise 2006. Different from DALY, QALY factors the quality and the quantity of the life lived.

**EcoInvent database** - It is a Swiss-made database gathering several thousands of life-cycle inventories regarding industrial processes mainly. It helps completing economy-environment interactions between a product system and its environment when data are not directly available, as a secondary source of information, to model background processes.

**Endpoint indicator** - Quantitative or qualitative compilation of results given by an impact assessment method within the framework of a Life Cycle Assessment. It aims at supporting the decision-making process by reducing the complexity of the model studied down to fewer impact categories which notions are easier to grasp. Endpoint indicators lead to the generation of results, reducing the original complexity of the model by "boiling it" down to few more general impact categories, making it easier to visualize the product system-related environmental issues. Sometimes subject to criticism, too simplistic endpoint indicators inevitably loose in accuracy and scientific validity. It is true in regards to the inherent value choices as to how temporal and spatial factors are valued, how the different factors constituting the quality of life category are pondered, etc.

**Energy carrier** - An energy carrier can be a substance or a reaction (energy system) that is used to feed a system which output is mechanical work, heat, or a chemical or physical process. This definition has been adopted in the international norms standard ISO 13600. From an energetic perspective, a more traditional definition limits an energy carrier to an energy form (not a system) used by the different sectors across the society. This definition proposed by ISO 13600 is considered in this study.

**Environmental mechanisms** – In the context of a life cycle assessment, a dose-response chain of causation between an emission and an impact. For example: the mechanism between the emission of a greenhouse gas and the increase of the atmosphere radiative forcing, or the mechanism between the emission of an acidifying gas and the increase of water compartments acidity.

**Environmental Production Declaration (EPD)** - Consists in a set of documents stating on the environmental performances of one or several products, encompassing a certain scope explicitly defined to the audience, relying on a full or partial life cycle assessment study. Besides the underlying LCA principles defined in ISO 14040/44, International standards norms ISO 14025 should be followed to ensure transparency and quality throughout the report. Additional Product Category Rule documents may apply according to the product studied. Such declarations are published by an EPD program operator and peer reviewed by verifiers. EPDs are often used in a business-to-business or business-to-customers' context, for semi-finished and finished products.

**Functional unit (FU)** – A functional unit is the expression of a certain utility obtained from the functional value of a product or service, used as scaling reference for life cycle assessments. For example: transporting one person over 1 km. A functional unit can be fulfilled in different ways. Therefore, functional units in life cycle assessment allows to compare alternative and substitutable products, systems or services that are able to fulfil the same function.

**Greenhouse gases** - Various types of gases observing the physical property of absorbing and re-emitting radiation coming from the infrared radiation wavelength range. If these gases form a layer in the upper atmosphere, between solar radiations and the Earth surface, a part of the solar radiations are prevented from being reflected back into space. "Trapped" within the atmosphere, the solar energy output is limited. It provokes a so-called greenhouse effect, leading to the progressive warming of the planet.

**Industrial Ecology** - It is the study of material and energy flows through industrial systems. The human-made economy can be modelled as a web of industrial entities that extract the planet's material and energy resources and to transform them into products which are then exchanged on markets to meet the needs of humanity. Industrial ecology seeks to quantify and report the flows of materials and describe industrial processes observed in the modern society. Industrial ecologists are often concerned about the impacts of industrial activities on the environment, with the use of the world's supply of natural resources, and problems with waste disposal. Industrial ecology is a young but increasingly multidisciplinary research that combines aspects of engineering, economics, sociology, natural sciences and toxicology.

**ISO 14040 and 14044** - Presents the principles and a framework for conducting Life Cycle Assessment. It defines the structure of a Life Cycle Assessment study as well as the content, explanations, clarity and transparency that must appear in the report. While ISO 14040 focuses more on establishing the reasons, concepts and principles of a Life Cycle Assessment, ISO 14044 is mainly giving the guidelines and requirements when conducting and reporting the analysis results. The Life Cycle Assessment work is peer reviewed by a third party organization and not by the International Standard Organization directly.

**Kilowatt** - One kilowatt (kW) is the power of an energy system in which an energy quantity of 1 000 joules is uniformly transferred during 1 second.

**Kilowatt-hour** - One kWh is a unit of energy quantity corresponding to the energy consumed by a device of 1000 watts (1 kW) of power for a period of one hour. It equals to 3,6 mega joules (MJ). It is mainly used to measure the generation and use of different types of energy (electricity, heat, . . .).

**Life Cycle Assessment (LCA)** - It is a tool to evaluate environmental impacts associated with all of a product life cycle stages. It allows a complete representation of the necessary economy-environment interactions that are involved in the manufacture of a product by compiling material and energy flows, evaluating the potential environmental harm of these flows and interpreting the results to draw conclusions on the product soundness. It is perceived as a strong tool supporting the Integrated Product Policy in offering a transparent, comprehensive and scientifically-recognized way to guide customers in their consumption choices towards "greener" products.

**Lifetime disease probability** - The term is here understood as the probability of suffering from a disease in a person's lifetime.

**Life Cycle Inventory (LCI)** - A Life cycle inventory analysis consists in creating an inventory of material and energy flows to and from the nature to the product system studied. To develop the inventory, a flow model of the technical system, such as a Mass Flow Analysis, is built using data on inputs and outputs. The input and output necessary for the construction of the model are collected for all activities within the system boundary, including the supply chain (called the technosphere inputs). Therefore, LCI is considered a subset of LCA since it observes the same methodology and uses the same tools. However, an LCI does not assess the environmental consequences implied by these material and energy flows nor gives it any interpretation based on this assessment.

**Lower heating value (LHV)** - The lower heating value is a quantity of heat energy (usually expressed as J, kcal or kWh) produced from the combustion of a material, while considering the gaseous state of water after combustion. It is different from the higher heating value (HHV) in which the latent heat of water vaporization is not taken into account – the energy required to vaporize the water is not considered as heat, hence LHV is always lower or equal to HHV.

**Mass Flow Accounting** - Materials Flow Accounting is a method/tool to quantify the flows and stocks of materials and energy exchanges between a system and its environment. The system studied becomes defined by the flows of material and energy coming in and out and/or accumulates within. It is, with Life Cycle Assessment one of the pillar tools of i.e. and is very accurate in defining physical consequences of human-nature interactions. Thus, MFA may be applied at different temporal scales to visualize flows evolution over time, but also at different spatial scales: nation-wide, to an industry or to a human-being. Such analysis allows in-depth look at efficiencies of processes, stock accumulations and helps explaining certain physical phenomenon and optimizing the studied systems.

**Midpoint indicator** - Quantitative or qualitative compilation of results given by an impact assessment method within the framework of a Life Cycle Assessment. It aims at supporting the decision-making process by reducing the complexity of the model studied down to several impact categories which notions are easier to grasp. Unlike endpoint indicators, midpoint indicators relate to impact categories of a lesser extent, giving less room to value choices but highlighting more specific and complex issues.

**Product Category Rule (PCR)** – A set of documents that contain additional rules for life cycle assessment studies used in EPDs for specific products, besides the LCA principles defined in ISO 14040/44 and the basic rules for EPDs defined in ISO 14025.

**Product life cycle** - Understood here from an engineering perspective. Designates the cyclic pattern of a product materialization and dematerialization. Materials are extracted and transformed to manufacture a product, which then circulates throughout the technosphere from the early stages of conception and use, to eventually reach back the ecosystem it originates at some point when discarded. A product life cycle is mostly determined by the life cycles of the components it is composed of. It is usually defined in 5 main stages: raw material extraction, design and production, distribution, use and disposal. This term refers to the analogy with the cyclical characteristic of most natural processes.

**Product System** – A group of transforming activities sustained by material and energy flows and with boundaries defined by a spatial and temporal scope, that delivers a reference flow. The reference flow should satisfy the conditions and properties defined in the functional unit.

**Reference flow** – A reference flow is a quantity of one or a set of products or services over time that fulfills the conditions and properties set in the functional unit. For example: 1 m3 of concrete, 500 kg of reinforcing steel and 1 ton of sand can be a reference flow to fulfill the functional unit: 1 meter of elevated drivable surface for 50 years.

**Scientific reliability** - Reliability is the consistency with which a series of measurements returns robust results, often used to describe a test. And reliability is negatively correlated to the random error. However, one must not mistake reliability for validity. A reliable measure means that the method of measuring is reproducible and returns results that do not vary when parameters remain unchanged. However, what is being measured may not be "relevant" to the problem, or the method used to test a hypothesis may not be the most appropriate one: it is an issue of validity.

**Scientific validity** - The definition of validity may vary depending on the concern. Yet, it is commonly accepted that the notion of scientific validity deals with the matter of measurement. However, in this study, validity refers more to the extent to which a concept, or the conclusion of the measurement, is correct and well-founded on solid and recognized scientific grounds.

**Scope –** In life cycle assessment studies, a scope is spatial and temporal. It defines the limits of the properties and applicability of a functional unit, and therefore the extent to which transforming activities that constitute the product system should be included.

**Second-order energy analysis** - A second-order energy analysis regarding Life Cycle Assessment differs from a first-order analysis in which it encompasses not only the production and transport stages in terms of material and energy needs, to achieve a functional unit, but also the different life-cycles of the processes needed to achieve the functional unit. It includes the respective life-cycles of the transport, the production and the other stages of the life-cycle of the functional unit: design, distribution, use and disposal. In the same way, it differs from a third-order energy analysis that does not account for the material and energy needs related to the life-cycle stages of the capital equipment present in every life-cycle stages of the functional unit. However, if a third-order analysis accounts for them, it usually only does for the production stage of the capital equipment, while the other stages are left out.

**Technosphere** - The technosphere must be here understood as the concept created by Vladimir Vernadsky, which designates the part of the physical environment affected by anthropogenic changes, that is to say, of human origin.

**Ton-kilometer** - One ton-kilometer (tkm) is a unit of quantity of transport corresponding to the transport of one ton (t) over one kilometer (km). The amount of transport expressed in tkm is calculated by taking the product of the mass transported in tons (t), by the distance travelled in kilometres (km). This unit of measurement is commonly used, especially in the field of transport, including carriage of goods and helps to measure its intensity.

# Life Cycle Assessment on concrete structures

**TECHNICAL REPORT – WORK PACKAGE I1**

## INTRODUCTION

### Life cycle assessment as a tool

Life cycle assessment (LCA) is a method and a tool used to quantify environmental impacts associated to a function (e.g. 1 meter of suspended drivable road structure) or service (e.g. the transport of one person over 1 km) provided by a series of man-made activities, sustained by the provision of inputs and outputs from and to natural compartments. Figure 1illustrates the entire supply chain of a bridge, made of several phases and transforming activities that provide the untransformed material (i.e. limestone) and energy (i.e. crude oil), intermediate (i.e. cement) and semi-finished (i.e. concrete) products as well as services (i.e. transport) necessary to the realization, maintenance, demolition and treatment of a suspended drivable surface and its components.

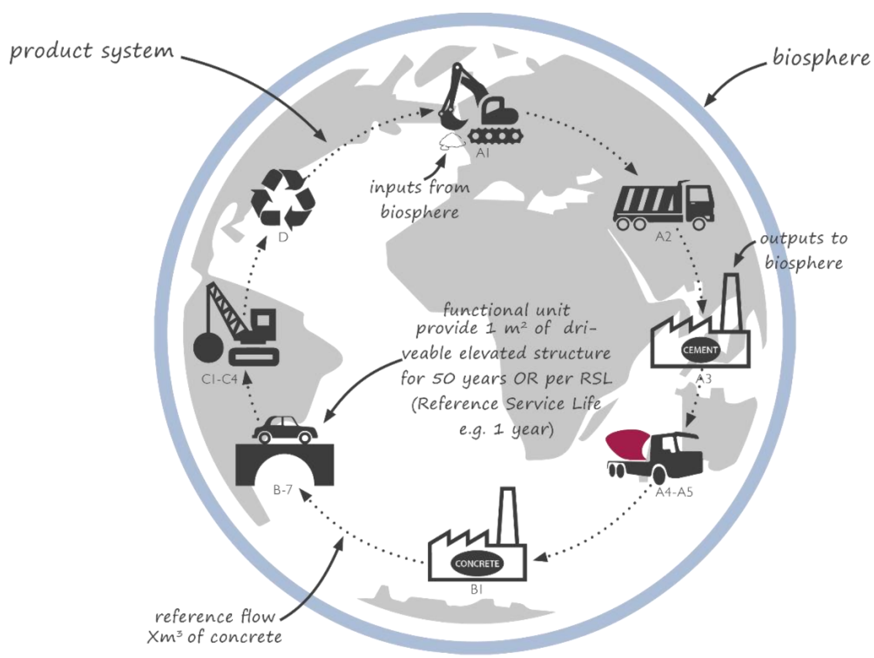


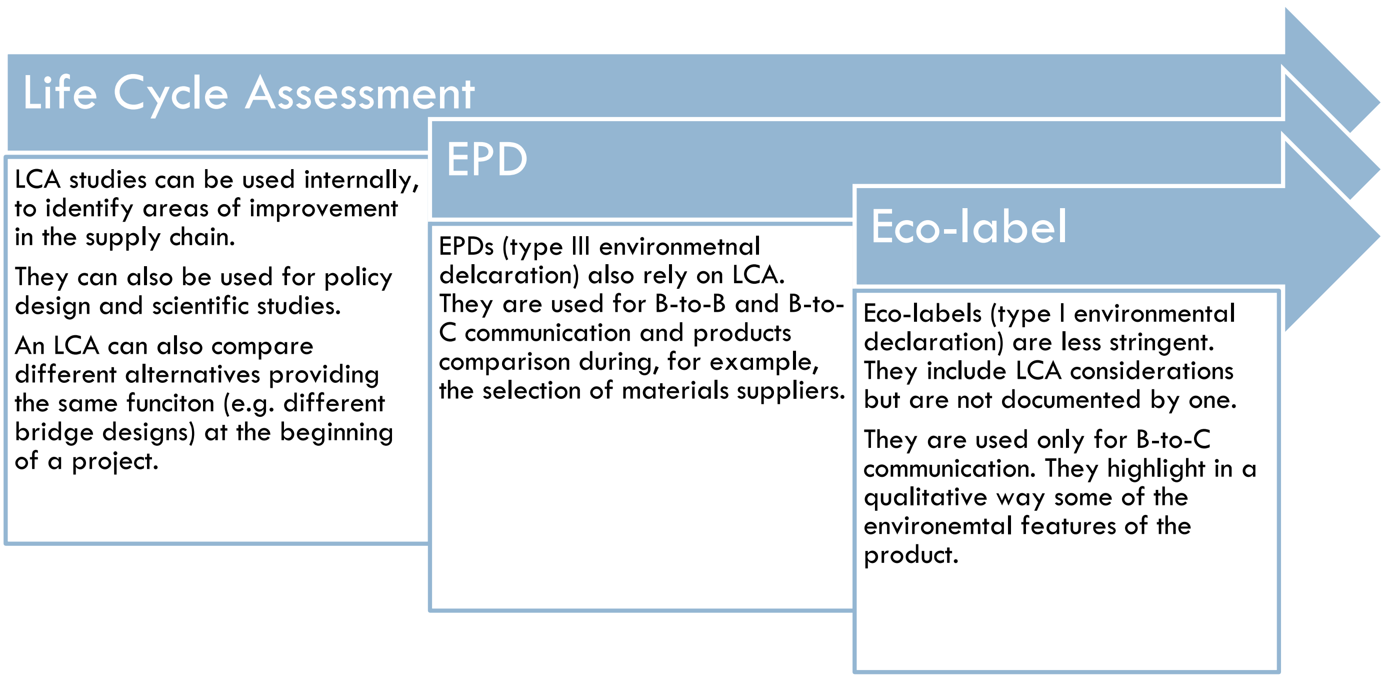

**FIGURE 1 LIFE CYCLE PHASES OF A BRIDGE**

Environmental impacts are measured by quantifying the use of natural resources and the interactions (usually under the form of solid or gaseous emissions) between the technosphere (theoretical compartments that encompasses the entirety of man-made activities) and the biosphere (a general natural compartment that contains the air, water, and soil sub-compartments on Earth). These interactions are called environmental mechanisms and usually quantify impacts on the basis of a simplified linear dose-response mechanism (e.g. the linear relation between the emission of 1 kg of CO2 and the warming of the atmosphere).

The strength of LCA is to consider the provision of a product or service by modelling the entirety of the supply chain (including its transforming activities) that is necessary to its realization, as opposed to considering each activity separately. LCAs are widely used among industries to:

- Identify environmental hotspots in the supply chain of a product or service and consider less-impacting alternatives (e.g. replacing toxic chemicals in a specific process with REACH-authorized substitutes),
- Communicate with customers and end-customers on the environmental footprint of a product to serve as basis for comparison.

The second purpose mentioned above is usually done so through the use of an Environmental Product Declaration documents (EPD), which offer a standardized and harmonized way of presenting product-specific environmental impacts for products comparison.




## Environmental Product Declaration document

The results of a Life Cycle Assessment study can be used in business-to-business and business-to-costumer contexts and serve as a basis for products comparison when reported in EPDs.

EPDs in the construction sector usually report the environmental impacts for the provision of a declared unit (e.g. 1000 kg of Portland cement or 1 meter of elevated drivable structure), as opposed to a functional unit (e.g. a structure that can sustain a specific load within a specific time frame). In that way, the EPD of an intermediate product (e.g. Portland cement) can be used as data input into the EPD of a finished or semi-finished product such as a cubic meter of concrete and a concrete-made building, respectively. Such practice is illustrated in Figure 2.

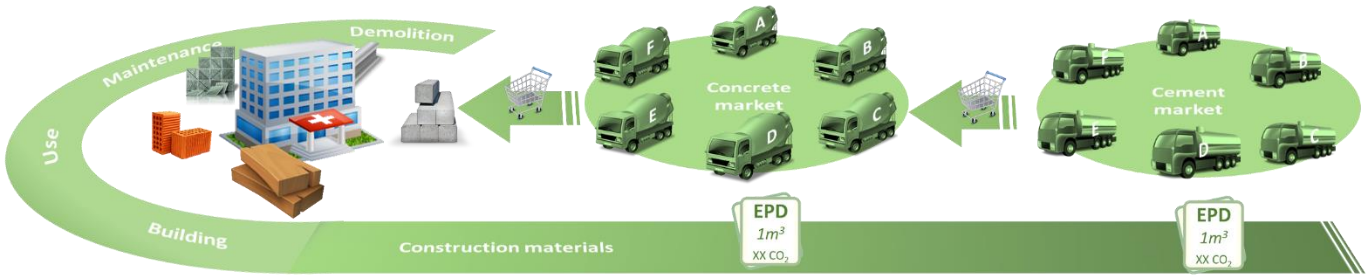



FIGURE 2 THE USE OF INTERMEDIATE PRODUCT EPDS IN SEMI FINISHED AND FINISHED PRODUCT EPD

### Attributional vs. consequential

To the knowledge of the author, all the guideline documents for EPDs on construction materials, building and road infrastructures recommend to follow a modelling approach known as attributional.

The attributional modelling approach aims at encompassing all the transforming activities necessary to fulfill the functional unit (in an LCA) or declared unit (in an EPD), from raw material extraction to a certain point in the supply chain (which can range from the factory gate down to the demolition and waste treatment phase) using average historical material and energy flow requirements and average suppliers to represent an average static footprint of the product system, cut away from the rest of the economy.

The environmental results of such EPD can be interpreted as the average historical environmental impacts associated with the delivery of the given declared or functional unit by that particular EPD owner/supplier.

Another major modelling approach, called consequential or change-oriented approach, aims at encompassing the marginal changes in the economy that follows the increase in demand for a given functional or declared unit. In such approach, the included material and energy flow requirements and their suppliers are only those that would react to the realization of an additional functional or declared unit. For example, with a declared unit of 1,000 kg of Portland cement, only the fuels and materials that would be used to produce an additional 1,000 kg of Portland cement would be included in the supply chain.

The environmental results that follow such approach can be interpreted as the environmental impacts associated with the decision of choosing a particular supplier.

In many ways, the consequential approach is better suited for decision-making as it describes the environmental impacts to expect following the decision to express an additional demand for a specific supplier, as explained in (Weidema 2014). However, for the sake of simplicity, EPDs in a business-to-business context have historically followed the attributional approach, which remains easier to understand and model. Such fundamental difference between both approaches is illustrated in a simplified way in Figure 3.

The rest of this technical document describes the different modelling concepts and challenges that relate to the realization of business-to-business EPDs, strictly using an attributional approach.

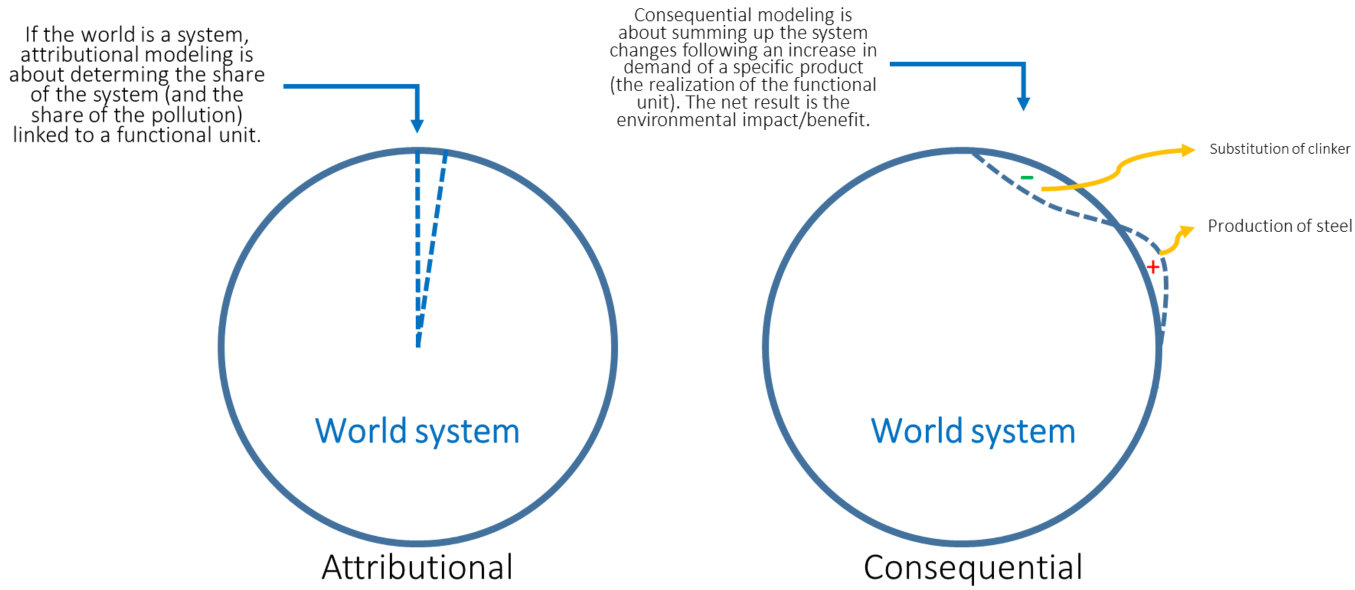



**FIGURE 3 FUNDAMENTAL DIFFERENCE BETWEEN ATTRIBUTIONAL AND CONSEQUENTIAL MODELLING APPROACHES. SOURCE: PRESENTATION FROM BO WEIDEMA**

## The International standards for Life Cycle Assessment

The presentation as well as the core analysis of an LCA, whether used in an EPD or not, follow the general recommendations given by the International Standard Organization in regards to the methodology and the reporting of the results, namely the norms series 14040:2006 (International Standards Organization 2006a) and 14044:2006 (International Standards Organization 2006b). The structure of a Life Cycle Assessment comprises four main parts as defined by the International Standard Organization is presented in Figure 4.

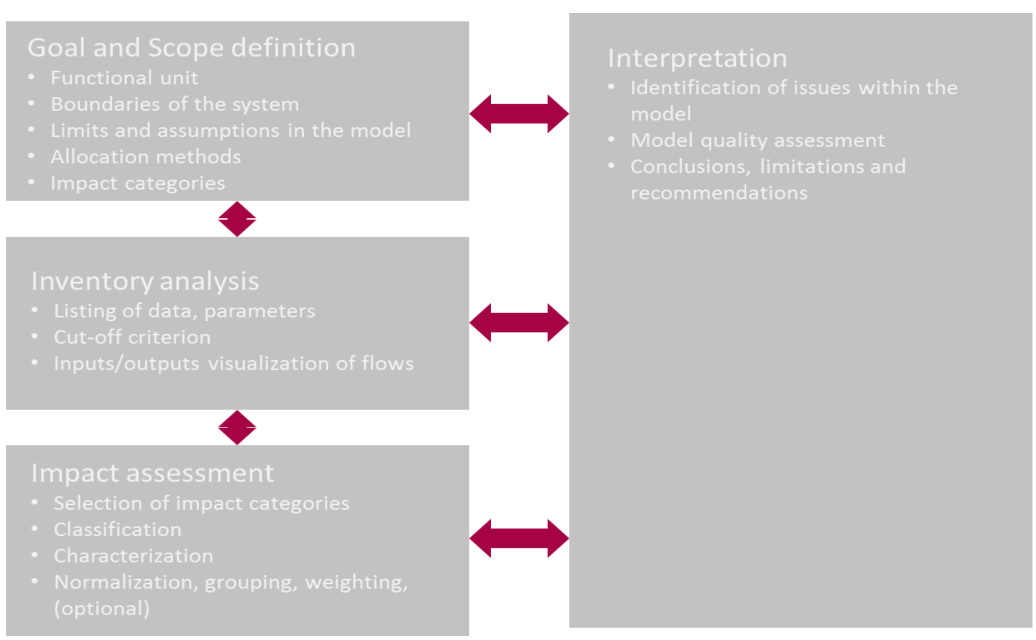



**FIGURE 4 STRUCTURE AND COMPONENTS OF AN LCA AS INDICATED BY THE FOUNDING INTERNATIONAL STANDARDS**

## Additional standards for Environmental Products Declarations

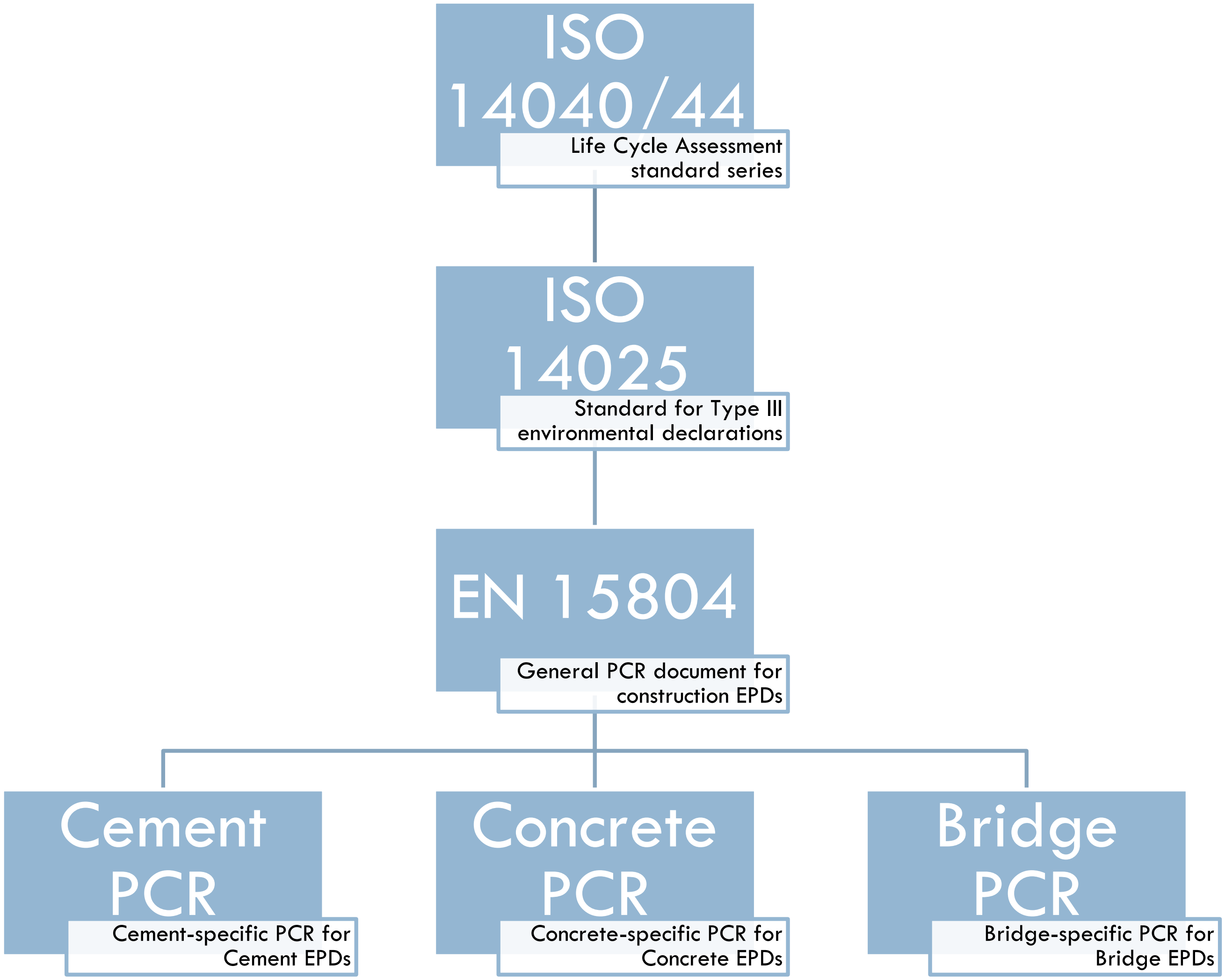
When the results of an LCA are to be used in an EPD, additional specifications on the scope and boundaries of the LCA model are given in a Product Category Rule (PCR) document for EPDs, which structure and rules are suggested in:

- the general Product Category Rule document for Type III Products Environmental Declaration for construction materials EN 15804:2012 + A1:2013 (AFNOR 2014). The applicability of the LCA results and its compliance to the guidelines of the PCR document EN 15804 are done so within the general principles and framework of ISO 14025:2006 (International Standards Organization 2006c) for the production of Type III environmental declarations.

Additionally, a product-specific PCR document (often commissioned by an EPD program operator such as EPD International or EPD Danmark and mutually recognized by those) is to be used, to complement the rules given by the ISO standards and to ensure a common and fair basis for comparison between EPDs.

- For example, in the case of cement: the Product Category Rule document UN CPC 3744 CEMENT, v. 2.1[1] with the registration number 2010:09 developed by the Centre for the Development of Product Sustainability and moderated by EPD International.
- In the case of concrete: the Product Category Rule document UN CPC 375 CONCRETE, v. 1.0[2] with the registration number 2013:02 developed by the WBCSD Cement Sustainability Initiative and moderated by EPD International.
- In the case of concrete structures: the Product Category Rule document UN CPC 53221 BRIDGES AND ELEVATED HIGHWAYS, v. 1.01[3] with the registration number 2013:23 developed by the R.T.I. NIER Ingeneria SpA, LCA-lab srl and moderated by EPD International.

[1] Can be accessed here: http://www.environdec.com/en/PCR/Detail/?Pcr=5942
[2] Can be accessed here: http://www.wbcsdcement.org/pdf/pcr1302_CPC_375_Concrete_1_0.pdf
[3] Can be accessed here: http://www.environdec.com/en/PCR/Detail/?Pcr=9377#login-window




## The phases of a Life Cycle Assessment and EPD modules

A life cycle study encompasses all the transforming activities needed to the realization of a functional or declared unit all along the different life phases of the product: extraction of untransformed material and energy, supply and transformation, delivery to users, use, maintenance, disposal and treatment.

The EPD system, which relies on a LCA model, sub-divides the different life cycle phases into A, B, C and D modules. Product-specific PCR documents specify which modules are mandatory to report. For example, for a cement EPD, it is mandatory to include the modules A1 to A3 (raw material and energy extraction down to the cement product at cement factory gate), which corresponds to the so-called Cradle-to-Gate scope. The following A4-A5, B, C and D modules (delivery of cement to costumers down to the waste treatment activity) are optional.

Figure 5 illustrates the EPD modules and corresponding supply chain for cement and concrete. Both supply chains are arranged so that the cement supply chain appears as an intermediate product in the concrete supply chain, which itself delivers a finished product in the life cycle of a concrete structure such as a bridge.

The grey and blue circled modules are mandatory in the cement and concrete EPDs, respectively.

The EPD of a bridge encompasses the processes illustrated by the brown circle: both the supply of intermediate products (cement) and finished products (concrete). The reader notices that the demolition and disposal phases of the bridge are not mandatory phases to be reported according to the above-mentioned bridge and elevated highways PCR document (only the construction and maintenance are mandatory).

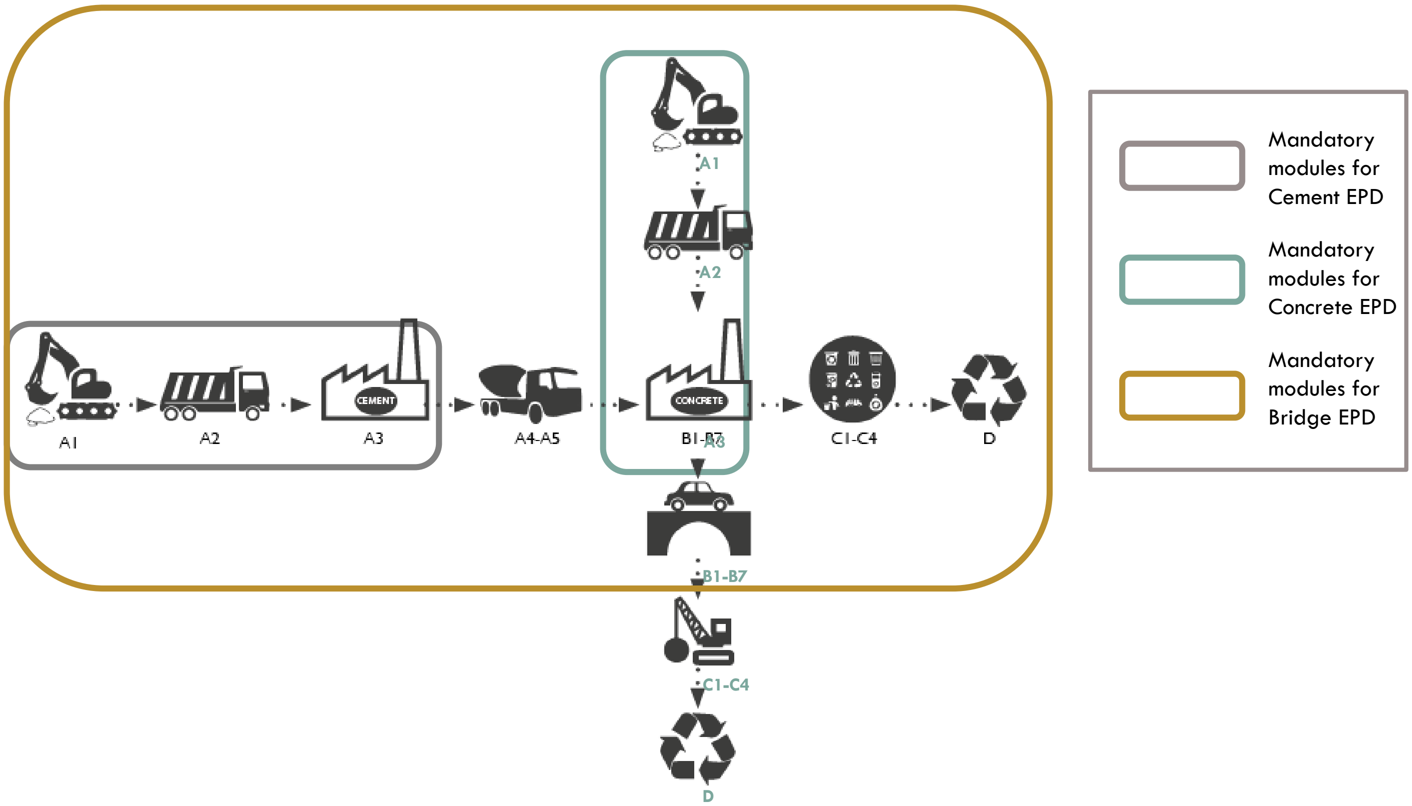



**FIGURE 5 LIFE CYCLE PHASES AND EPD MODULES**

# SCOPE

## Functional unit vs. declared unit

While the term of functional unit is usually encountered in LCA studies, declared unit is the preferred expression used to design the reference quantity to which EPDs refer to. A declared unit often refers to a quantity, a mass or a volume of product/service, while a functional unit refers to a function or service that can be realized by one or several substitutable products or services. Both the functional unit and the declared unit should be satisfied by the reference flow produced by the product system.

Example of a functional unit: "Provide a load-bearing elevated drivable surface of 1 meter for 1 year". In this case, a range of alternatives (concrete bridge, wooden bridge, etc.) can fulfill the functional unit, and the LCA study compares these alternatives against environmental indicators.

Examples of a declared unit:

- "1000 kg of Portland cement" in the case of a cement EPD,
- "1 cubic meter of concrete" in the case of a concrete EPD,
- "1 meter of infrastructure referring to per year of RSL" in the case of a bridge EPD

"1 meter of infrastructure per year of Reference Service Life" is the declared unit to use in bridge EPDs.

## Spatial boundaries

Defining the spatial boundaries of an LCA study is very important. As a general rule, the LCA practitioner tries to cut-away the processes that will engage in the realization of a declared unit from the processes that do not engage otherwise. The selected processes form the product system. How spread is the product system across the economy defines the spatial boundaries, sometimes also called spatial scope. The economy, or technosphere, is essentially seen in the practice of LCA as a network of interconnected processes that rely on another's inputs and outputs to operate.

For example, the Figure 6 below illustrates some of the activities the cement production activity is linked to, either as receiving inputs from suppliers of electricity, suppliers of alternative and conventional fuels, suppliers of raw materials, etc., or sending outputs to the concrete mixing factory, or the district heating system (in case of heat co-generation). Defining the spatial boundaries of the product system is therefore deciding which processes should legitimately be included in the group of processes necessary to realize the declared unit.

While it is easy to identify the necessary processes required to produce cement or concrete, or a bridge within the factory or the construction site, it is more difficult to know which processes to include at an earlier stage in the supply chain (e.g. generation of electricity, production of super-plasticizers, etc.). The group of processes that engage in the realization of a declared unit, but that are not identified within the factory, but rather earlier in the supply chain are usually called background processes. Data on background processes are supplied by LCA database, such as Ecoinvent, GABI or ELCD.

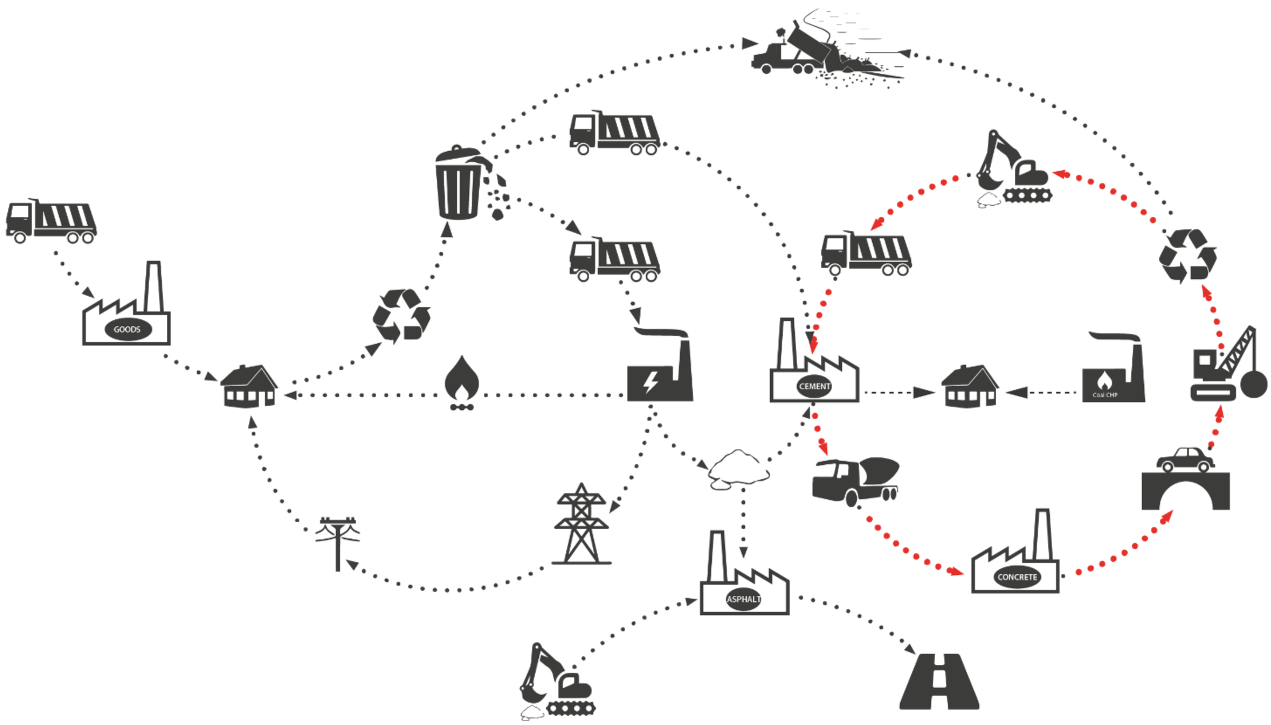



**FIGURE 6 INTERCONNECTED ACTIVITIES TO THE CEMENT PRODUCTION ACTIVITY**

The PCR document help to decide which processes to include when developing the EPD of a product or structure. The Figure 7 below illustrates the way processes can be sub-divided into EPD modules for cement production, to form a Cradle-to-Gate scope (i.e. the finished cement product is available at the factory gates).

The module A3 consists of cement factory processes, while the module A2 consists of transport operations, and finally the module A1 consists of background processes (electricity generation, construction of infrastructures, etc.). As we go back up in the supply chain, the A1 module also contains the very first processes that use inputs from natural compartments (e.g. coal mining operations) for energy capture and transformation as well as raw materials (e.g. limestone quarry operations).

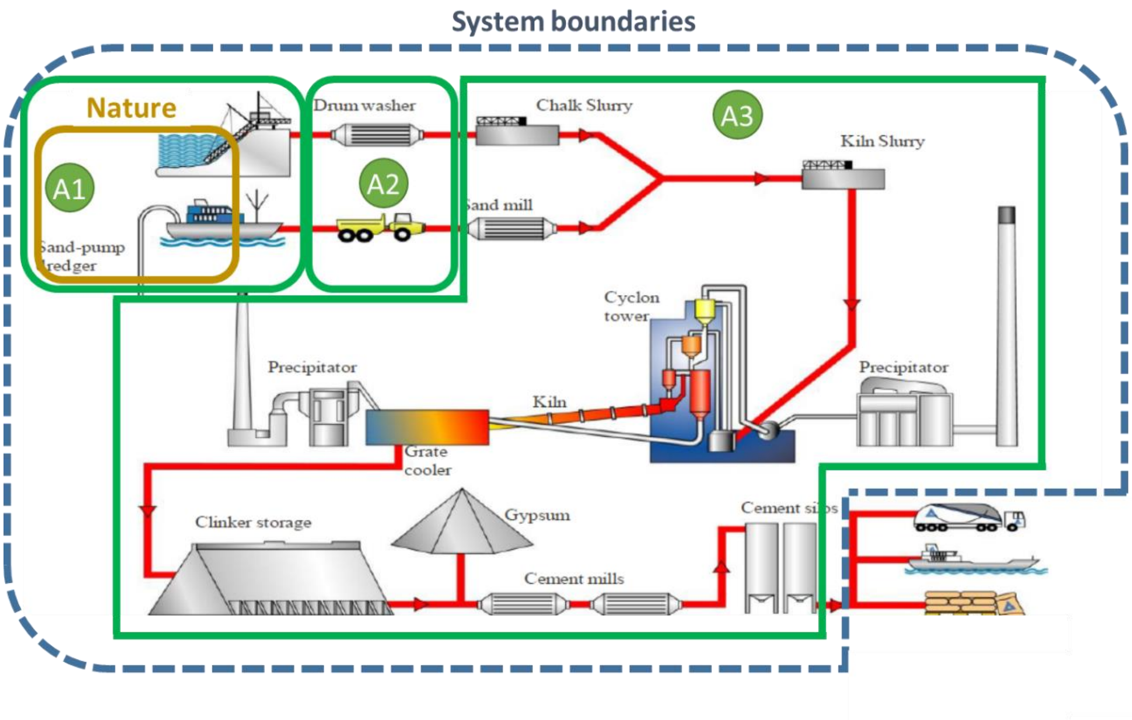
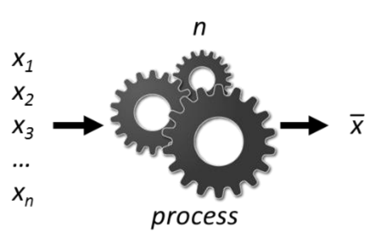


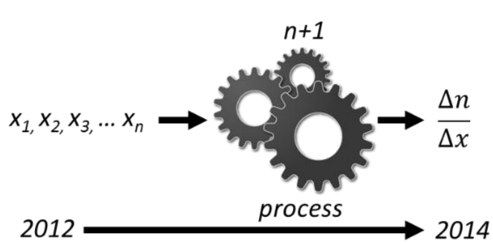

FIGURE 7 SYSTEM BOUNDARIES FOR CEMENT PRODUCTION

## Temporal boundaries

Equally important, temporal boundaries define the length in time over which the material and energy inputs and outputs of the processes contained in the product system are accounted for. In attributional LCAs and EPDs, it usually consists of the average over one year.




In the consequential approach, an interval of time (usually around 5 years) is instead considers, to capture the marginal quantities over the mid- to long-term.




# INVENTORY

## Modelling

When the scope of the product system is defined over space and time, input and output data for each process must be accounted for, and processes must be linked to one another to form a coherent supply chain. In most LCA tools, processes are modelled separately first. Figure 8 below shows how sub-processes (slurry, clinker, mills, electricity, etc.) in the cement factory have been modelled with an output flow (of 1 ton, 1 kWh and 1 MJ for materials, energy carriers and fuels, respectively) and then linked to one another in proportions as indicated by historical average production data (either given by the company's ERP system or the LCA database).

Second order energy analyses and mass balances must be performed to ensure that all significant inputs and outputs are included in the product system.

Sometimes, partitioning issues may arise. For example, circled in red are processes that either deliver more than one output or that the output needs to be distributed among several receiving processes. The top red circle represents the overhead electricity consumption of the factory that needs to be distributed among the finished products following a specific rule. The bottom red circle represents the production of white clinker that also co-produces excess heat.

The multi-output partitioning case is discussed in the Allocation section. Unfortunately, when a multi-outputs process is partitioned and its inputs are allocated between several co-products, the balance of mass and energy flows is often violated: allocation of inputs based on the mass of co-products compromises the energy balance, and the allocation of inputs based on the embodied energy of the co-products compromises the mass balance. Allocation performed based on an economic key usually compromises both energy and mass balances. This is a sensitive issue, where the EN 15804 PCR document forces allocation (economic or mass-/energy-based) which inevitably breaks the physical balances of flows. The integrity of the flows energy and mass balance is one of the pillar principles found in the LCA standards ISO 14040.

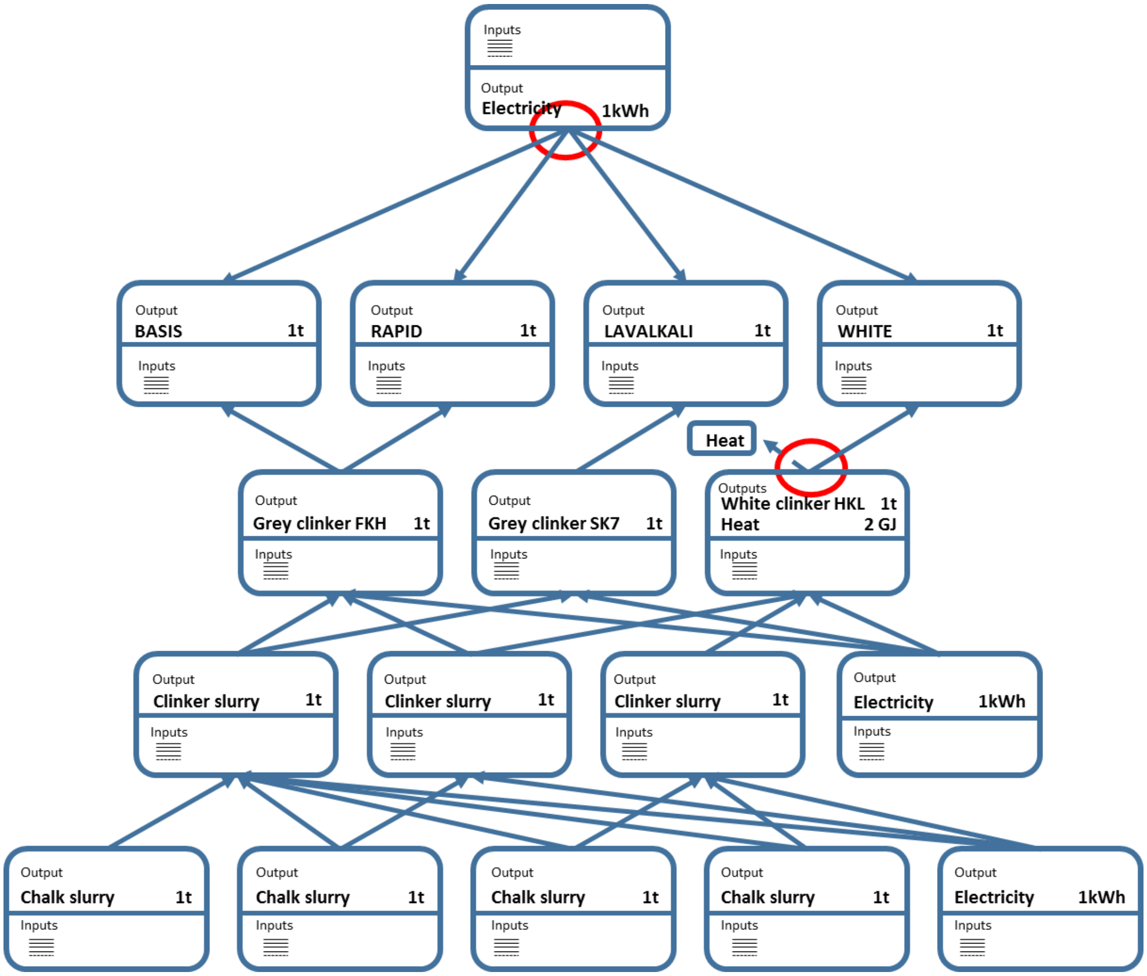



FIGURE 8 MODELLING OF THE PORTLAND CEMENT PRODUCT SYSTEM

## Data collection and LCI databases

As previously mentioned, the necessary inputs and outputs data for modelling the processes included in the product system usually rely on different sources. As an example, for the modelling of the cement product system of Aalborg Portland, the Figure 9 indicates that:

- Data corresponding to the module A1 have been sourced mostly from a LCA database (as well as scientific publications for the transformation and preparation of fuels),
- Data corresponding to the module A2 have been sourced partly from an LCA database (i.e. transport operations) but also from sources internal to the cement factory (i.e. origins and quantities of good transported),
- And data corresponding to the module A3 have been mostly sourced from the factory ERP system as well as external laboratory analyses.

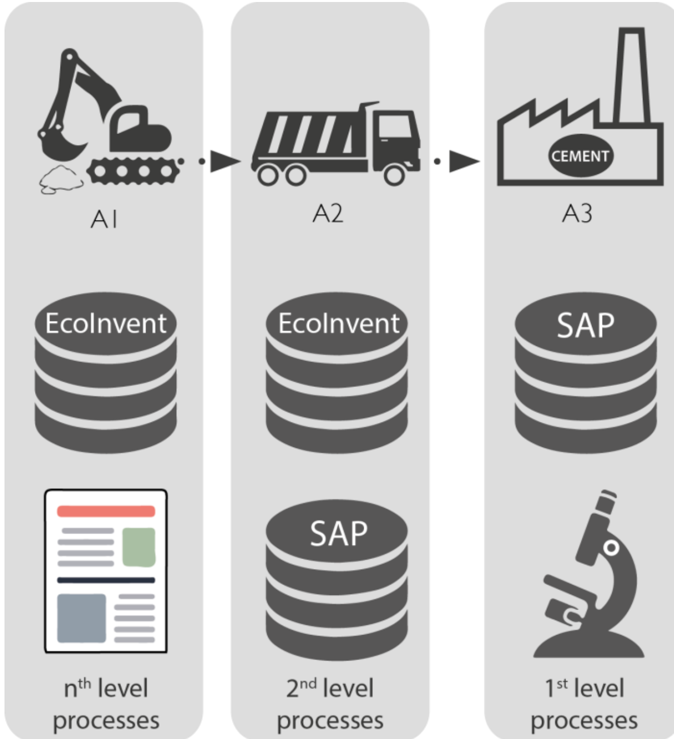



FIGURE 9 DATA SOURCES PER EPD MODULE

### Allocations

In attributional LCA models, and therefore in EPDs, allocation problems may arise when including production processes that co-supply two products or more. Since attributional LCAs can only contain single output processes, the practitioner needs to single out the share of the process responsible for the second output.

The partitioning of inputs and emissions between the products of a processes is a delicate task in a LCA and often subject to debate and criticism, as there is not ideal way to proceed.


FIGURE 10 ALLOCATION ISSUE BETWEEN CLINKER, GYPSUM AND EXCESS HEAT

In the example of cement production, the development of the EPD for white Portland cement from Aalborg Portland leads to an allocation exercise between the production of white clinker, gypsum and heat. They are three co-products from a same process, where none of them can be produced independently from the two others.

The general PCR document EN 15804 suggests to follow the founding principles of the ISO standards, but also adds that:

- If the difference in the relative economic value between the co-products is large (>25%), then the environmental burden of the process should be partitioned based on an economic key,
- If the difference in the relative economic value between the co-products is low (<25%), then the environmental burden of the process should be partitioned based on a physical property common to all the co-products.

However, it is to note that economic allocation leads to the violation of both mass and energy balances, and is therefore in contradiction with the founding ISO principles.

The cement- and concrete-specific PCR documents suggest to follow the above priority for allocation choices. The bridge PCR document suggests, if possible, to allocate based on physical properties first (mass or embodied energy).

Sometimes, although physical allocation is recommended by the PCR document (i.e. PCR document for bridges), but the co-products share no common physical properties (neither mass, energy, moles, etc.), allocation based on an economic key has to be performed.

The allocation of inputs and emissions between the co-production of white clinker and excess heat at Aalborg Portland can also be solved using system expansion, a method proper to the consequential LCA approach (hence not used in EPDs). In this case, to obtain the environmental burden of white clinker, cut away from the burden of the recovered heat, the environmental burden caused by the recovery of heat in the district heating system of Aalborg is withdrawn from the overall environmental burden of the clinker oven. In this case, the recovery of heat and its supply in the district heating system of Aalborg allows to save the combustion of about 80 kg of hard coal at the city's main coal-fired CHP unit, Nordjyllandsværket. The avoided environmental burden associated to the avoided combustion of coal is withdrawn from the clinker oven overall emissions. As opposed to allocation, system expansion has the merit to not violate mass and energy balances, which is a principle of prime importance in the LCA standards 14040/44.

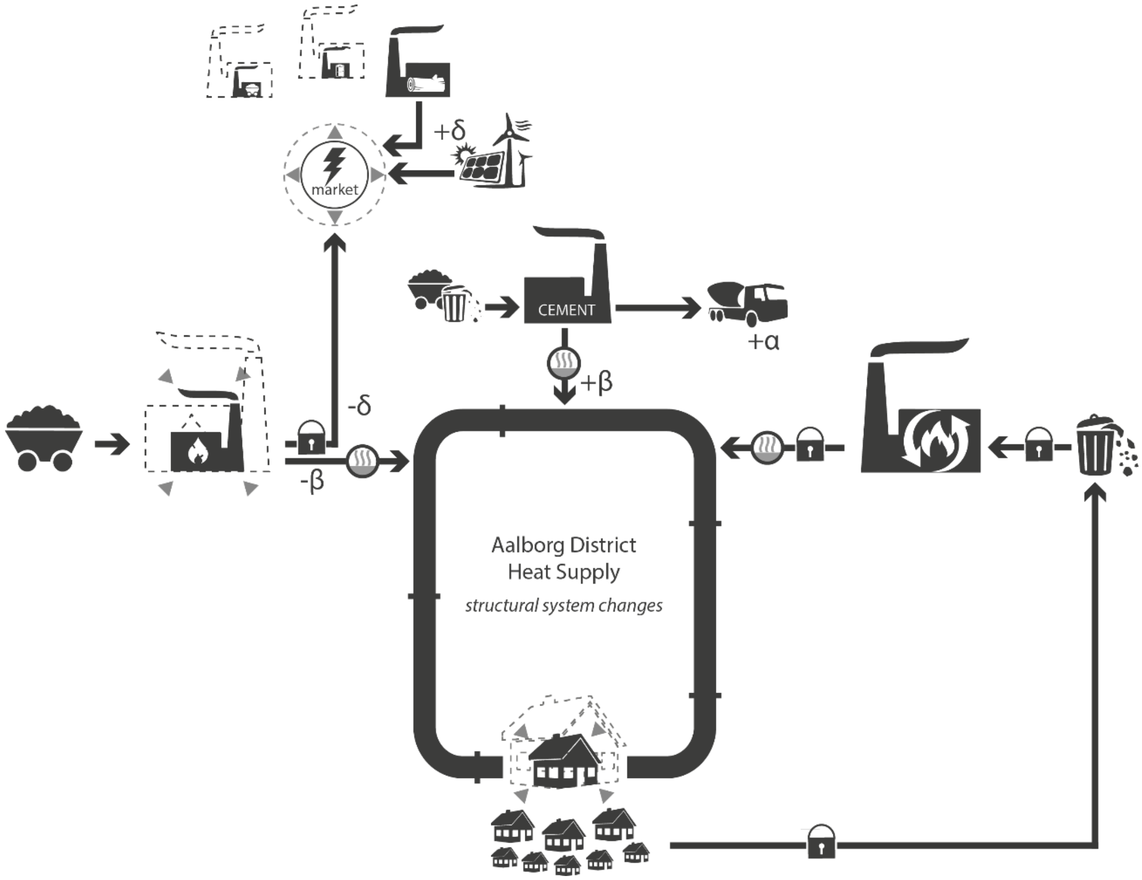



**FIGURE 11 THE ENVIRONMENTAL BURDEN OF CO-PRODUCED HEAT USING SYSTEM EXPANSION**

More information on this case: https://consequential-lca.org/clca/marginal-suppliers/increasing-or-slowly-decreasing-market/heat-recovery-system-expansion/

### End-of-waste state

In EPDs, as a general rule, when a product system uses residual and waste materials in the production process, the 100:0 polluter-pay principle applies. This means that the environmental burden associated to the waste material is reported on the EPD of the waste emitter, not the waste receiver.

For example, when a yogurt plastic package is used as alternative fuel in the cement production process, the environmental burden associated to the manufacture and disposal of the package is reported in the yogurt EPD (if such exists), not in the EPD of the cement producer. However, activities necessary to make the disposed yogurt package usable in the receiving process (cleaning, shredding, transport) must be reported in the EPD of the cement producer. The limit beyond which additional processes must be reported in the EPD of the waste receiver is called the End-of-waste State.

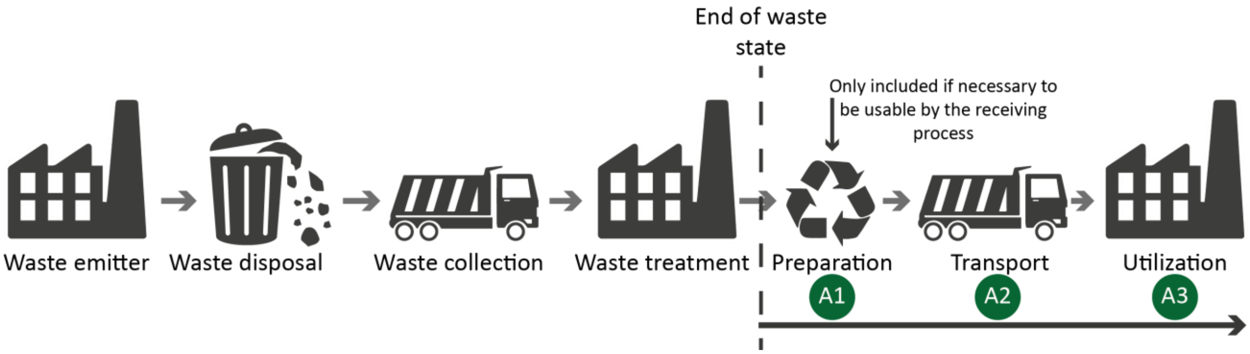



**FIGURE 12 END-OF-WASTE STATE DEFINITION**

## Quality assessment

It is usually recommended by the ISO standard series and the EPD program operators to conduct a quality assessment to inform the reader about the scientific validity, reliability and robustness of the inventory, results and underlying model and assumptions.

Such quality tests as shown in Table 1 can be used.

| | **Reliability (30%)** | | **Validity (30%)** | | **Pedigree (40%)** | |
|---|---|---|---|---|---|---|
| **Application level** | *Reliability of data (15%)* | *Reliability of the model (15%)* | *Validity of data (15%)* | *Validity of the model (15%)* | *Procedure* | *Methods* |
| **Goal and scope** | | | | | Peer review | External review of the models |
| *Functional unit* | Linearity between functional unit and end-results | Linearity between input data and end-results | Choice of the functional unit | | Sensitivity analysis | Change processes sources and inputs |
| **Inventory** | | | | | Dominance analysis | Identify relevant processes |
| *Process* | Data variability coverage | Statistical representativeness | Process data in/excluded, temporal and technological representativeness | | Scenario analysis | Change variables and model assumption |
| *System* | Inventory data uncertainty | Reproducibility of the transformation model | Consistency of cut-off criteria application | Validity of LCA model, multi-output and open-loop allocations | Perturbation analysis | Marginal changes applied to significant processes or assumptions |
| **Assessment** | | | | | | Monte Carlo analysis |
| *Environmental flow* | | | | Scientific recognition of the characterization methods | Comparison to other models | Comparison with previous EPDs |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Environmental issue* | | Temporal and geographical representativeness of the characterization methods | | | Experience of the LCA practitioner | |
| *Set of environmental issues* | | | | Adequate characterization methods | | |
| **Interpretation** | | | | | | |
| *Set of environmental issues* | | Answer to the Goal objectives | | Completeness of the evaluation | | |
| | Score: /30 | | Score: /30 | | Score: /40 | |

**TABLE 1 QUALITY ASSESSMENT FRAMEWORK**

Quality assessment tests usually include scenario and sensitivity analyses, where the data and model assumptions and their impacts on the conclusion of the study are evaluated.

# IMPACT ASSESSMENT

When the scope of an LCA/EPD is defined, and when the inventory of the product system is calculated, the next phase, Impact Assessment, consists into:

- listing all the processes/environment flows (under the form of gaseous or solid input/output exchanges),
- classifying these interactions into categories,
- multiplying these flows by characterization factors to obtain a list of characterized impact *midpoint* and *endpoint* indicators.

For example, certain gaseous flows to air compartments, such as methane, carbon monoxide, carbon dioxide, halon gases, etc., will be multiplied by a corresponding characterization factor (which result from a scientific consensus from the International Panel for Climate Change) in order to obtain an indicator expressed in kg of $CO_2$-eq (all the gases are "converted" in an equivalent mass of $CO_2$ depending on their potency in terms of radiative forcing, in the case of global warming).

Table 2 below shows a non-exhaustive list of characterizations factors for a number of gaseous emissions, to express them in kg of $CO_2$-equivalent. Unsurprisingly, carbon dioxide has a characterization factor of 1. Negative characterization factors in this table indicate carbon sequestration.

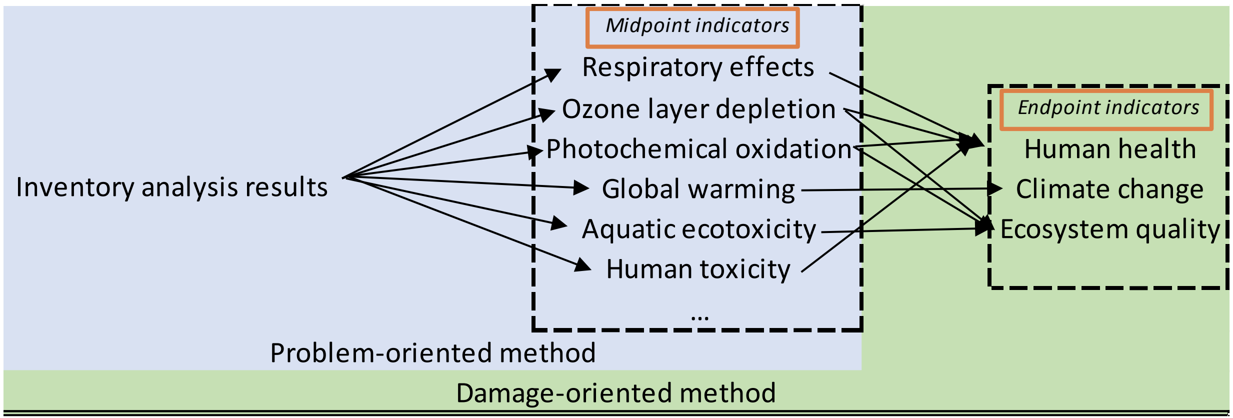
| Flow | Unit | Factor |
|---|---|---|
| **1-Propanol, 3,3,3-trifluoro-2,2-bis(trifluoromethyl)-, HFE-7100** | kg CO2 eq./kg | 297.0 |
| **Butane, perfluoro-** | kg CO2 eq./kg | 8860.0 |
| **Butane, perfluorocyclo-, PFC-318** | kg CO2 eq./kg | 10300.0 |
| **Carbon dioxide** | kg CO2 eq./kg | 1.0 |
| **Carbon dioxide** | kg CO2 eq./kg | -1.0 |
| **Carbon dioxide, fossil** | kg CO2 eq./kg | 1.0 |
| **Carbon dioxide, from soil or biomass stock** | kg CO2 eq./kg | 1.0 |
| **Carbon dioxide, in air** | kg CO2 eq./kg | 1.0 |
| **Carbon dioxide, in air** | kg CO2 eq./kg | -1.0 |
| **Carbon dioxide, land transformation** | kg CO2 eq./kg | 1.0 |
| **Carbon monoxide** | kg CO2 eq./kg | 1.9 |
| **Carbon monoxide, biogenic** | kg CO2 eq./kg | 1.9 |
| **Carbon monoxide, fossil** | kg CO2 eq./kg | 1.9 |
| **Carbon monoxide, from soil or biomass stock** | kg CO2 eq./kg | 1.9 |
| **Dinitrogen monoxide** | kg CO2 eq./kg | 298.0 |
| **Ethane, 1,1,1,2-tetrafluoro-, HFC-134a** | kg CO2 eq./kg | 1430.0 |
| **Ethane, 1,1,1-trichloro-, HCFC-140** | kg CO2 eq./kg | 146.0 |
| **Ethane, 1,1,1-trifluoro-, HFC-143a** | kg CO2 eq./kg | 4470.0 |
| **Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113** | kg CO2 eq./kg | 6130.0 |
| **Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b** | kg CO2 eq./kg | 725.0 |
| **Ethane, 1,1-difluoro-, HFC-152a** | kg CO2 eq./kg | 124.0 |
| **Ethane, 1,2-dibromotetrafluoro-, Halon 2402** | kg CO2 eq./kg | 1640.0 |
| **Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114** | kg CO2 eq./kg | 10000.0 |
| **Ethane, 1-chloro-1,1-difluoro-, HCFC-142b** | kg CO2 eq./kg | 2310.0 |
| **Ethane, 1-chloro-2,2,2-trifluoro-(difluoromethoxy)-, HCFE-235da2** | kg CO2 eq./kg | 350.0 |
| **Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123** | kg CO2 eq./kg | 77.0 |
| **Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124** | kg CO2 eq./kg | 609.0 |
| **Ethane, chloropentafluoro-, CFC-115** | kg CO2 eq./kg | 7370.0 |
| **Ethane, hexafluoro-, HFC-116** | kg CO2 eq./kg | 12200.0 |
| **Ethane, pentafluoro-, HFC-125** | kg CO2 eq./kg | 3500.0 |
| **Ether, 1,1,1-trifluoromethyl methyl-, HFE-143a** | kg CO2 eq./kg | 756.0 |
| **Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcc3** | kg CO2 eq./kg | 575.0 |

| | | |
|---|---|---|
| **Ether, 1,1,2,2-Tetrafluoroethyl methyl-, HFE-254cb2** | kg CO2 eq./kg | 359.0 |
| **Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcc3** | kg CO2 eq./kg | 110.0 |
| **Ether, di(difluoromethyl), HFE-134** | kg CO2 eq./kg | 6320.0 |
| **Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245cb2** | kg CO2 eq./kg | 708.0 |
| **Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa2** | kg CO2 eq./kg | 659.0 |
| **Ether, nonafluorobutane ethyl-, HFE569sf2 (HFE-7200)** | kg CO2 eq./kg | 59.0 |
| **Ether, pentafluorodimethyl-, HFE-125** | kg CO2 eq./kg | 14900.0 |
| **Hexane, perfluoro-** | kg CO2 eq./kg | 9300.0 |
| **HFC-245fa** | kg CO2 eq./kg | 1030.0 |
| **HFE-236ca12 (HG-10)** | kg CO2 eq./kg | 2800.0 |
| **HFE-338pcc13 (HG-01)** | kg CO2 eq./kg | 1500.0 |
| **HFE-347pcf2** | kg CO2 eq./kg | 580.0 |
| **HFE-43-10pccc124 (H-Galden1040x)** | kg CO2 eq./kg | 1870.0 |
| **Methane** | kg CO2 eq./kg | 25.0 |
| **Methane, biogenic** | kg CO2 eq./kg | 25.0 |
| **Methane, bromo-, Halon 1001** | kg CO2 eq./kg | 5.0 |
| **Methane, bromochlorodifluoro-, Halon 1211** | kg CO2 eq./kg | 1890.0 |
| **Methane, bromotrifluoro-, Halon 1301** | kg CO2 eq./kg | 7140.0 |
| **Methane, chlorodifluoro-, HCFC-22** | kg CO2 eq./kg | 1810.0 |
| **Methane, chlorotrifluoro-, CFC-13** | kg CO2 eq./kg | 14400.0 |
| **Methane, dichloro-, HCC-30** | kg CO2 eq./kg | 8.7 |
| **Methane, dichlorodifluoro-, CFC-12** | kg CO2 eq./kg | 10900.0 |
| **Methane, difluoro-, HFC-32** | kg CO2 eq./kg | 675.0 |
| **Methane, fossil** | kg CO2 eq./kg | 25.0 |
| **Methane, from soil or biomass stock** | kg CO2 eq./kg | 25.0 |
| **Methane, monochloro-, R-40** | kg CO2 eq./kg | 13.0 |
| **Methane, tetrachloro-, R-10** | kg CO2 eq./kg | 1400.0 |
| **Methane, tetrafluoro-, R-14** | kg CO2 eq./kg | 7390.0 |
| **Methane, trichlorofluoro-, CFC-11** | kg CO2 eq./kg | 4750.0 |
| **Methane, trifluoro-, HFC-23** | kg CO2 eq./kg | 14800.0 |
| **Nitrogen fluoride** | kg CO2 eq./kg | 17200.0 |
| **Pentane, 2,3-dihydroperfluoro-, HFC-4310mee** | kg CO2 eq./kg | 1640.0 |
| **Pentane, dodecafluoro-, PFC-4-1-12** | kg CO2 eq./kg | 9160.0 |
| **Pentane, perfluoro-** | kg CO2 eq./kg | 9160.0 |
| **PFC-9-1-18** | kg CO2 eq./kg | 7500.0 |
| **PFPMIE** | kg CO2 eq./kg | 10300.0 |
| **Propane, 1,1,1,2,3,3,3-heptafluoro-, HFC-227ea** | kg CO2 eq./kg | 3220.0 |
| **Propane, 1,1,1,3,3,3-hexafluoro-, HCFC-236fa** | kg CO2 eq./kg | 9810.0 |
| **Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb** | kg CO2 eq./kg | 595.0 |
| **Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca** | kg CO2 eq./kg | 122.0 |
| **Propane, perfluoro-** | kg CO2 eq./kg | 8830.0 |
| **Sulfur hexafluoride** | kg CO2 eq./kg | 22800.0 |
| **trifluoromethyl sulphur pentafluoride** | kg CO2 eq./kg | 17700.0 |

**TABLE 2 LIST OF CHARACTERIZATION FACTORS FOR GLOBAL WARMING (CML 2001)**

While midpoint indicators are usually stripped from any interpretation (e.g. Global warming expressed in kg of $CO_2$-eq., Ozone depletion expressed in kg of CFC-11-eq.), endpoint indicators are damage-oriented: based on midpoint indicators, they assess the damage inflicted on end-recipients such as humans, nature, etc. Admittedly, while endpoint indicators are helpful for decision-making (as they present less indicators), they are often also obtained through societal and normative choices.

In EPDs, only midpoint indicators are reported.




The list of characterization factors used to go from the list of inventory flows from the product system to characterized midpoint and endpoint impacts figures are developed as "methods" by different organizations, most often the work of universities and research groups.

## Midpoint indicators methods

Most impact assessment methods contain midpoint and endpoint indicators. Impact categories with midpoint indicators describe an environmental mechanism within a specified temporal and geographical scale. Figure 13 below shows the usual temporal and geographical definitions used by the common midpoint indicators methods.

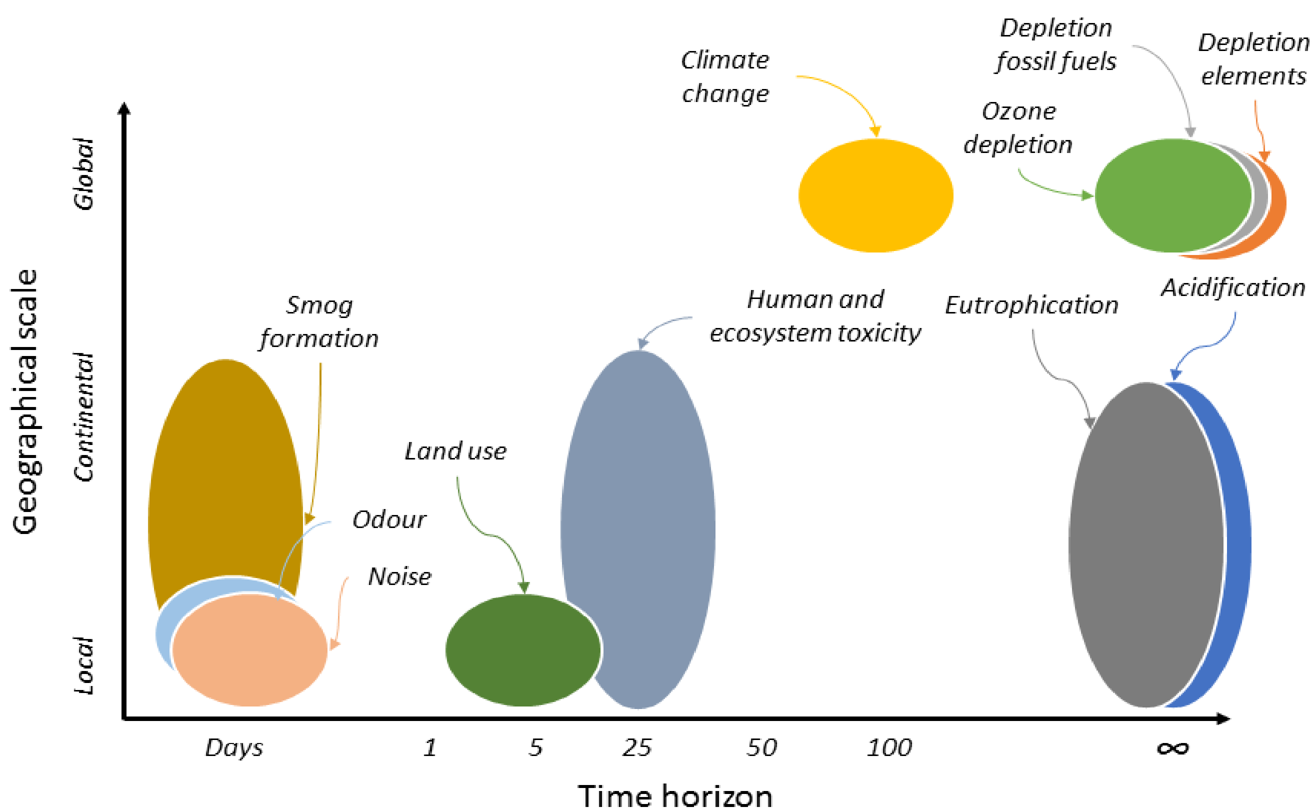



FIGURE 13 GEOGRAPHICAL AND TEMPORAL DEFINITIONS OF COMMON MIDPOINT INDICATORS

## CML 2001

Online documentation: http://www.leidenuniv.nl/cml/ssp/projects/lca2/

Developed by the Institute of Environmental Sciences at Leiden University, the CML 2001 method is restricted to midpoint indicators. The baseline list of midpoint indicators contained in CML 2001 are those required currently in general PCR document for EPDs EN-15804.

| Impact required by EN-15804 | Impact category included in CML 2001 | Description | Geographical and temporal scale |
|---|---|---|---|
| **Depletion of abiotic resources-elements**<br>**Depletion of abiotic resources-fossil fuels** | Depletion of abiotic resources | The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation. | Global scale, infinity |
| **Acidification for soil and water** | Acidification potential | Acidification Potential (AP) for emissions to air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as kg SO2-eq/ kg of emission.<br><br>Characterization factors including fate were used when available. When not available, the factors excluding fate were used (In the CML baseline version only factors including fate were used). The method was extended for Nitric Acid, soil, water and air; Sulphur acid, water; Sulphur trioxide, air; Hydrogen chloride, water, soil; Hydrogen fluoride, water, soil; Phosphoric acid, water, soil; Hydrogen sulfide, soil, all not including fate. Nitric oxide, air (is nitrogen monoxide) was added including fate. | Continental scale, infinity |
| **Ozone depletion** | Stratospheric ozone depletion | The characterization model is developed by the World Meteorological Organization (WMO) and defines ozone depletion potential of different gasses (kg CFC-11 equivalent/kg emission). The geographic scope of this indicator is at global scale. | Global scale, infinity |
| **Global warming** | Climate change | The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg of carbon dioxide-eq/kg of emission. | Global scale, 100 years |
| **Eutrophication** | Eutrophication potential | Eutrophication potential (NP) is based on the stoichiometric procedure of Heijungs (1992), and expressed as kg PO4 equivalents per kg emission. Fate and exposure is not included. | Continental scale, infinity |
| **Photochemical ozone creation** | Photochemical Ozone Creation Potential | Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg of emission. | Continental scale, 5 days |

## ReCiPe

Online documentation: www.lca-recipe.net

The ReCiPe method is a collaboration between RIVM, CML, PRé Consultants, and Radboud Universiteit Nijmegen. It contains both midpoint indicators (18) and endpoint indicators (3). The method also has the option to weight between the endpoint indicators to obtain a single aggregated score. It has been largely based on the work developed in the CML 2001 method (see previous section), extending it to endpoint indicators and single score.

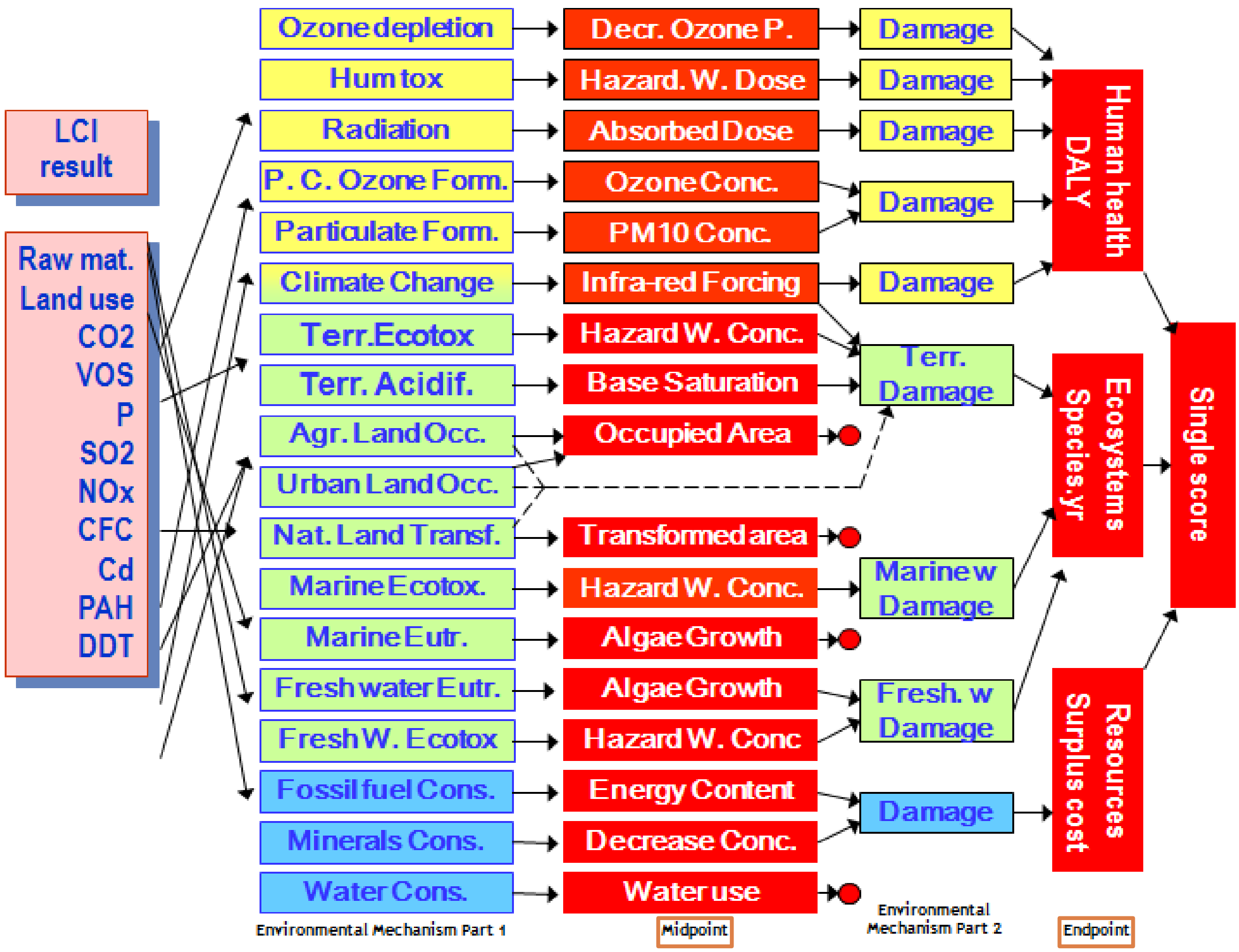



FIGURE 14 MIDPOINT AND ENDPOINT INDICATORS STRUCTURE IN THE RECIPE METHOD

## EDIP 2003

Online documentation: http://orbit.dtu.dk/en/publications/background-for-spatial-differentiation-in-life-cycle-impact-assessment-the-edip2003-methodology(d41b5c77-350b-4af5-ac77-af5432b914ef).html

The EDIP 2003 method has been developed by DTU Copenhagen. It extends the previous work on EDIP 1997 by covering a larger part of the causality chain (and become more damage-oriented) and by introducing spatial variation in impact assessment (as opposed to site-generic impact assessment), where granularity in terms of receiving compartments and country/region adds accuracy in impacts assessment.

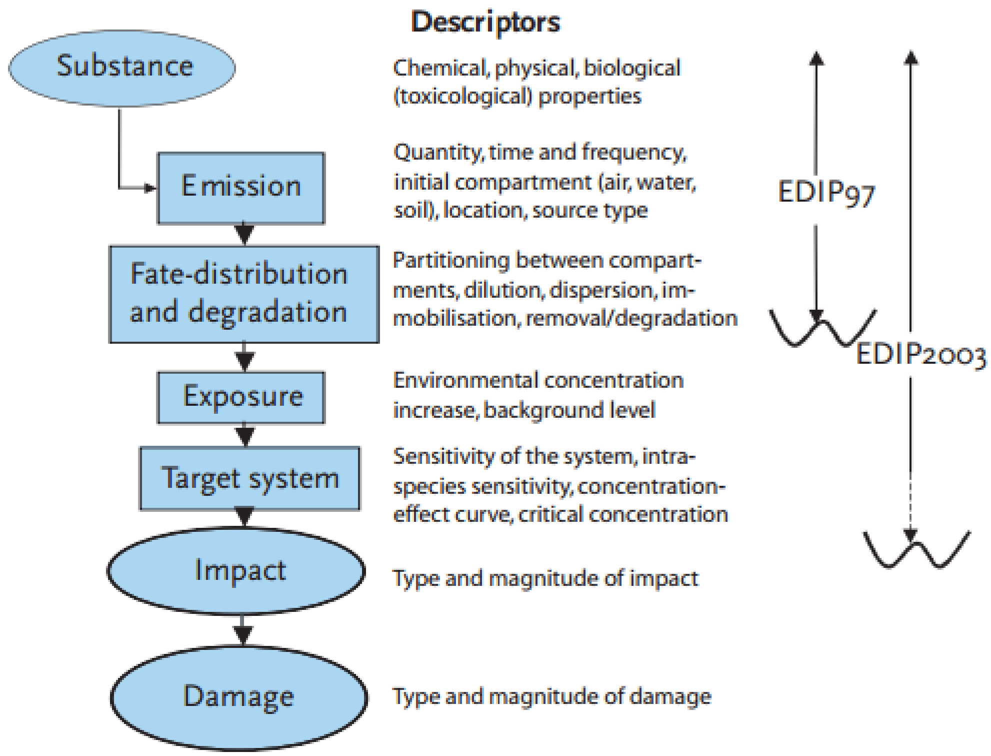



FIGURE 15 PATHWAY STRUCTURE OF THE EDIP METHOD. SOURCE: THE EDIP MANUAL.

| Name | Description | Reference unit |
|---|---|---|
| **acidification - acidification** | acidification | m2 |
| **ecotoxicity - acute, in water** | acute, in water | m3 water |
| **ecotoxicity - chronic, in soil** | chronic, in soil | m3 soil |
| **ecotoxicity - chronic, in water** | chronic, in water | m3 water |
| **ecotoxicity - in sewage treatment plants** | in sewage treatment plants | m3 waste water |
| **eutrophication - combined potential** | combined potential | kg NO3- |
| **eutrophication - separate N potential** | separate N potential | kg N |
| **eutrophication - separate P potential** | separate P potential | kg P |
| **eutrophication - terrestrial eutrophication** | terrestrial eutrophication | m2 |
| **global warming - GWP 100a** | GWP 100a | kg CO2-Eq |
| **global warming - GWP 20a** | GWP 20a | kg CO2-Eq |
| **global warming - GWP 500a** | GWP 500a | kg CO2-Eq |
| **human toxicity - via air** | via air | m3 air |
| **human toxicity - via soil** | via soil | m3 soil |
| **human toxicity - via surface water** | via surface water | m3 water |
| **land filling - bulk waste** | bulk waste | kg waste |
| **land filling - hazardous waste** | hazardous waste | kg waste |
| **land filling - radioactive waste** | radioactive waste | kg waste |
| **land filling - slag and ashes** | slag and ashes | kg waste |
| **non-renewable resources - aluminium** | aluminium | kg |

| | | |
|---|---|---|
| **non-renewable resources - antimony** | antimony | kg |
| **non-renewable resources - brown coal** | brown coal | kg |
| **non-renewable resources - cadmium** | cadmium | kg |
| **non-renewable resources - cerium** | cerium | kg |
| **non-renewable resources - coal** | coal | kg |
| **non-renewable resources - cobalt** | cobalt | kg |
| **non-renewable resources - copper** | copper | kg |
| **non-renewable resources - gold** | gold | kg |
| **non-renewable resources - iron** | iron | kg |
| **non-renewable resources - lanthanum** | lanthanum | kg |
| **non-renewable resources - lead** | lead | kg |
| **non-renewable resources - manganese** | manganese | kg |
| **non-renewable resources - mercury** | mercury | kg |
| **non-renewable resources - molybdenum** | molybdenum | kg |
| **non-renewable resources - natural gas** | natural gas | kg |
| **non-renewable resources - nickel** | nickel | kg |
| **non-renewable resources - oil** | oil | kg |
| **non-renewable resources - palladium** | palladium | kg |
| **non-renewable resources - platinum** | platinum | kg |
| **non-renewable resources - silver** | silver | kg |
| **non-renewable resources - tantalum** | tantalum | kg |
| **non-renewable resources - tin** | tin | kg |
| **non-renewable resources - zinc** | zinc | kg |
| **photochemical ozone formation - impacts on human health** | impacts on human health | person.ppm.h |
| **photochemical ozone formation - impacts on vegetation** | impacts on vegetation | m2.ppm.h |
| **renewable resources - wood** | wood | m3 |
| **stratospheric ozone depletion - ODP total** | ODP total | kg CFC-11-Eq |

**TABLE 3 MIDPOINT INDICATORS CONTAINED IN EDIP2003**

### IMPACT 2002+

Online documentation:
https://pdfs.semanticscholar.org/8350/5a9fc28797b8ac45d1222f2f291d81fc5b7d.pdf

IMPACT 2002+ is an impact assessment method originally developed at the Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland. It consists of 17 midpoint indicators and 4 endpoint indicators.

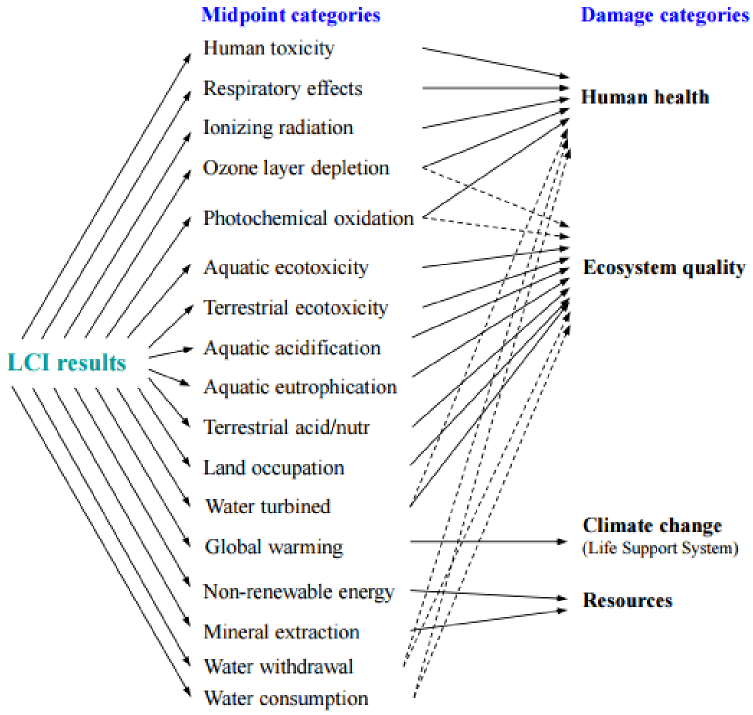



**FIGURE 16 MIDPOINT AND ENDPOINT INDICATORS STRUCTURE OF IMPACT2002+. SOURCE: THE IMPACT2002+ MANUAL.**

## Normalization

In order to give meaning to a set of midpoint indicators, they can be normalized to a given reference. Many impact assessment methods offer normalization factors to normalize results. For example, the results of an LCA can be normalized to the average impact of a European person or to the whole European Union for a given year. In this manner, the step of normalization renders obvious the impacts that are abnormally high compared to the average annual impacts associated to the reference.

For example, Table 4 shows the characterized results for the production of 1 ton of a European average grey Portland cement. Besides the situation where one can compare these results to another set of results, they do not help much in figuring out which impacts are relatively more important than the rest. In the Figure 17 below, the same results are normalized to the average impacts of the European union (25 countries) in 2000. Marine aquatic ecotoxicity impacts appear relatively more important than the rest, contributing to a fraction of 4E-9 of the overall impacts of the EU25 in 2000 in that impact category. An in-depth analysis of the results helps to determine what causes impacts in terms of Marine ecotoxicity (in this case, it is mainly due to the waste treatment activities during the mining of coal).

| Impact category | Result | Reference unit |
|---|---|---|
| **Terrestrial ecotoxicity - TETP inf** | 1,75535 | kg 1,4-dichlorobenzene eq. |
| **Eutrophication - generic** | 0,42292 | kg PO4--- eq. |
| **Depletion of abiotic resources - fossil fuels** | 3144,321 | MJ |
| **Freshwater aquatic ecotoxicity - FAETP inf** | 54,49509 | kg 1,4-dichlorobenzene eq. |
| **Ozone layer depletion - ODP steady state** | 2,60E-05 | kg CFC-11 eq. |
| **Marine aquatic ecotoxicity - MAETP inf** | 1,78E+05 | kg 1,4-dichlorobenzene eq. |
| **Photochemical oxidation - high Nox** | 0,06039 | kg ethylene eq. |

| | | |
|---|---|---|
| **Human toxicity - HTP inf** | 95,04611 | kg 1,4-dichlorobenzene eq. |
| **Depletion of abiotic resources - elements, ultimate reserves** | 0,00032 | kg antimony eq. |
| **Climate change - GWP100** | 885,7167 | kg CO2 eq. |
| **Acidification potential - average Europe** | 1,57491 | kg SO2 eq. |

**TABLE 4 CHARACTERIZED RESULTS WITH CML 2001 OF 1 TON OF GREY EUROPEAN PORTLAND CEMENT**

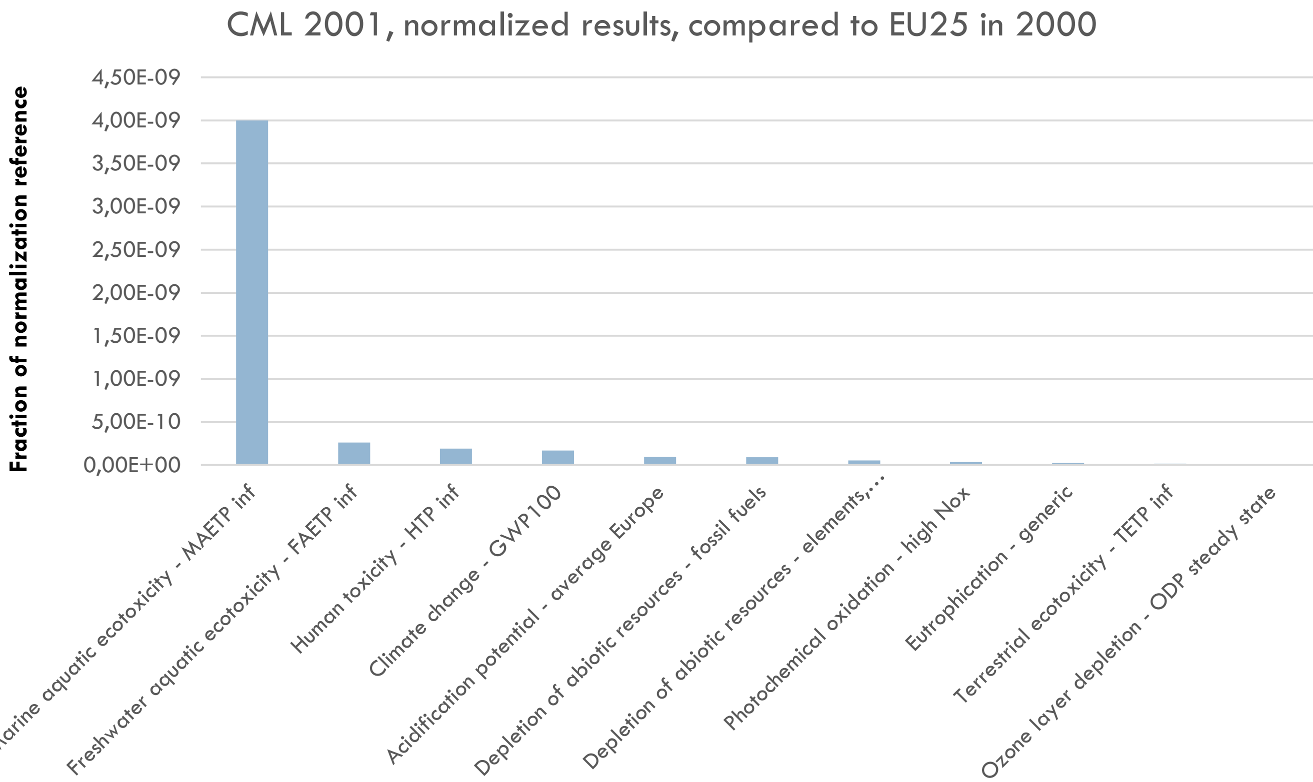



**FIGURE 17 CNORMALIZED RESULTS WITH CML 2001 OF 1 TON OF GREY EUROPEAN PORTLAND CEMENT MIDPOINT INDICATORS**

## Endpoint indicators methods and weighting

Endpoint indicators are commonly use to ease the interpretation of LCA results are reduced the number of indicators. Almost all the methods presented above have endpoint indicators besides the existing midpoint indicators. Endpoint indicators are usually more damage-oriented and represent the damage recipients as stakeholders (humans, nature, animals, etc.) while midpoint indicators usually represent something closer to environmental mechanisms (Global warming, Acidification, etc.).

Endpoint indicators are obtained by applying weighting coefficients to midpoint indicators. Weighting coefficients can be criticized as they often result from societal norms and choices.

While most endpoint indicators methods do not offer the possibility to choose the weighting coefficients applied to the different midpoint indicators, some other methods such as ReCiPe or Eco-indicator 99, can produce endpoint indicators according to three cultural perspectives (that the LCA practitioner can choose from) that give priority to some impacts: individualistic, hierarchist and egalitarian perspectives:

- **Individualistic** (I) perspective: short term, optimism that technology can avoid many problems in future. It has a short time scope (around 20 years), meaning that it gives less importance to problems occurring for the next generations.
- **Hierarchist** (H) perspective: consensus model, as often encountered in scientific models, this is often considered to be the default model. It is the usual model, and it has a time scope of 100 years.
- **Egalitarian** (E) perspective: long term based on precautionary principle thinking. It is the most "sustainable" perspective in the way that it does not discount at all the future problems, making an impact happening in 100 years as important as an impact happening now, and therefore supporting the sustainable definition of not reducing the ability of the next generation to benefit from the present natural capital.

To illustrate the idea of endpoint indicators, Table 5 represent the characterized impact results for the production of 1 ton of grey European average Portland cement using the midpoint indicators of the EDIP 2003 method, while Table 6 shows the same product system but with its impacts characterized with endpoint indicators of that same method.

The resources-related impact (13$) includes metal and fossil reserves depletion by calculating the additional cost of mining such resources at a comparable grade quality in the future (since, as reserves deplete, deeper mining will be required). The human health impact is expressed in DALY (Disability-adjusted life year), which represents the amount of years of healthy life lost due to illness or death. Finally, Ecosystems-related impacts quantify the amount of disappeared species (biodiversity loss) in a year.

| Impact category | Result | Reference unit |
|---|---|---|
| climate change | 860,8923 | kg CO2-Eq |
| marine eutrophication | 0,5183 | kg N-Eq |
| freshwater ecotoxicity | 1,9018 | kg 1,4-DCB-Eq |
| terrestrial acidification | 1,73627 | kg SO2-Eq |
| natural land transformation | 0,05226 | m2 |
| urban land occupation | 2,18931 | m2*a |
| water depletion | 1,02255 | m3 |
| marine ecotoxicity | 2239,555 | kg 1,4-DCB-Eq |
| particulate matter formation | 0,63642 | kg PM10-Eq |
| metal depletion | 8,37562 | kg Fe-Eq |
| fossil depletion | 79,47809 | kg oil-Eq |
| agricultural land occupation | 11,21889 | m2*a |
| photochemical oxidant formation | 1,49225 | kg NMVOC |
| terrestrial ecotoxicity | 0,16491 | kg 1,4-DCB-Eq |
| human toxicity | 2818,824 | kg 1,4-DCB-Eq |
| ionizing radiation | 30,43303 | kg U235-Eq |
| freshwater eutrophication | 0,07531 | kg P-Eq |
| ozone depletion | 2,62E-05 | kg CFC-11-Eq |

TABLE 5 1 TON OF AVERAGE EUROPEAN PORTLAND CEMENT, EDIP 2003, MIDPOINT INDICATORS

| Resources | 13 | $ |
|---|---|---|
| Human health | 1,03E-02 | DALY |
| Ecosystems | 3,96E-05 | species.yr |

TABLE 6 1 TON OF AVERAGE EUROPEAN PORTLAND CEMENT, EDIP 2003, ENDPOINT INDICATORS

## Weighting and monetization

To further assist the decision-making process, midpoint indicators can be aggregated into a single score with the weighting of impacts, or even monetized to be expressed in terms of costs, in the desired currency.

However, one has to understand that the further away from midpoint indicators the results are processed, the more uncertain and subject to interpretation and normative values the conclusions of the LCA become. Also, the weighting of impacts poses important question: should Global Warming-related impacts have more weight than Acidification-related impacts?

**StepWise2006**

Online documentation: https://lca-net.com/services-and-solutions/impact-assessment-option-full-monetarisation/

The StepWise2006 method is developed by 2.0 LCA consultants. 2.0 LCA consultants are located at Aalborg University. The method is built on the merge between midpoint indicators developed in the EDIP2003 and the IMPACTS2002+ methods. Using methods based on expressed and indirect preferences as well as direct economic valuation, StepWise2006 monetizes the said impacts on human health, natural resources and productivity in a single score in Euros base 2003.

Figure 18 shows the monetized impacts of producing 1 ton of average European grey Portland cement. Relatively to the rest of the impacts, Global warming and Respiratory Inorganics score much higher. The total monetized environmental impact for producing 1 ton of European Portland cement is 100,43 €$_{2003}$.

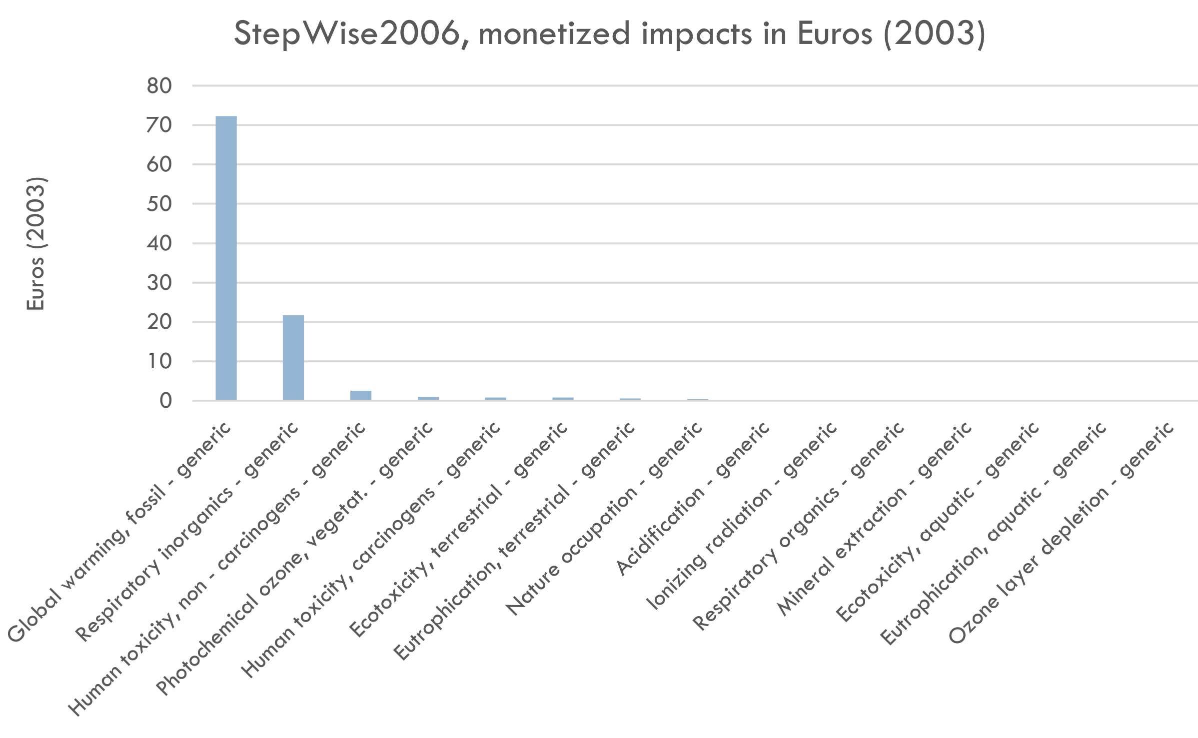



**FIGURE 18 MONETIZED RESULTS FOR 1 TON OF GREY EUROPEAN PORTLAND CEMENT, STEPWISE2006**

Table 7 below lists the main impact assessment methods and their characteristics. The next section presents LCA results characterized with these methods.

| | Development/Applicability | Has midpoint indicators? | Has endpoint indicators? | Has normalization factors? | Has single score indicator? | Choice of cultural perspective? | Has monetization factors? |
|---|---|---|---|---|---|---|---|
| **CML 2001** | The Netherlands/Europe | X | | X | | | |
| **EDIP 2003** | DTU/Europe | X | | | | | |
| **IMPACT 2002** | Switzerland/Europe | X | X | | X | | |
| **Eco-indicator 99** | Switzerland/Europe | | X | X | | X | |
| **TRACI** | U.S. EPA/USA | X | | X | | | |
| **ReCiPe** | The Netherlands/Europe | X | X | X | X | X | X[4] |
| **StepWise2006** | AAU/Europe | X | X | X | X | | X |

**TABLE 7 LIST OF COMMON IMPACT ASSESSMENT METHODS**

[4] An attempt to apply monetization factors to endpoint ReCiPe indicators has been done and used in DuboCalc, a tool to estimate the environmental footprint of road projects in the Netherlands. However, these monetization factors are no longer proper for use, and only representative of the Netherlands and its climate objectives in the 2000-2010-time scope.

# CASE STUDY 1 - COMPARISON OF METHODS WITH THE DEMONSTRATION BRIDGE IN HOLSTEBRO

The demonstration bridge in Holstebro is used as a case to compare the above-mentioned impact assessment methods. The purpose of the demonstration bridge is to showcase the development of a new concrete recipe, referred in this documents as GB-3. The LCA model of the demonstration bridge follows the general requirements of the LCA standard series ISO 14040/44, the general framework for Type III environmental declarations as described in EN-15804 and the bridge-specific rules described in the PRC document UN CPC 53221 BRIDGES AND ELEVATED HIGHWAYS, v. 1.01.

### Declared unit(s)

- 1 meter of elevated bridge, over one year of reference service life, using grey E40 concrete

### Recipes

The following recipe is used to model the reference ordinary E40 grey concrete.

| *Flow* | *Amount* | *Unit* |
|---:|---:|---|
| *gravel, round* | 1084,8 | kg |
| *sand* | 621,4 | kg |
| *Lavalkali cement* | 390 | kg |
| *transport, freight, sea, transoceanic tanker* | 238 | t*km |
| *transport, freight, lorry >32 metric ton, EURO5* | 208 | t*km |
| *tap water* | 151,1 | kg |
| *fly ash* | 58,5 | kg |
| *transport, freight, lorry >32 metric ton, EURO5* | 53 | t*km |
| *heat, district or industrial, other than natural gas* | 45,6 | MJ |
| *diesel, burned in building machine* | 22,7 | MJ |
| *electricity, high voltage* | 6,73 | kWh |

**TABLE 8 GREY E40 REFERENCE CONCRETE RECIPE**

The following recipe is used to model the GB-3 E40 concrete recipe, with high content of fly ash.

| *Flow* | *Amount* | *Unit* |
|---:|---:|---|
| *gravel, round* | 1084,8 | kg |
| *sand* | 621,4 | kg |
| *RAPID cement* | 282,2 | kg |
| *transport, freight, sea, transoceanic tanker* | 245 | t*km |
| *transport, freight, lorry >32 metric ton, EURO5* | 214 | t*km |
| *tap water* | 148,9 | kg |
| *fly ash* | 141,1 | kg |
| *heat, district or industrial, other than natural gas* | 45,6 | MJ |
| *transport, freight, lorry >32 metric ton, EURO5* | 38 | t*km |
| *diesel, burned in building machine* | 22,7 | MJ |

| | | |
|---|---|---|
| *electricity, high voltage* | 6,73 | kWh |

**TABLE 9 GREY E40 GB-3 CONCRETE RECIPE**

### Geographical and temporal scope

Cradle-to-Gate, including the entirety of Module A -- Delivery, Construction, Maintenance and Operation, in 2016.

The Reference Service Life of the structure is 120 years.

### Excluded flows and operations

A certain numbers of operations during the erection and maintenance phases of a bridge should be included in an LCA model. However, such information could not be obtained. Maintenance-related operations that would normally be included in a bridge LCA are:

- Inspections
- Cleaning of steel, edge beams and columns
- Repair of drainage systems
- Partial repair of concrete columns and edge beams
- Impregnation of edge beams and columns
- Replacement of edge beams
- Replacement of insulation
- Replacement and maintenance of bearings
- Cleaning and replacement of expansion joints
- Replacement of surface (asphalt) layer
- Repair of surface (asphalt) layer
- Repainting of steel structure
- Patch painting of steel
- Painting of railings

In order not to completely dismiss these aspects, an Ecoinvent dataset averaging the construction and maintenance of roads, bridges and tunnels is used. It contains inputs in terms of electricity and fuel expenditures (in transport and excavation machines mostly) as well as the treatment of waste generated on site (steel scrap, aggregates). It also includes land transformation flows (from natural land to traffic area). All of the above is presented in the next sections as the Construction phase.

### Allocation

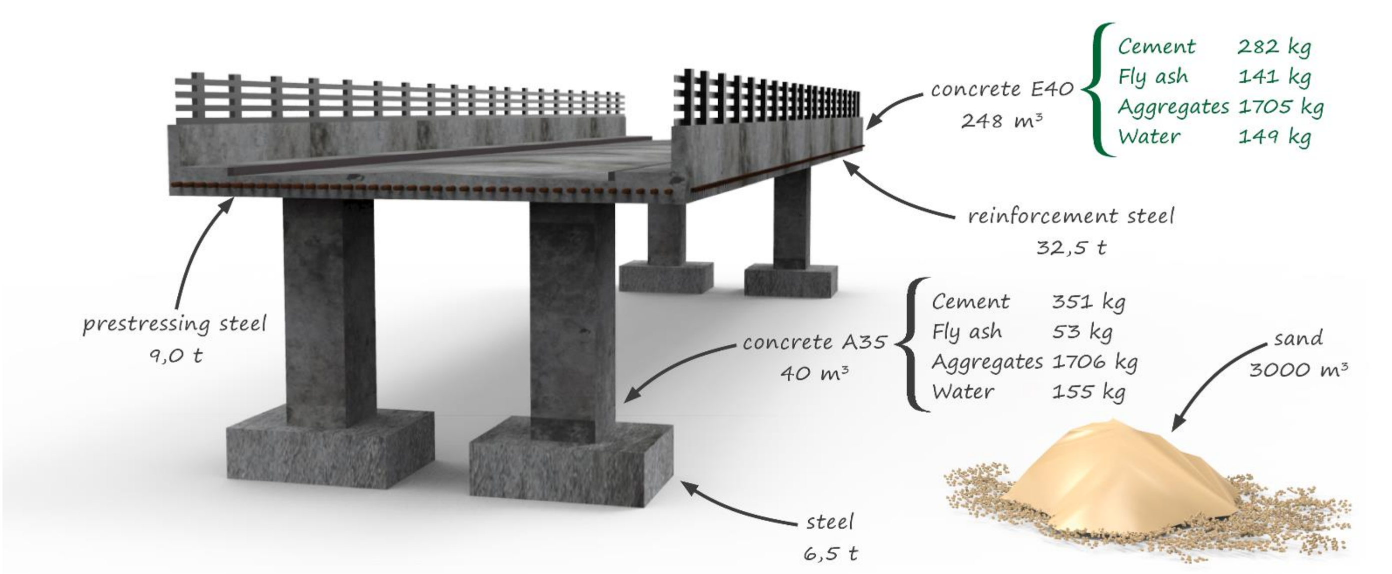
Two major cases of allocations are to be noted:

- at the electricity generation level, allocation between heat and electricity at CHP units has been done based on energy,
- at the fuels supply level, regarding the supply of petroleum coke, the allocation between petroleum coke and other co-products has been done using an economic partitioning key.

### Main assumptions

- The cement is produced at Aalborg Portland

- The concrete mixing factory is located in Midtjylland and the inventory has been modelled using data from Unicon A/S
- The sand is sourced 40 km away from the construction site, needed for the foundations
- The reinforced steel mostly originates from non-EU regions (71%) and EU-regions (29%).



# IMPACT ASSESSMENT RESULTS

In the following sections, end-results are presented and sub-divided into categories: Concrete, Steel, Construction and Sand. The table below indicates what phases are included in the categories.

| | Concrete | Steel | Construction | Sand |
|---|---|---|---|---|
| **Production of materials** | X | X | | X |
| **Delivery** | X | X | | X |
| **Assembly/construction** | | | X | |
| **Maintenance** | | | X | |
| **Waste treatment** | | | X | |

TABLE 10 PHASES AND CATEGORIES

## Relative importance of components contribution in EPD

This section analyses the relative importance of the bridge components (concrete, steel, sand and the construction and maintenance operations) in terms of contribution in EPD results, using the CML 2001 midpoint indicators. The declared unit is 1 linear meter of bridge (over the 7-meter width) over 1 year (based on a reference service life of 120 years).

It is important to note that the environmental burden associated to the transport of the materials on site is included the material categories Concrete, Steel and Sand.

| | Concrete | Steel | Construction | Sand | Grand Total | Unit |
|---|---|---|---|---|---|---|
| **Acidification potential** | 0,030 | 0,015 | 0,000 | 0,033 | 0,078 | kg of SO2-eq. |
| **Climate change - GWP100** | 17 | 4 | 0 | 6 | 27 | kg of CO2-eq. |
| **Depletion of elements, ultimate reserves** | 8,94E-06 | 2,32E-05 | 1,19E-07 | 2,51E-05 | 5,74E-05 | kg of antimony-eq. |
| **Depletion of fossil fuels reserves** | 79 | 31 | 1 | 86 | 197 | MJ |
| **Eutrophication** | 0,012 | 0,007 | 0,000 | 0,028 | 0,047 | kg of PO4--eq. |
| **Freshwater aquatic ecotoxicity** | 1,8 | 2,8 | 0,1 | 1,6 | 6,3 | kg 1,4-dichlorobenzene eq. |
| **Human toxicity** | 2,5 | 4,6 | 0,0 | 4,1 | 11,3 | kg 1,4-dichlorobenzene eq. |
| **Marine aquatic ecotoxicity** | 4397 | 5025 | 47 | 4380 | 13849 | kg 1,4-dichlorobenzene eq. |
| **Ozone layer depletion** | 5,22E-07 | 2,19E-07 | 1,17E-08 | 9,83E-07 | 1,74E-06 | kg of CFC-11-eq. |
| **Photochemical oxidation** | 1,22E-03 | 1,74E-03 | 1,39E-05 | 1,35E-03 | 4,33E-03 | kg of ethylene-eq. |
| **Terrestrial ecotoxicity** | 0,03 | 0,12 | 0,00 | 0,05 | 0,20 | kg 1,4-dichlorobenzene eq. |

TABLE 11 1 LINEAR METER OF BRIDGE OVER 1 YEAR, CHARACTERIZED WITH CML 2001 BASELINE METHOD

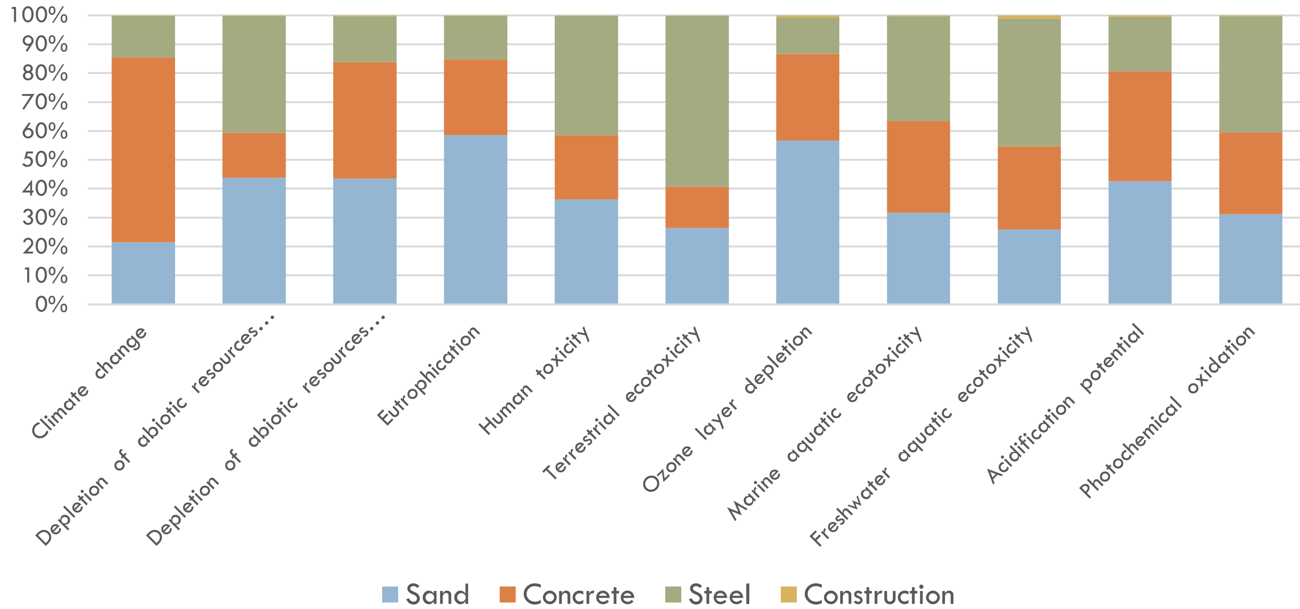



**FIGURE 19 RELATIVE CONTRIBUTION OF BRIDGE COMPONENTS, FOR 1 LINEAR METER OF BRIDGE, CHARACTERIZED WTH CML 2001 BASELINE METHOD**

## Relative importance of components contribution in total impacts

This section analyses the relative importance of the bridge components (concrete, steel, sand and the construction and maintenance operations) in terms of contribution for different impact categories across different midpoint methods. This means that the contribution in term of impact of each bridge components is calculated, for each impact category in each method. An arithmetic average of the contribution values per bridge element per method, across all categories is illustrated in the bar graph below.

| Method | CML 2001 | Eco-Indicator 99 | EDIP 2003 | ReCiPe | StepWise2006 | TRACI 2.1 |
|---|---|---|---|---|---|---|
| **Number of impact categories the average contribution is based on** | 11 | 15 | 46 | 17 | 16 | 10 |
| | Ozone layer depletion - ODP steady state | Human Health - Respiratory effects caused by inorganic substances | ecotoxicity - chronic, in soil | particulate matter formation | Eutrophication, aquatic - generic | Acidification |
| | Terrestrial ecotoxicity - TETP | Ecosystem Quality - Land occupation | acidification - acidification | water depletion | Human toxicity, non - carcinogens - generic | Ecotoxicity |
| | Human toxicity - HTP | Resources - minerals | global warming - GWP 500a | urban land occupation | Respiratory inorganics - generic | Ozone Depletion |
| | Depletion of abiotic resources - fossil fuels | Resources-total | non-renewable resources - tin | agricultural land occupation | Nature occupation - generic | Human Health - carcinogenics |
| | Marine aquatic ecotoxicity - MAETP | Human Health - Carcinogenics | eutrophication - separate N potential | freshwater ecotoxicity | Non - renewable energy - generic | Photochemical ozone formation |
| | Eutrophication - generic | Ecosystem Quality - Land conversion | global warming - GWP 100a | human toxicity | Global warming, non - fossil - generic | Respiratory effects |
| | Freshwater aquatic ecotoxicity - FAETP | Ecosystems Quality - Acidification and Eutrophication | non-renewable resources - palladium | terrestrial ecotoxicity | Respiratory organics - generic | Human Health - non-carcinogenics |
| | Depletion of abiotic resources - elements, ultimate reserves | Human Health-total | non-renewable resources - lanthanum | ozone depletion | Eutrophication, terrestrial - generic | Resource depletion - fossil fuels |
| | Acidification potential - average Europe | Human Health - Respiratory effects caused by organic substances | non-renewable resources - platinum | ionising radiation | Ozone layer depletion - generic | Eutrophication |
| | Photochemical oxidation - high Nox | Human health - Ozone layer depletion | non-renewable resources - lead | natural land transformation | Global warming, fossil - generic | Global Warming |
| | Climate change - GWP100 | Resources - fossil fuels | ecotoxicity - acute, in water | climate change | Mineral extraction - generic | |
| | | Human health - Ionising radiation | non-renewable resources - cadmium | fossil depletion | Ecotoxicity, terrestrial - generic | |
| | | Ecosystems-total | non-renewable resources - molybdenum | terrestrial acidification | Photochemical ozone, vegetat, - generic | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Human Health - Climate change | human toxicity - via soil | photochemical oxidant formation | Ionizing radiation - generic | |
| | | Ecosystems Quality - Ecotoxicity | non-renewable resources - copper | marine eutrophication | Acidification - generic | |
| | | | land filling - bulk waste | marine ecotoxicity | Ecotoxicity, aquatic - generic | |
| | | | human toxicity - via surface water | freshwater eutrophication | Human toxicity, carcinogens - generic | |
| | | | eutrophication - separate P potential | metal depletion | | |
| | | | non-renewable resources - coal | | | |
| | | | non-renewable resources - brown coal | | | |
| | | | ecotoxicity - chronic, in water | | | |
| | | | ecotoxicity - in sewage treatment plants | | | |
| | | | non-renewable resources - mercury | | | |
| | | | non-renewable resources - cobalt | | | |
| | | | land filling - hazardous waste | | | |
| | | | non-renewable resources - silver | | | |
| | | | non-renewable resources - aluminium | | | |
| | | | land filling - radioactive waste | | | |
| | | | photochemical ozone formation - impacts on human health | | | |
| | | | non-renewable resources - nickel | | | |
| | | | global warming - GWP 20a | | | |
| | | | non-renewable resources - natural gas | | | |
| | | | human toxicity - via air | | | |
| | | | non-renewable resources - manganese | | | |
| | | | non-renewable resources - iron | | | |
| | | | eutrophication - combined potential | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | non-renewable resources - antimony | | | |
| | | | land filling - slag and ashes | | | |
| | | | renewable resources - wood | | | |
| | | | non-renewable resources - cerium | | | |
| | | | photochemical ozone formation - impacts on vegetation | | | |
| | | | non-renewable resources - gold | | | |
| | | | non-renewable resources - tantalum | | | |
| | | | eutrophication - terrestrial eutrophication | | | |
| | | | non-renewable resources - oil | | | |
| | | | non-renewable resources - zinc | | | |
| | | | stratospheric ozone depletion - ODP total | | | |

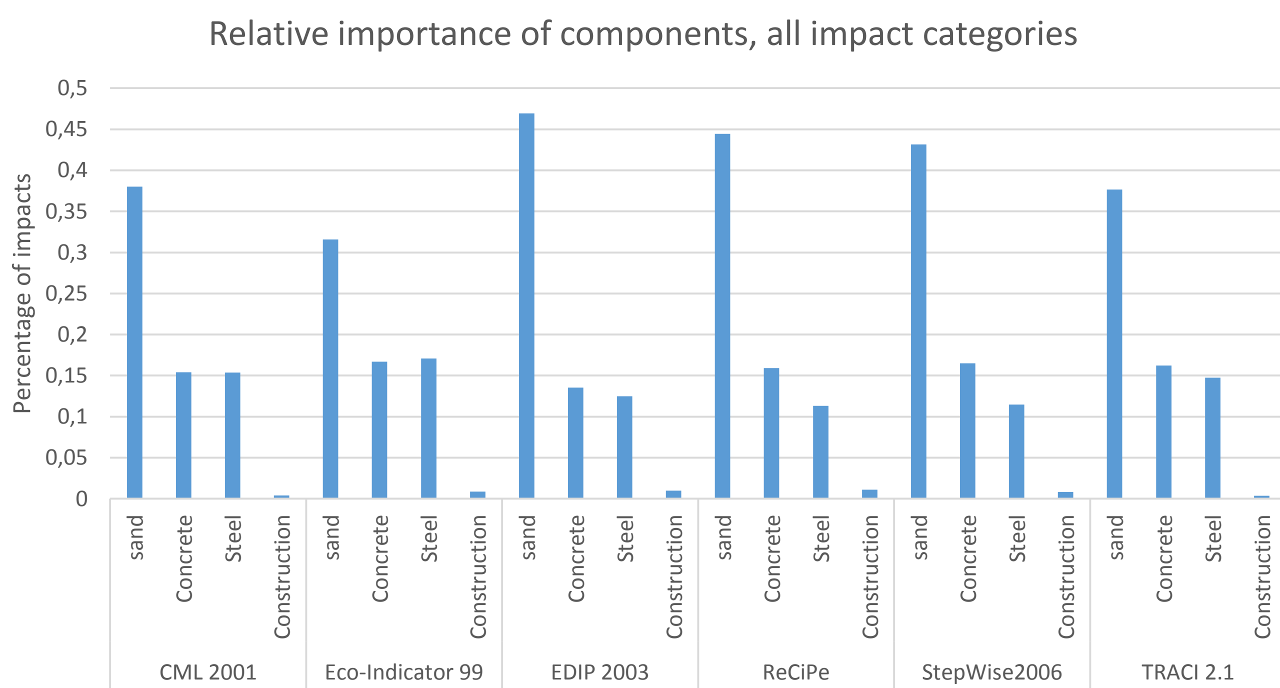


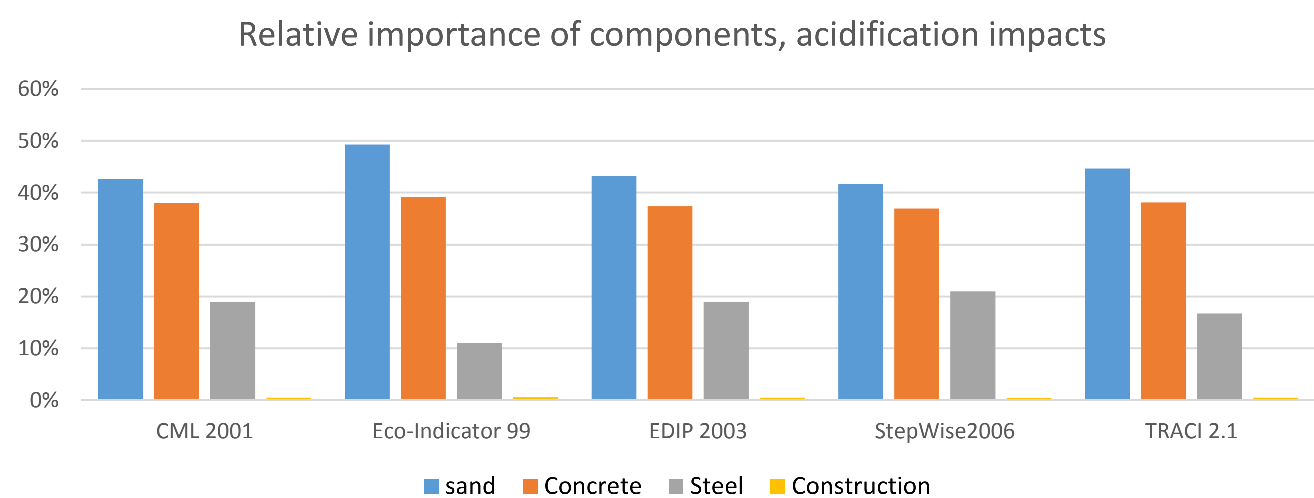

**FIGURE 20 RELATIVE CHARACTERIZED CONTRIBUTION OF BRIDGE COMPONENTS ACROSS METHODS**

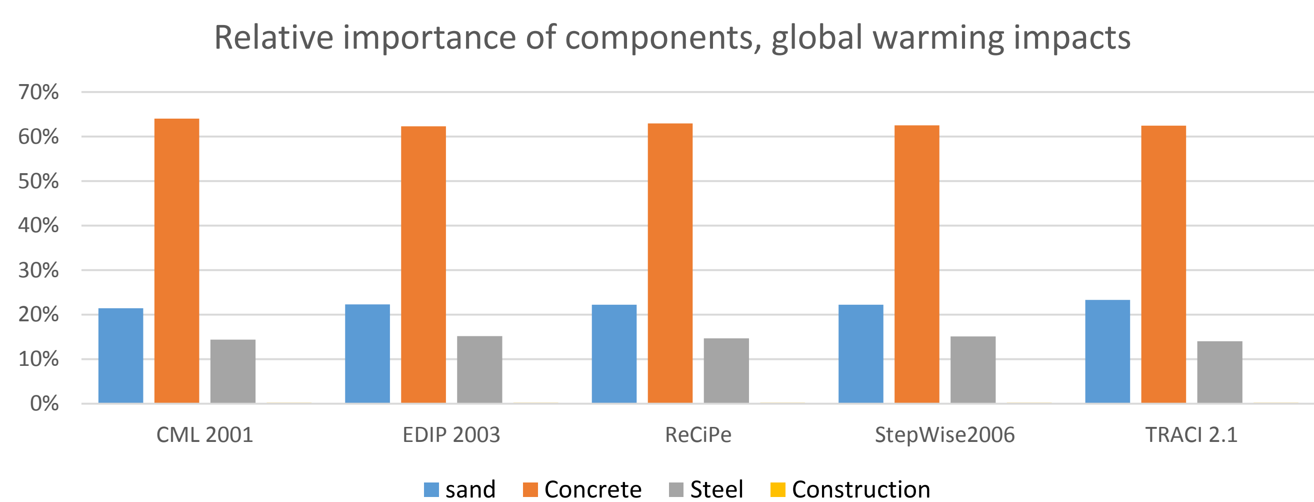
This bar graph represents a non-weighted arithmetic average contribution of the bridge components across all impact categories, for each method. Interpretation: in CML 2001, Concrete has an average contribution of

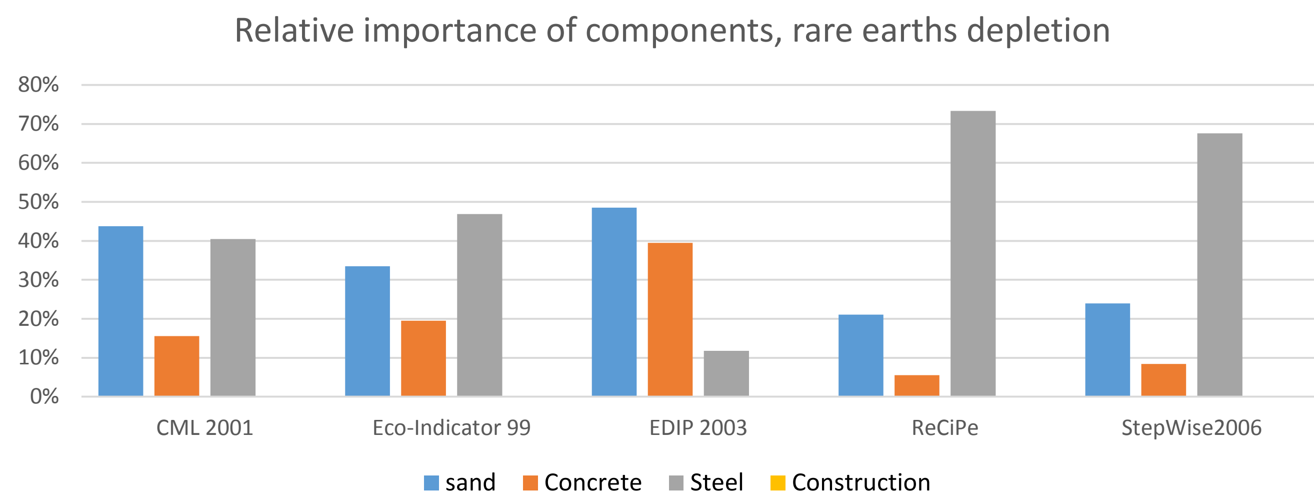
15% in all impact categories. Of course, in specific impact categories, Concrete has a much larger contribution (e.g. Climate change) compared to others (e.g. elements reserve depletion). The next section presents the contribution of bridge elements per type of impact category. The reader will remark that since the contributions are averages, their sum do not add up to 100%.

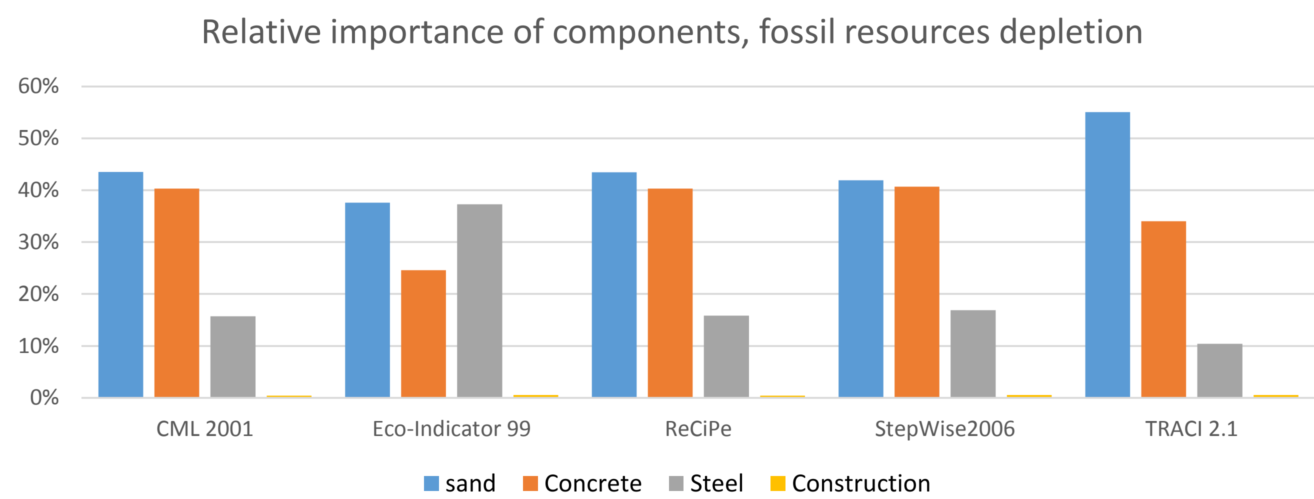
## Relative importance of components per impact type

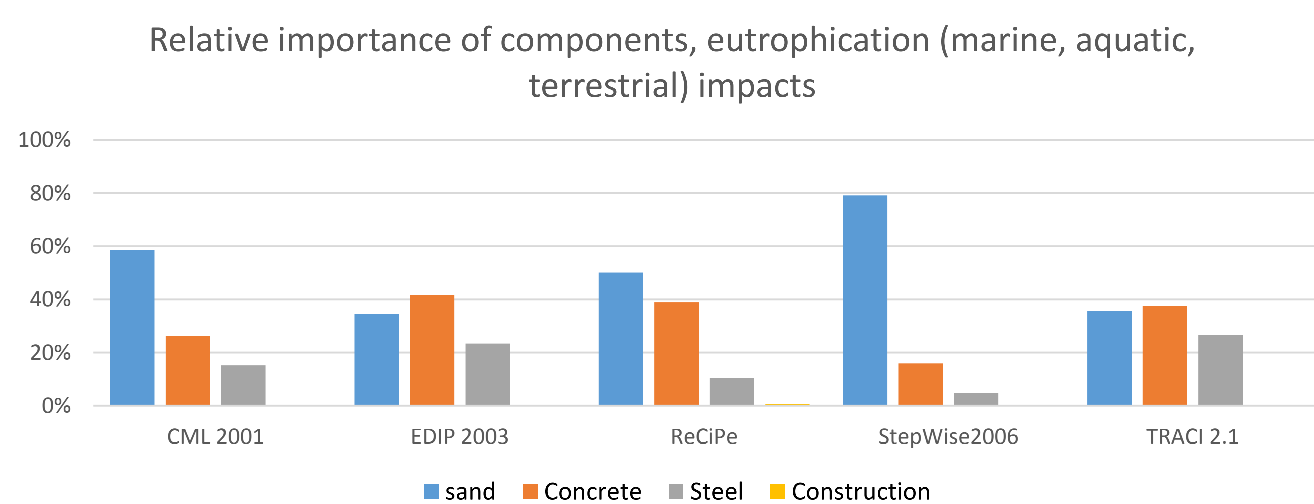
This section illustrates the relative environmental contribution of the bridge components per common impact category type for the selected methods. However, some specific impact categories are not common to all methods. Generally speaking, the bar graphs below show an overall consensus on the contribution of the components for a given impact: the distribution pattern between the components does not differ much between the methods.

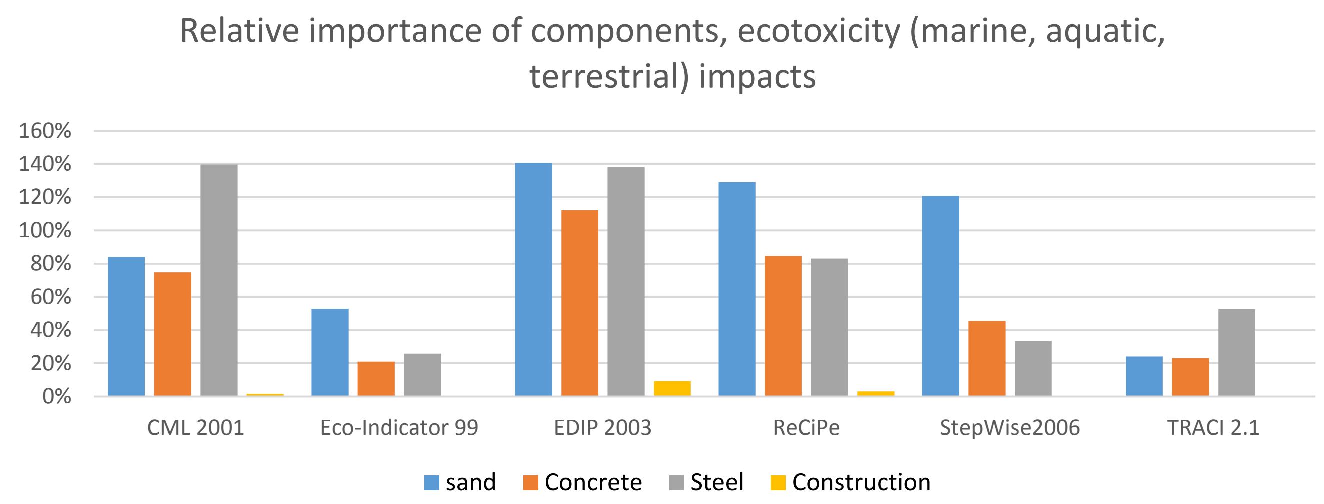


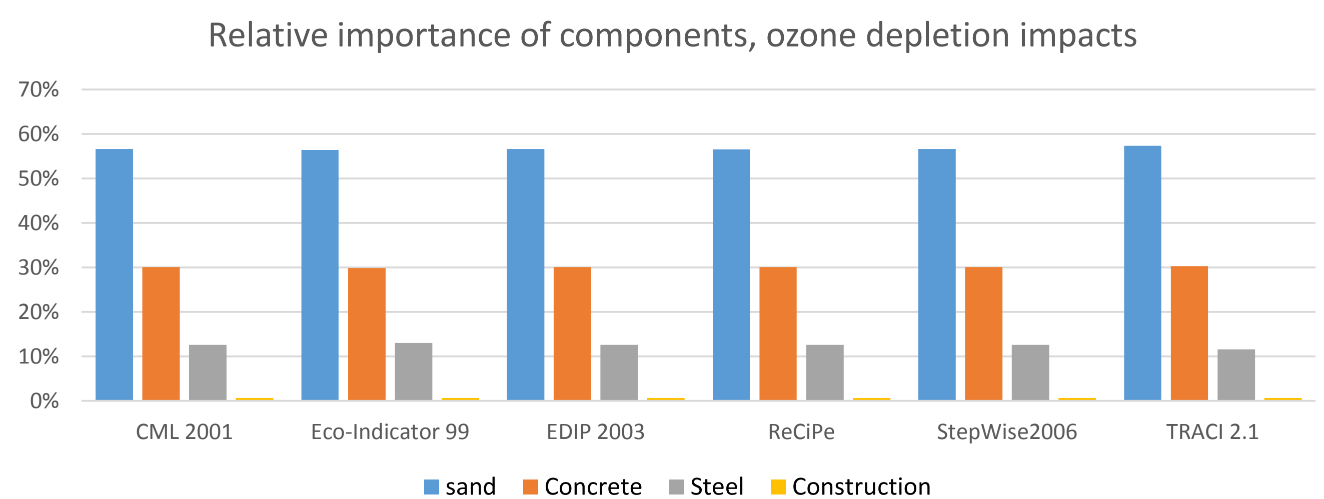

Relative importance of components, rare earths depletion
80%
70%
60%
50%
40%
30%
20%
10%
0%
CML 2001
Eco-Indicator 99
EDIP 2003
ReCiPe
StepWise2006
sand
Concrete
Steel
Construction

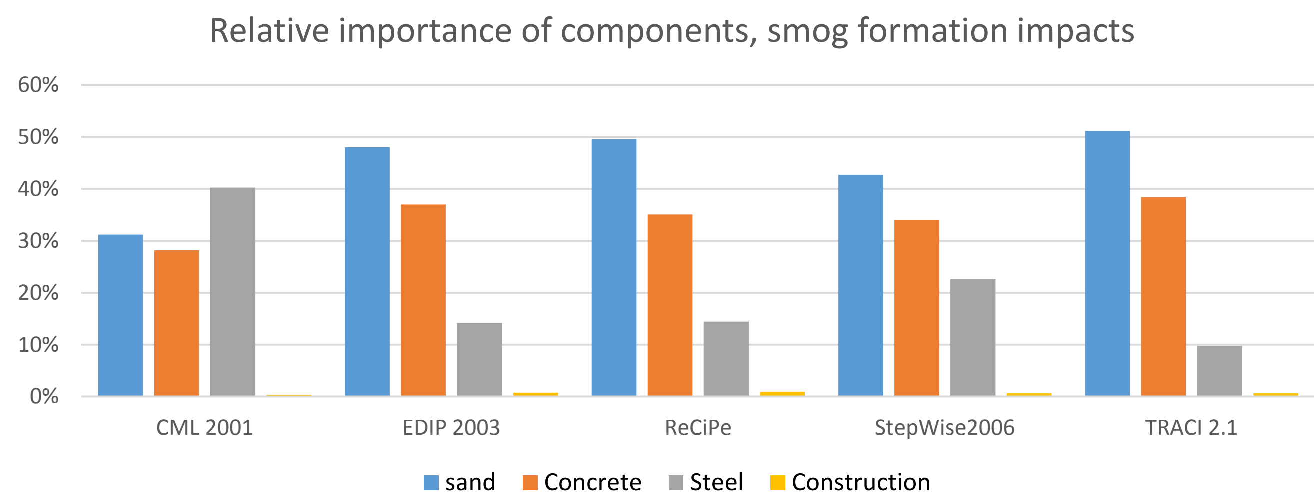

Relative importance of components, fossil resources depletion
60%
50%
40%
30%
20%
10%
0%
CML 2001
Eco-Indicator 99
ReCiPe
StepWise2006
TRACI 2.1
sand
Concrete
Steel
Construction


Relative importance of components, eutrophication (marine, aquatic, terrestrial) impacts
100%
80%
60%
40%
20%
0%
CML 2001
EDIP 2003
ReCiPe
StepWise2006
TRACI 2.1
sand
Concrete
Steel
Construction




Note: in the case of ecotoxicity, the sum of the contributions per bridge components adds up to more than 100% as several types of ecotoxicity recipients are considered (marine, freshwater and terrestrial).






| | Acidification | Global warming | Rare elements | Fossil resources | Eutrophication | Ecotoxicity | Ozone depletion | Smog formation |
|---|---|---|---|---|---|---|---|---|
| **Concrete** | High | High | Moderate | High | Moderate | Moderate | Low | High |
| **Sand** | High | Moderate | High | High | High | High | High | High |
| **Steel** | Moderate | Moderate | Moderate | Moderate | Low | High | Low | High |
| **Construction** | Negligible | Negligible | Negligible | Negligible | Negligible | Negligible | Negligible | Negligible |

**TABLE 13 CONTRIBUTION OF BRIDGE COMPONENTS PER IMPACT CATEGORY TYPE**

Concrete has an important contribution in terms of Global warming impacts, Fossil fuels resource depletion, Acidification and Smog formation, as all the different selected methods confirm. It also has a significant contribution in impacts such as Eutrophication, mostly due to power generation (coal-fired power plants and related mining operations) as well as direct kiln emissions.

Other materials used of civil works structures have large environmental footprints. Steel has high impacts on rare earth depletion. Another significant share of the impacts is associated with the supply of sand, and most notably by its transport. This is especially the case for Ozone depletion, Eutrophication, and Acidification-related impacts.

This suggests, to a larger extent, that the overall environmental footprint of the bridge structure could be reduced by:

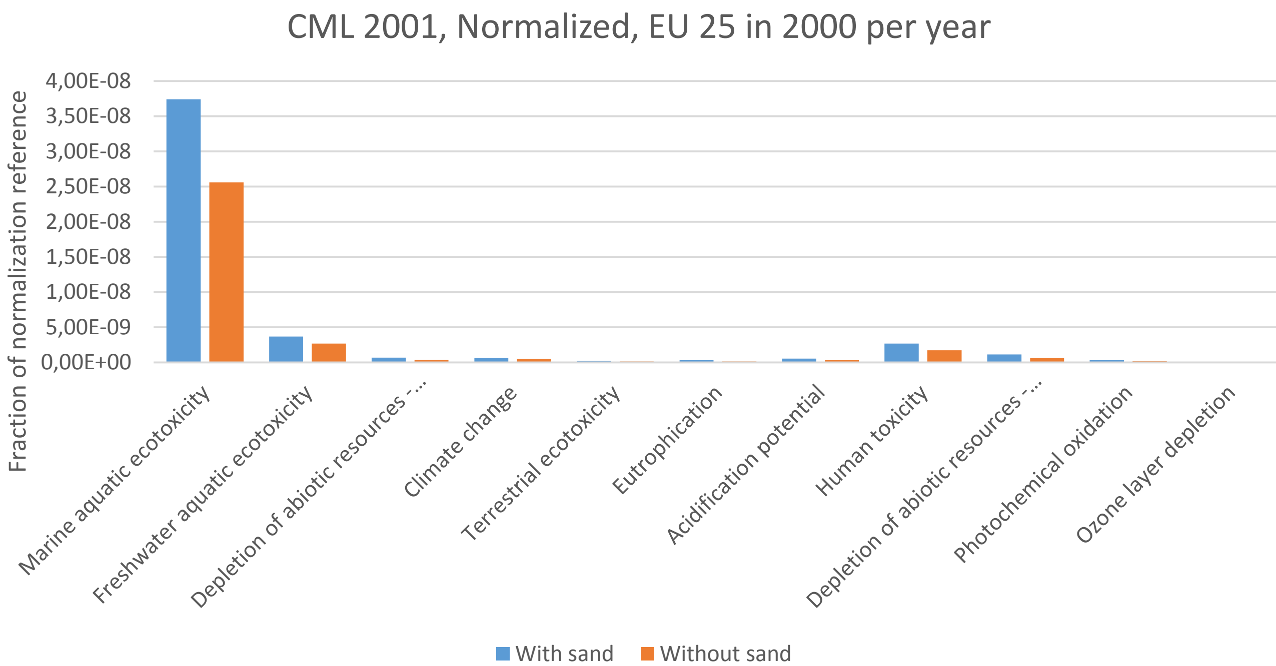
- optimizing the materials requirements for the foundations,
- and decreasing the transportation distance from the sand quarry to the construction site.

This underlines the potential for environmental optimization at the design phase.

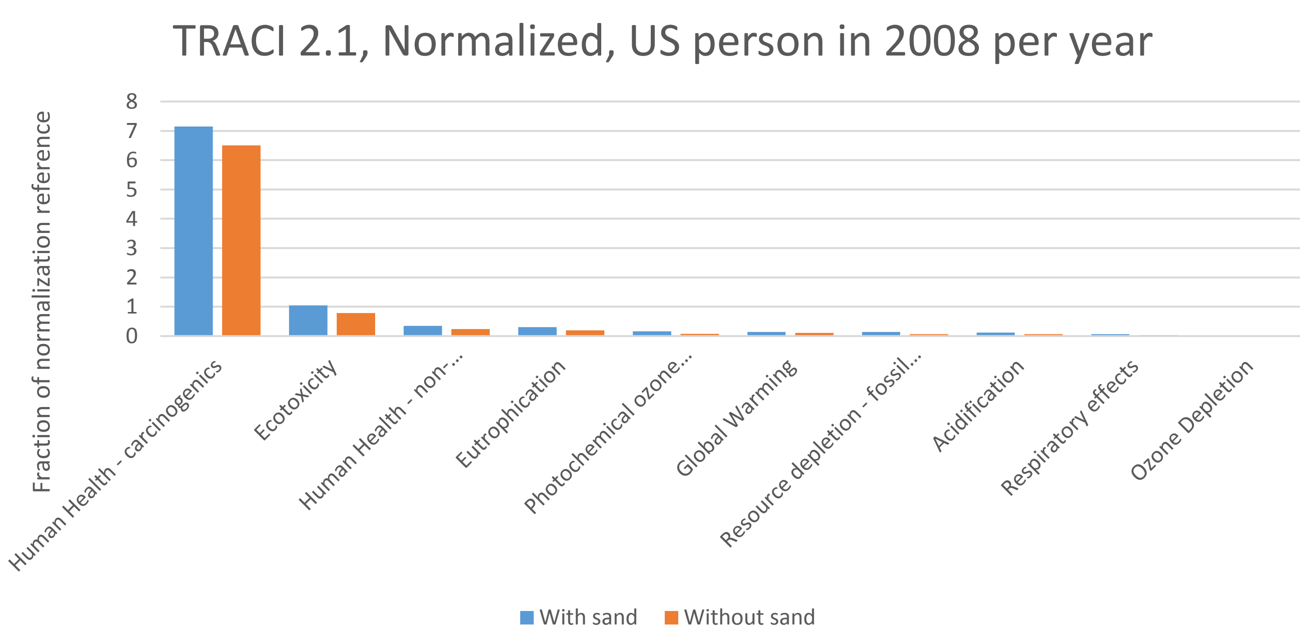
## Normalization

This section shows characterized impact results expressed against a normalization reference for the different selected methods.

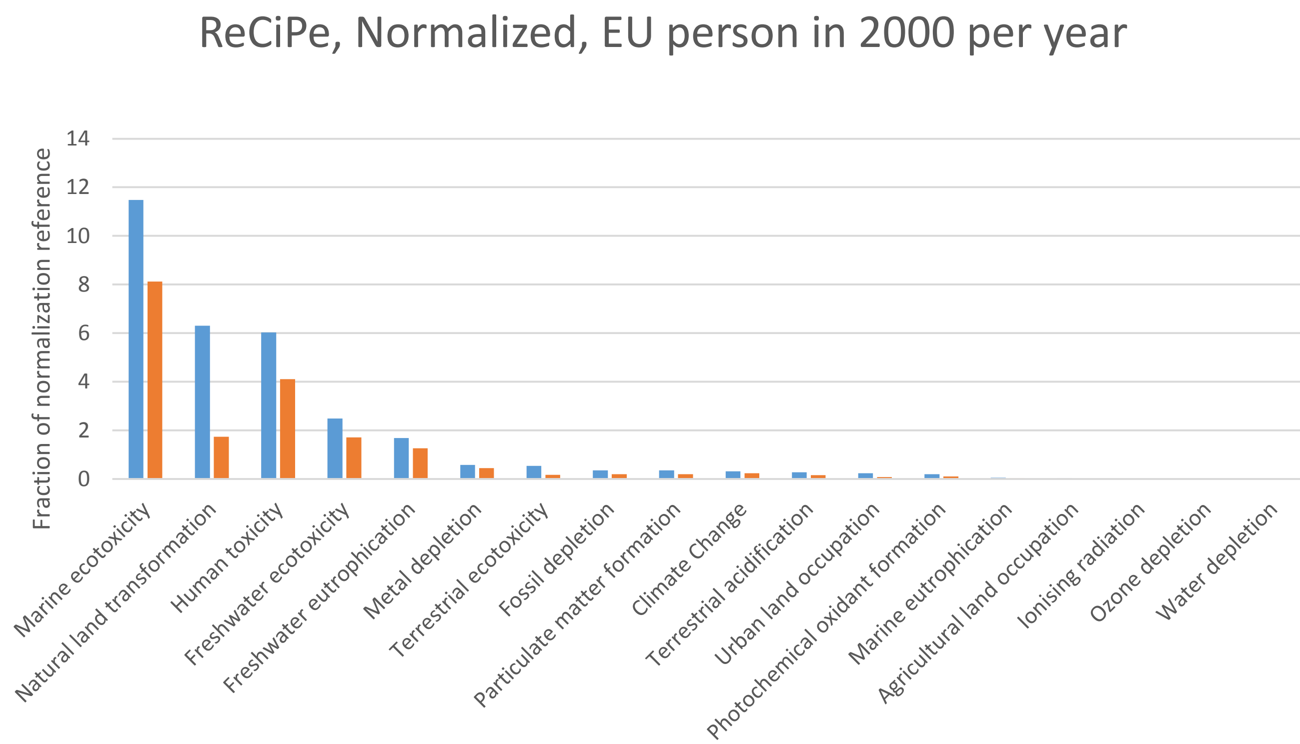
The normalization reference used by CML 2001 is the average annual environmental burden of the European Union in 2000.




The normalization reference used in TRACI 2.1 is the average annual environmental burden of an American person in 2008.



The normalization reference used by ReCiPe is the average annual environmental burden of a European person in 2000.




The different methods underline different impacts categories. This is partly due to a different reference for normalization. The boundaries used to attribute environmental impacts to the normalization reference may also difference from method to method (while some methods use the environmental impact within the borders of a country, divided by the population, other methods include imports and exports).

However, Aquatic and Marine ecotoxicity, as well as Human toxicity are the impacts that are, in reference to the normalization factors, predominant in CML, TRACI and ReCiPe. To a lesser extent, Natural Land Occupation is scores also high in ReCiPe.

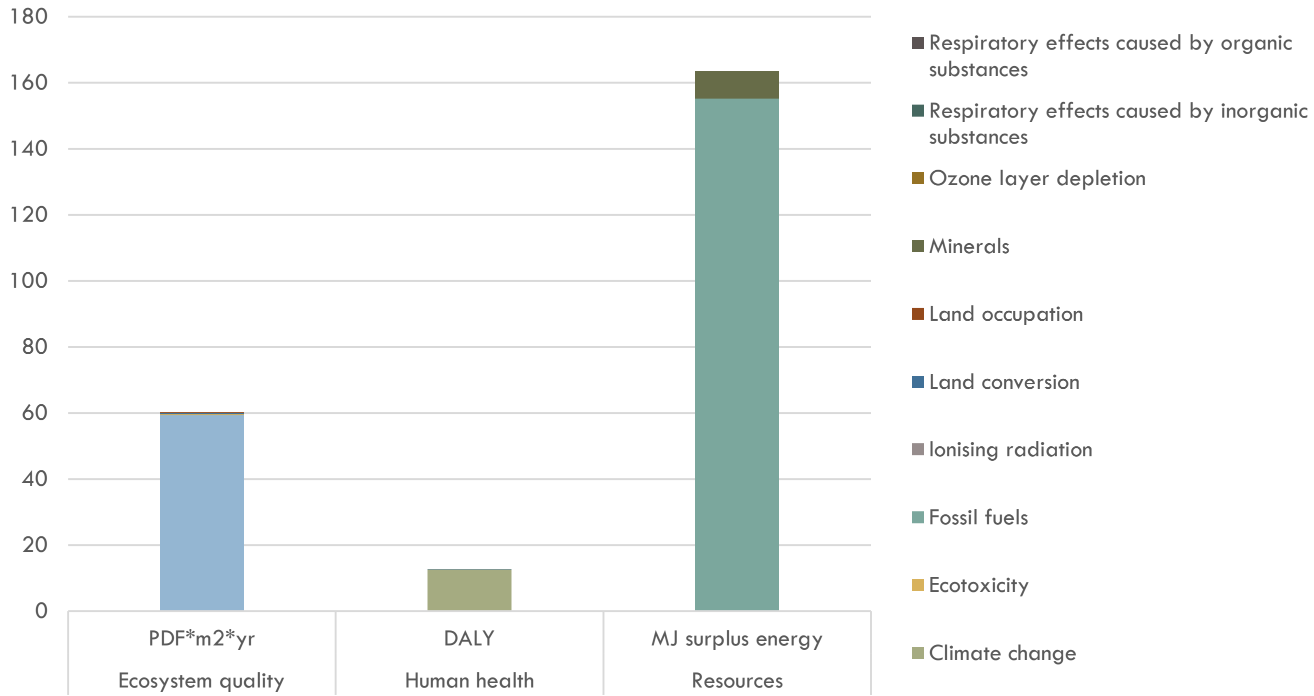
Aquatic and Marine ecotoxicity impacts in CML 2001, TRACI and ReCiPe are rooted in the waste treatment operations during coal mining operations. It is mainly due to the contamination of fresh and marine water compartments by metal ions (nickel, beryllium, selenium, copper, etc.) during the treatment of spoil and sulfidic tails from hard coal mining. In the product system, coal is mostly used for the production of clinker, and to a lesser extent, for power generation. Another significant share of Marine ecotoxicity impacts come from the refining of crude oil (to produce diesel for transport operations) as well as steel manufacturing.

Natural land transformation is heavily weighted in the ReCiPe method. It originates the sand quarry operations, that convert natural land areas into mining areas.

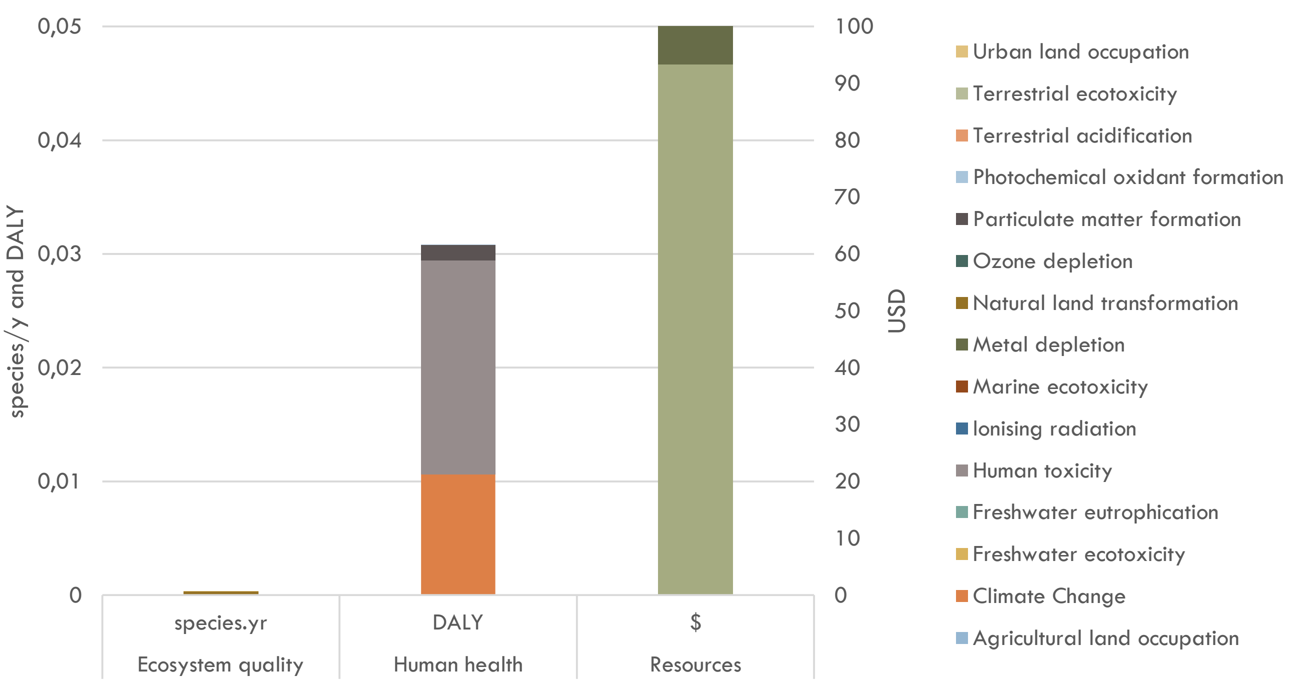
For all the three normalized sets of results, Climate change, comparatively to other impact categories, and in relation to the normalization reference, does not score high.

## Endpoint indicators

### Eco-indicator 99 (Egalitarian)




### ReCiPe (Egalitarian)



Global warming/Climate change is the impact that has the most weight in regards to Human health indicators for both Eco-Indicator 99 and ReCiPe. However, while climate change contributes to damage towards Human health impacts in both methods, there is a very important difference in terms of absolute contribution (12 DALY for Eco-Indicator 99 against 0,03 for ReCiPe). This is explained by a different characterization factor for greenhouse gases. For example, 1 kg of $CO_2$ has a characterization factor of 3.51E-6 DALY/kg in the ReCiPe method, while in Eco-Indicator 99, the factor is 0.06 DALY/kg. It is often the case that disparities among endpoint methods originate different factors regarding Climate change because of a large uncertainty regarding the long term effect of Global warming.

Regarding damage towards ecosystems, Acidification and Eutrophication are the most contributing impact categories when characterizing the results with Eco-indicator 99.

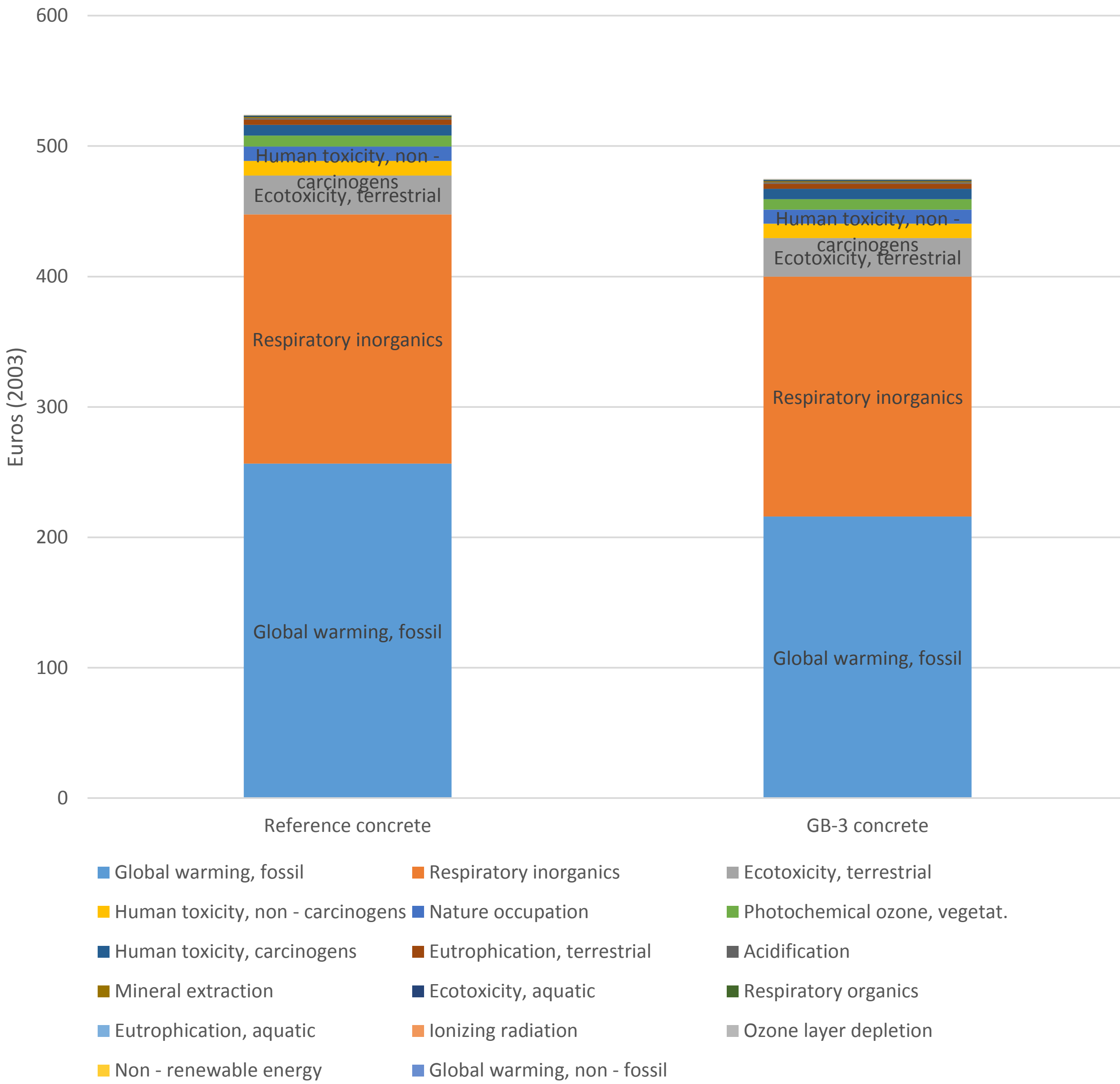
Finally, both in the Eco-indicator 99 and the ReCiPe methods, the use of fossil fuels is the major contributing aspect to the damage towards Resources. This reflects the future additional costs (for Eco-indicator 99) or the future additional energy (for ReCiPe) of extracting and exploiting similar grade fossil resources in depleted reserves.

## Monetized results and single score results (weighting)

Methods that produce monetized results or a single score are practical to compare alternatives fulfilling a same function. But they are also often delicate to use as normative choices and weighting coefficients are applied to impact categories. In this section, we present such methods and compare the same 1 meter of bridge made with the Reference concrete recipe and the GB-3 concrete recipe.

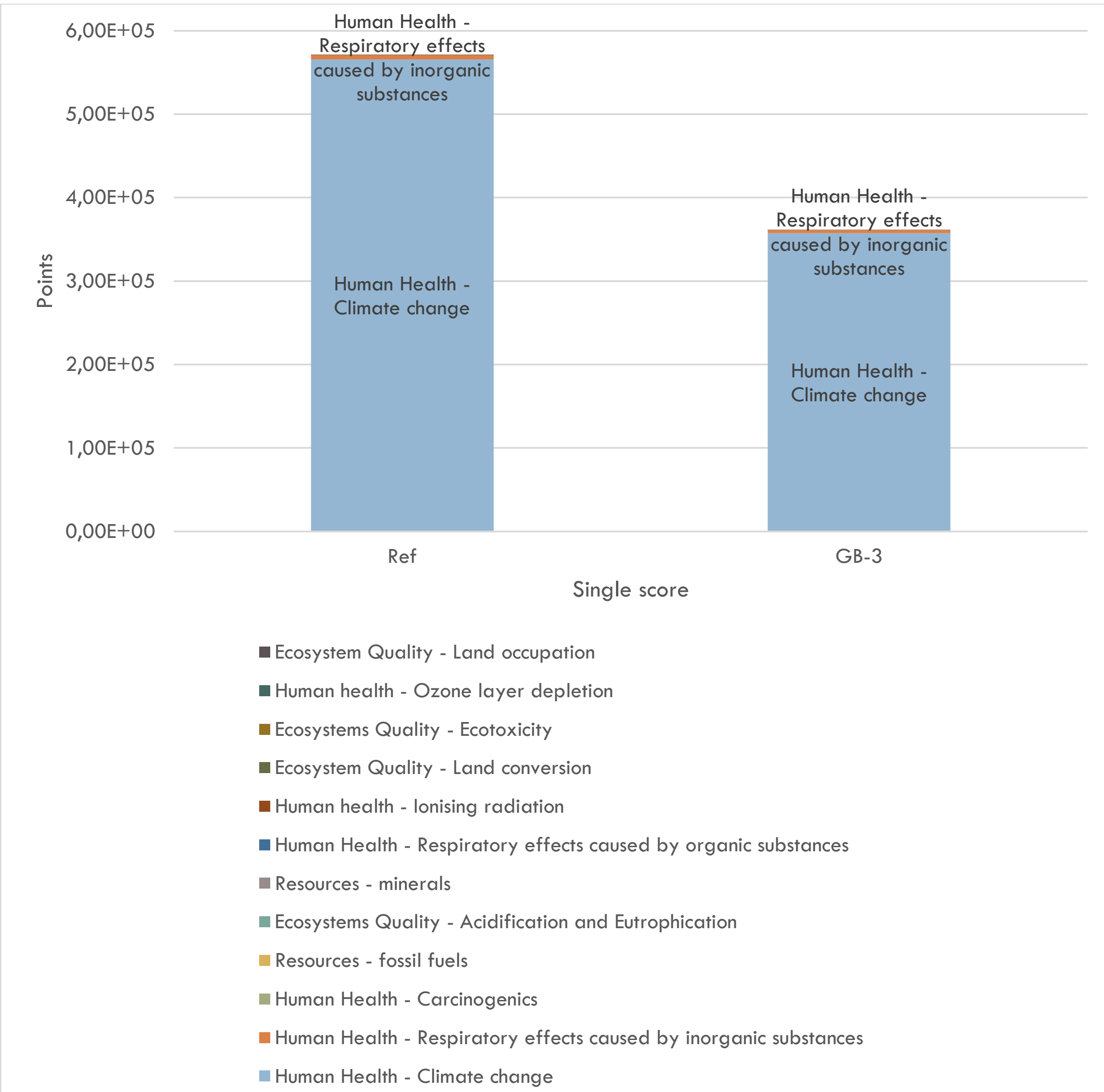
Note that the GB-3 E40 concrete was only used for the bridge deck. A recipe for a grey A35N32 concrete is used for the rest of the structure in both bridges.

### StepWise 2006



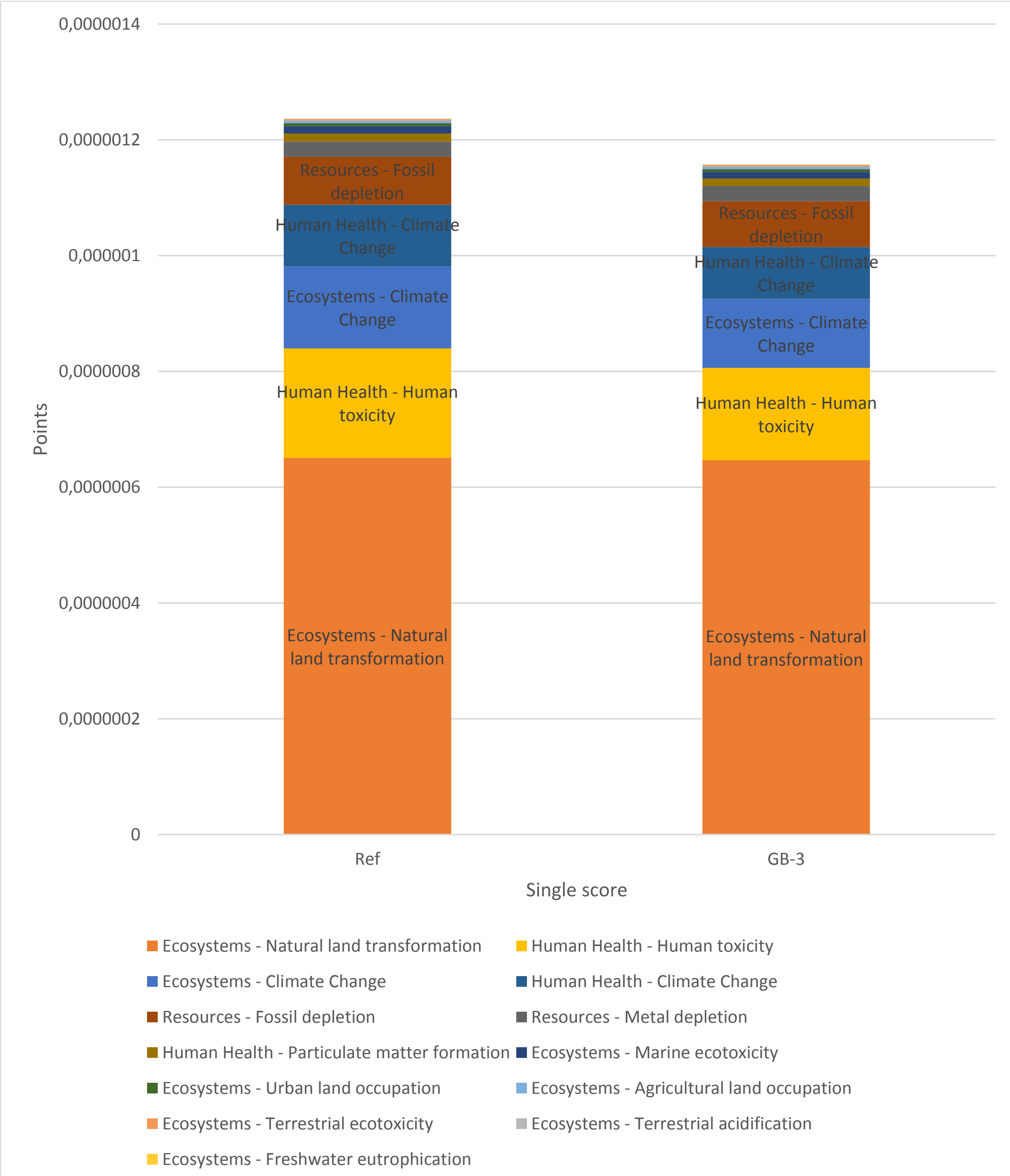

In the monetized results of Stepwise 2006, Global warming is the dominant contributing impact category in the overall damage, followed by Respiratory Inorganics. A ton of CO2-eq. has a monetization factor of 83€, which translates into 83€ of environmental, economic and human damage (species migration, crops losses, civil wars, etc.). Respiratory Inorganics mostly relate to human health with cardiac and respiratory risks (lungs cancer) by inhalation of inorganics particulate matters. Among the existing efforts towards monetizing environmental impacts, the assessment of Climate change damage remains the most critical impact category. Across different existing monetization methods (StepWise2006, ExternE, CML), monetization factors for Global warming can range from 3€/ton CO2-eq. up until 200€. The difficulty in assessing such damage lies in the uncertainty of the long term damages and the extent to which Climate change can affect ecosystems and civilizations.

**Eco-indicator 99 (Egalitarian)**




The Eco-Indicator 99 single score results give weight to Climate Change impacts, as does StepWise 2006, but much less importance to respiratory damages due to inorganics.

**ReCiPe (Egalitarian)**




The single score results of ReCiPe with an Egalitarian cultural perspective have a weighting distribution key more even among impact categories. Damages to ecosystems have more weight than damage to human health, with natural land occupation being the dominant impact category.

# Conclusions

### Standardized LCA of concrete structures

- ISO 14040/44 set the principles and rules of LCA
- PCR documents for constructions and specific products apply when producing EPDs of products or structures, to ensure harmonized rules and basis for comparison
- EPDs of semi-finished products (i.e. cement) can be used as input in EPDs of finished products (i.e. concrete)
- EPDs of finished products (i.e. concrete) can be used as input in EPD of structures (i.e. a bridge)
- The main European EPD program operators propose now a mutual recognition of EPDs
- However, certain rules (notably, allocation rules) in the bridge PCR document are different from the rules defined in the cement and concrete PCR documents: while the former gives priority to physical allocation, the cement and concrete PCR documents base themselves of the relative economic difference between the co-products to decide whether economic or physical allocation should be done. This shows a lack of alignment between the PCR documents and can potentially have a significant impact.
- All PCR documents indicate the use of an attributional approach (average historical environmental impacts), as opposed to a consequential approach (marginal environmental impacts), failing to reflect the true environmental consequences of decision-making and supplier selection.
- The use of an attributional approach implies the allocation of inputs and emissions of multi-output processes between co-products, using an allocation key. Regardless of the allocation key used, it inevitably leads to the violation of mass and/or energy balances. This is in contradiction with the second law of thermodynamics and, paradoxically, in contradiction with the standard series ISO 14040/44.

### Midpoint and endpoint impact assessment methods

- Midpoint indicators, as proposed in CML 2001, EDIP 2003, etc., describe environmental mechanisms
- Midpoint indicators are required in EPDs
- Because they are numerous and difficult to interpret, midpoint indicators can be weighted to produce endpoint indicators
- Endpoint indicators are more damage-oriented, often representing broad classes of stakeholders (nature, humans, resources)
- Endpoint indicators synthesize impacts down to easy-to-interpret indicators, but the interpretation and the weighting of midpoint indicators to endpoint indicators depend heavily on the preferences and normative choices made during the development of the method
- Some endpoint indicator methods propose different cultural perspectives in order to apply different weighting in regards to time and geographical scale
- Some methods take synthesis of indicators a step further and propose single score impact assessments

### Characterized impact of the demonstration bridge in Holstebro

- The characterized impacts of the declared unit of 1 linear meter (with a 7-meter width) of bridge over 1 year (with a reference service file of 120 years) have been calculated and displayed using midpoint and endpoint indicators

- Regarding midpoint indicators:
  - the provision of concrete contributes the most to the Global warming impact category
  - the provision of steel contributes the most to Depletion of abiotic elements, Human and Freshwater toxicity impact categories
  - the provision of sand contributes the most to Eutrophication and Ozone layer depletion impact categories

- Regarding normalized midpoint indicators:
  - The normalization references used are the annual environmental footprint of the EU 25 in 2000, the annual environmental footprint of an American citizen in 2008 and the annual environmental footprint of a European citizen in 2000
  - Human, marine and freshwater toxicity, as well as natural land occupation are the impacts that tend to represent the largest fraction of the normalization reference
  - The main culprits for marine and freshwater toxicity impacts are the waste treatment operations during coal mining, the refinery of crude oil into diesel as well as the production of steel

- Regarding endpoint indicators:
  - Global warming and Human toxicity contribute the most to damages to Human health
  - The use of fossil fuels contributes the most to damages to Resources
  - Acidification and Eutrophication contribute the most to damages to Ecosystem quality

- The use of single score methods (StepWise2006, Eco-Indicator 99 and ReCiPe) is illustrated by comparing the realization of the declared unit using the reference concrete and the GB-3 concrete recipe
  - The benefits of using the GB-3 recipe are clear with Eco-Indicator 99, since Climate change-related impacts represent about 99% of the characterized impacts
  - The benefits of using GB-3 are more moderate with StepWise2006 and ReCiPe (between 8 and 10% improvement):
    - Most of the impacts in StepWise2006 come from the emission of inorganic compounds (PMs) leading to human health impact. Using the GB-3 recipe does not lead to a reduced emission of inorganic compounds.
    - Most of the impacts in ReCiPe come from the Natural Land Transformation impact category, which remains virtually unchanged when using the GB-3 recipe.

## References

AFNOR. 2014. NF EN 15804 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. *Association Francaise de Normalisation*.

International Standards Organization. 2006a. ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework. *International Standard Organisation*.

International Standards Organization. 2006b. ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines. *International Standard Organisation*.

International Standards Organization. 2006c. ISO 14025:2006 Environmental labels and declarations -- Type III environmental declarations -- Principles and procedures. *International Standard Organisation*.

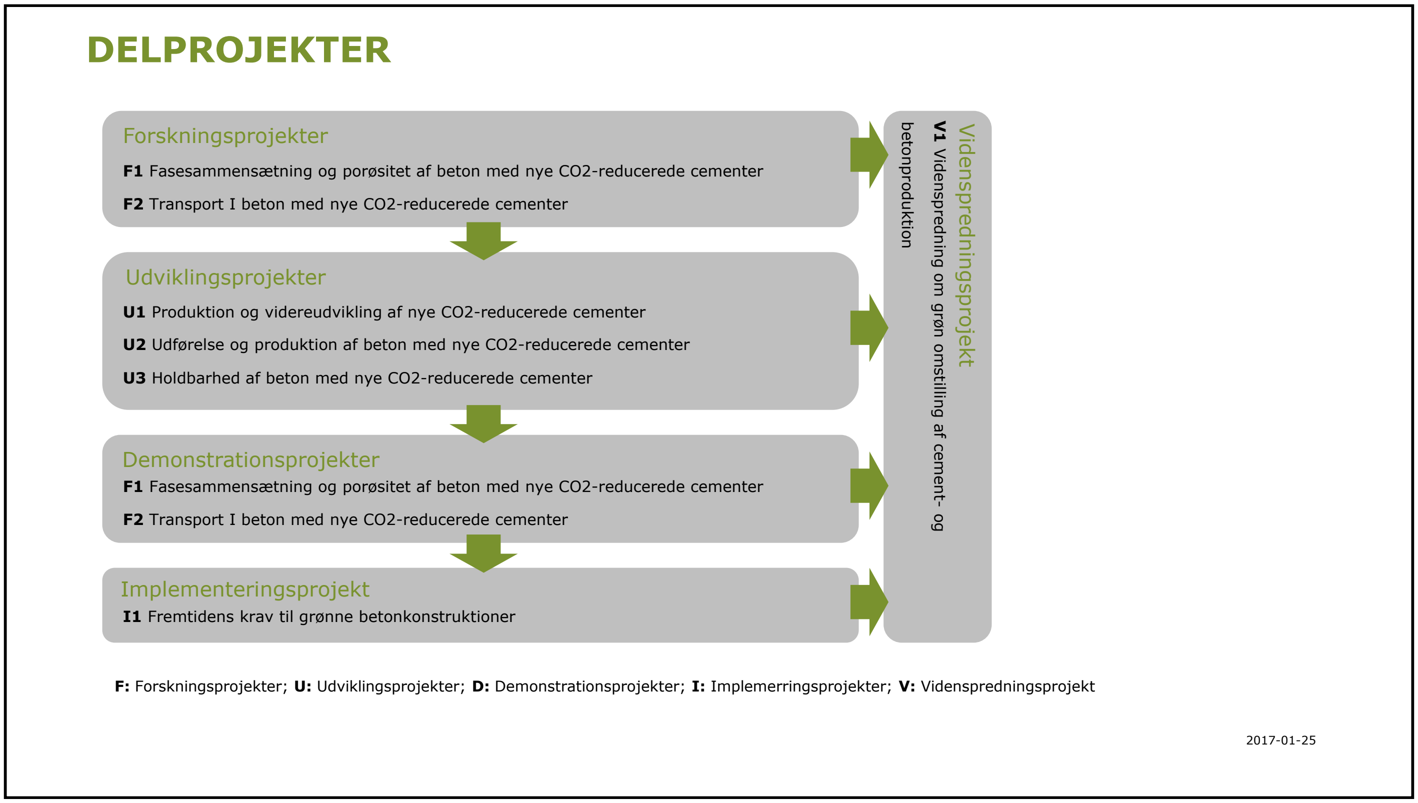
Weidema, B. 2014. Has ISO 14040/44 Failed Its Role as a Standard for Life Cycle Assessment? *Journal of Industrial Ecology* 18(3): 324-326.

# 8. Bilag 2: *DGNB systemet*, præsentation givet på Dansk Beton Fabriksbetongruppens årsmøde, 2017

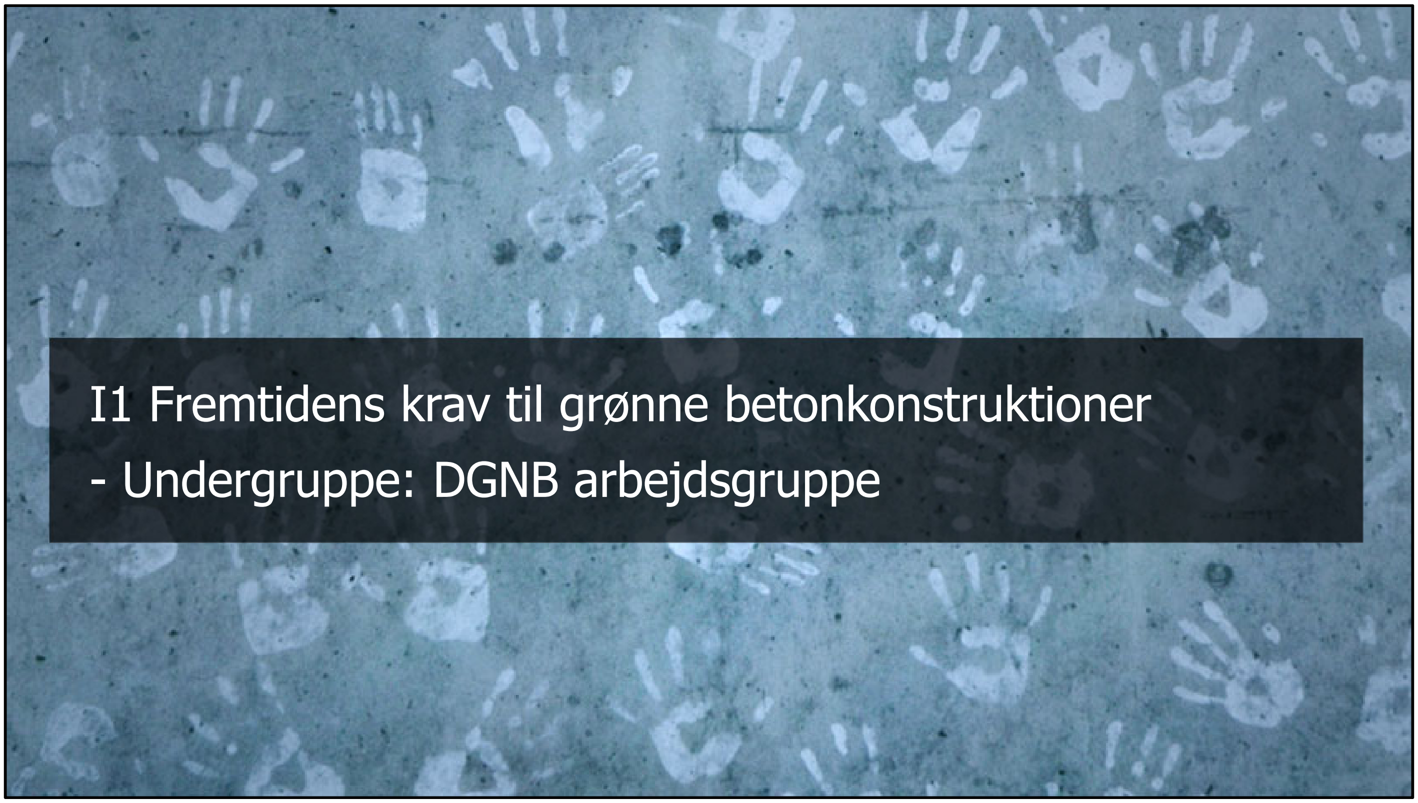
GRØN
BETON II

# Innovationskonsortium

## Grøn Omstilling af Cement- og Betonproduktion




Alternative title slide. Image size: 6 cm x 25,4 cm or 227 x 960 pixels


I1 Fremtidens krav til grønne betonkonstruktioner
- Undergruppe: DGNB arbejdsgruppe


Content slide

## FORMÅLET MED DGNB ARBEJDSGRUPPEN

- Bæredygtighed er på dagsordenen, både i Danmark og globalt
- Bæredygtighed er sat på formel via bygningscertificeringsordninger
  - Tyske DGNB
  - Engelske BREEAM
  - Amerikanske LEED
- Stort fokus på at udvikle produkter, der belaster miljøet i mindre grad end tidligere
- Beton har forholdsvis stor miljøpåvirkning i produktions- og bortskaffelsesfasen
- Men beton har lang levetid og minimalt behov for vedligehold, så det har lille miljøpåvirkning i driftsfasen
- Hvilke positive effekter har grøn beton for certificering af et byggeri, såfremt byggeriet skal DGNB-certificeres?

2017-01-25

Bæredygtighed er på dagsordenen, både i Danmark og globalt. Kunder indenfor mange forskellige segmenter stiller i stigende grad krav til de produkter, de køber og anvender, og ofte vælges de mere miljørigtige produkter, frem for de miljøbelastende produkter. Mange virksomheder har, pga. markedsudviklingen, stort fokus på at udvikle produkter, der belaster miljøet i mindre grad end tidligere.

Der er mange forskellige måder at vurdere bæredygtighed på. F.eks. er der flere, som har sat bæredygtighed på formel via bygningscertificeringsordninger. Der eksisterer bl.a. den engelske BREEAM-, amerikanske LEED- og den tyske DGNB-certificeringsordning. I Danmark er den mest udbredte bygningscertificeringsordning DGNB, da den er tilpasset danske standarder.

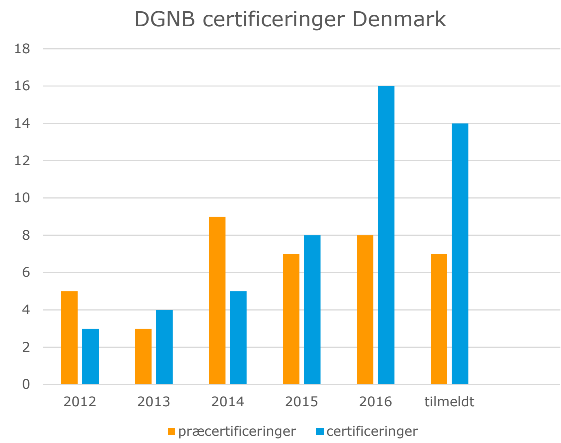
Bygningscertificeringsordningerne indeholder bl.a. vurdering af i hvor stort omfang de materialer der anvendes i byggeriet belaster miljøet. Beton anvendes i stort set alle byggerier i Danmark, og det er derfor interessant at undersøge, hvorvidt beton kan udvikles til at have en mindre miljøpåvirkning. Beton er et byggemateriale, der har en forholdsvis stor miljøpåvirkning når der ses på produktions- samt bortskaffelsesfasen. Til gengæld har det en lang levetid og minimalt behov for vedligehold, så det har en lille miljøpåvirkning i driftsfasen.

Der ses i nærværende projekt nærmere på, hvilke positive effekter grøn beton har for certificering af et byggeri, såfremt byggeriet skal DGNB-certificeres.


INDHOLD
• Om DGNB
• Livscyklusvurderinger (LCA)
• Betons indflydelse på DGNB score
• Miljøvaredeklarationer (MCD/EPD)
• Konklusion
2017-01-25

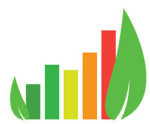

OM DGNB

# OM DGNB
## -BYGGERI – MARKEDET TENDENS




Kilde:"Bæredygtigt byggeri, markedsundersøgelse april 2016" v. Green Building Council Denmark. Baseret på besvarelser fra 45 virksomheder og organisationer


**90%**
vurderer at bygningens samlede værdi stiger som følge af bæredygtighedscertificering

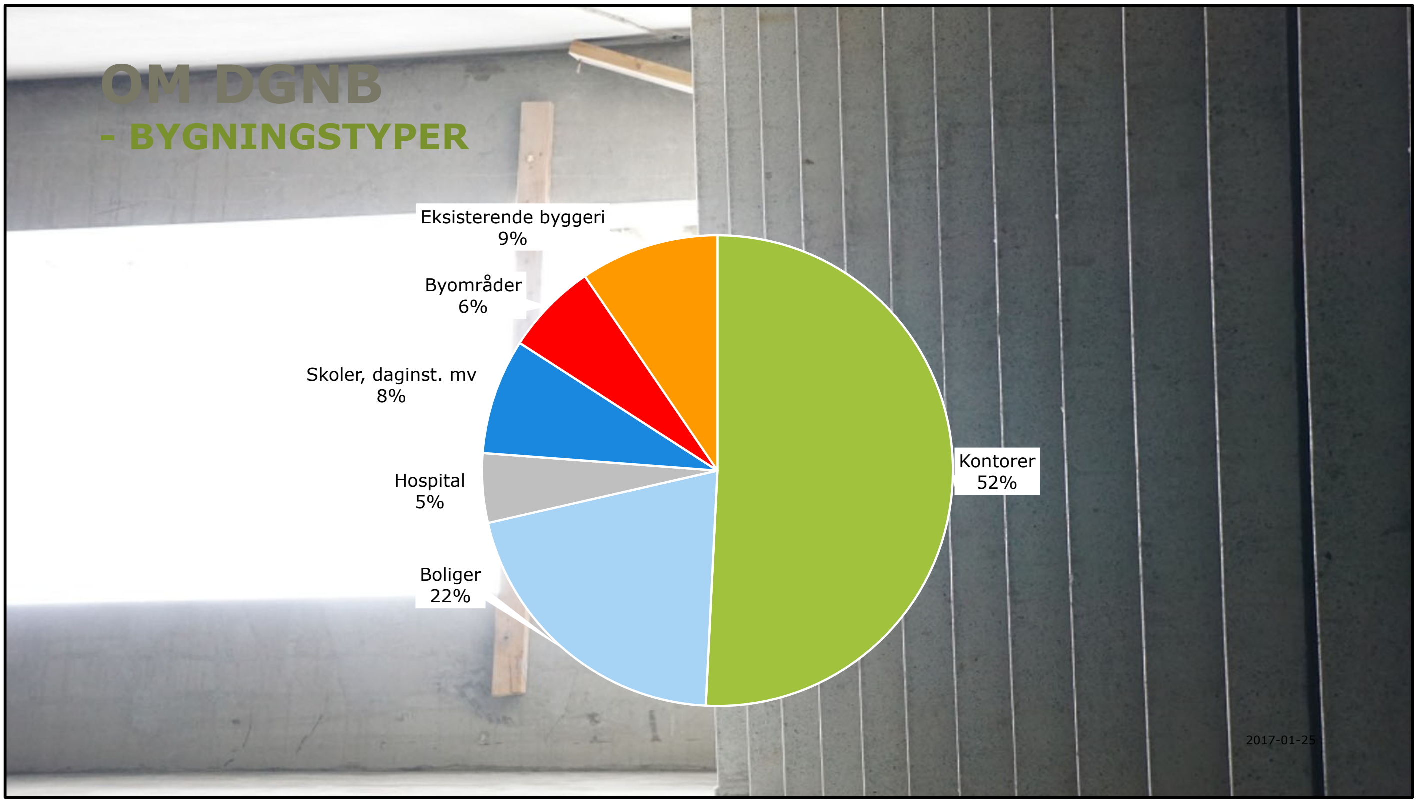


**80%**
forventer stigende efterspørgsel på bæredygtigt byggeri

**85%**
forventer stigende ambitioner inden for bæredygtigt byggeri


**48%**
ser bedre totaløkonomi som et afgørende argument for at bygge bæredygtigt

2017-01-25




Den viste graf er et billede på fordelingen af DGNB certificeringer som udføres i Danmark (gennemførte certificeringer fra 2012 til januar 2017). Her ses en klar overvægt af DGNB certificeringer for kontorer. Dette skyldes bl.a. at DGNB manualen for kontorer udkom først og dermed er den mest etablerede DGNB certificering. For udlejere af kontordomiciler har det givet god mening at stille krav om DGNB certificering, både for at kunne markedsføre sig som bæredygtige, i form af fx godt indeklima som er vigtigt for medarbejdertrivslen men også for at mindske drifts og vedligeholdsomkostningerne ved byggeriet.

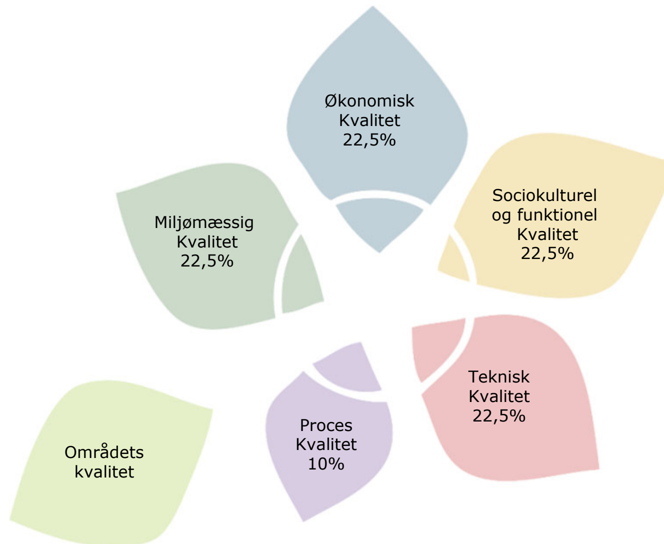
Efter at flere DGNB certificeringsordninger er kommet til for bl.a. boliger, byområder og skoler, dagsinstitutioner m.m. forventes det at disse områder vil blive større. Der kan allerede ses en tendens i at flere og flere boligbyggerier DGNB certificeres, idet DGNB certificering stilles som lokalplankrav i mange nye byområder. (Herunder bl.a. Nordhavnen, Sydhavnen og Ørestad.)

Der ses også en tendens i at investorer/bygherre for såvel kontorbyggeri som boligbyggeri stiller krav om DGNB certificering i deres byggeprojekter.

# OM DGNB

## - KVALITETER

"DGNB er en bygningscertificering – **ikke** en produktcertificering"




**DGNB for kontorbygninger:**

36 forskellige kriterier under de fem kvaliteter

191 underkriterier

2017-01-25

DGNB er en bæredygtighedscertificering af byggeri, hvor bæredygtighed sættes på formel.

I DGNB evalueres fem overordnet kvaliteter: Miljømæssig, økonomisk, social samt teknisk kvalitet vægtes hver med 22,5 % mens kvalitet i processen vægtes med 10 %. Området kvalitet beregnes særskilt og påvirker derfor ikke vurderingen af selve bygningen. Det er dog et krav for at opnå certificering at områdets kvalitet evalueres. Hver kvalitet er yderligere opdelt i kriteriegrupper og underkriterier, der indeholder relevante parametre til vurdering af den enkelte kvalitet.

DGNB kan ikke bruges til at certificere enkelte produkter da DGNB certificeringen bygger på en helhedsvurdering og en bygning/byområde etc. DGNB systemet evaluere altså det enkelte produkts indflydelse på den samlede ydeevne for bygningen.

For diverse produkter kan det i stedet anbefales at samle relevant dokumentation i en såkaldt DGNB dokumentationspakke som indeholder de informationer og certificeringer som kræves af DGNB ordningen, for på den måde at gøre produktet let tilgængeligt og brugbart for rådgiveren/arkitekten/entreprenøren.

http://www.dgnb-system.de/fileadmin/en/dgnb_ev/home/Construction_Products_in_the_DGNBSystem.pdf?pk_campaign=en_sysloopconstruction_products

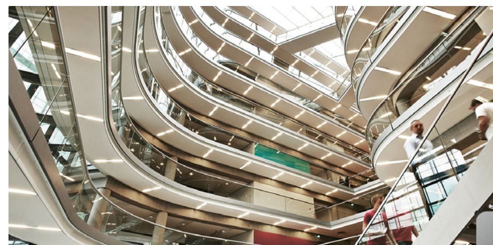
# OM DGNB
## - KVALITETER

**DGNB kræver, at der er balance i bæredygtighed**

- Bygningen skal opnå minimum 35 % i alle kvaliteter og 50 % samlet score for at opnå sølv
- Bygningen skal mindst opnå sølv i alle kvaliteter og 65 % i samlet score for at opnå guld
- Bygningen skal mindst opnå guld i alle kvaliteter og 80 % i samlet score for at opnå platin

DGNB Platin | DGNB Guld | DGNB Sølv

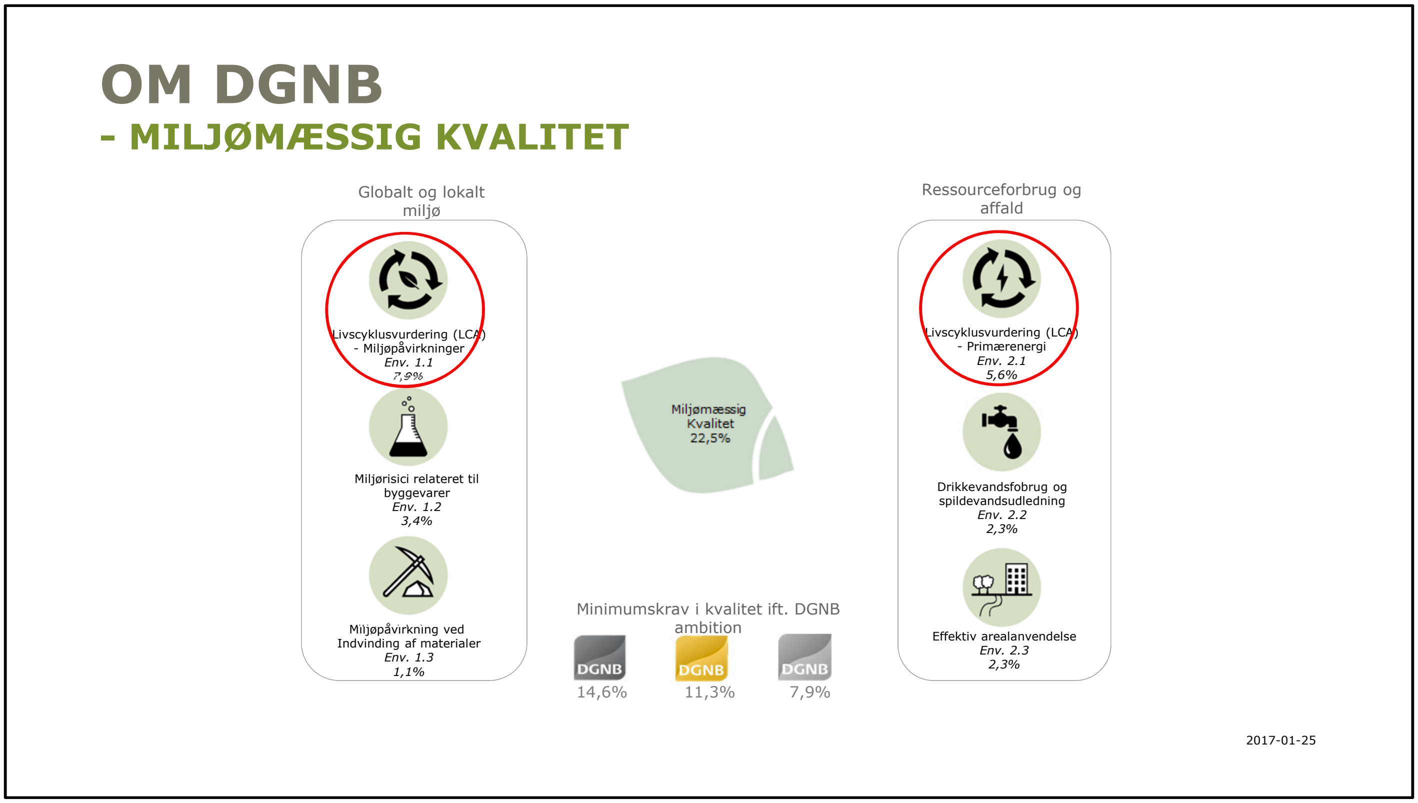
DGNB Platin



DGNB Sølv

2017-01-25

Bedømmelsen af bygningen baseres på point opnået i de 40 kriterier og 213 underkriterier, som vægtes i henhold til evalueringsmatricen udstedt af GBC-DK. Udover en samlet score er der krav til minimumsscore inden for hver kvalitet. F.eks. Er kravet til platin certifikat en samlet score på mindst 80% og at hver kvalitet som minimum scorer 65% svarende til guld niveau.




Beton (og andre byggematerialer i det hele taget) vil have indflydelse på de to markerede områder ENV. 1.1 og ENV. 2.1 som omhandler livscyklusvurdering (LCA) i forhold til miljøpåvirkning og i forhold til primærenergi.

Livscyklusvurderingen (LCA) vægter højt i DGNB certificeringen og et bæredygtigt materialevalg har derfor stor indflydelse på den samlede DGNB certificering af bygningen.

# OM DGNB
## - ØKONOMISK KVALITET

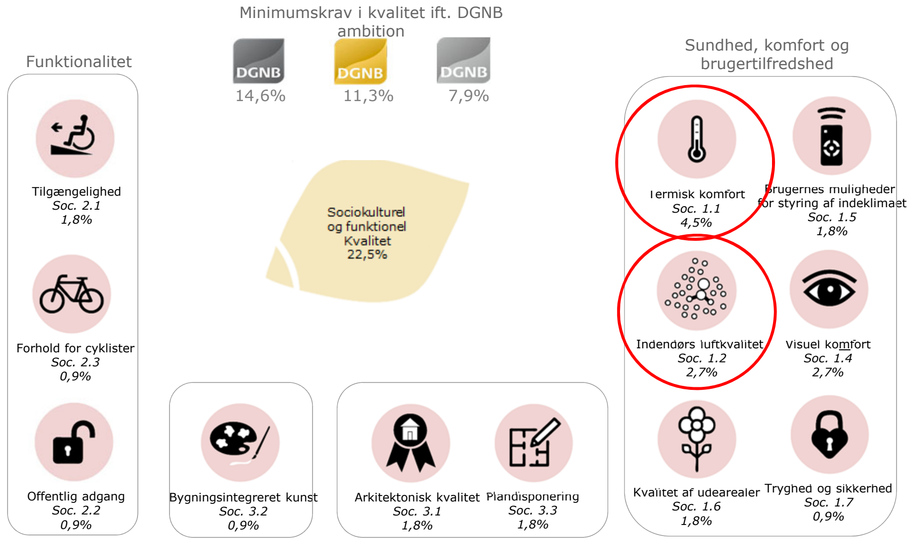

2017-01-25

Beton vil have indflydelse på parameteren ECO. 1.1 som handler om bygningsrelaterede levetidsomkostninger. Længere materialelevetid og mindre vedligehold vil have en positiv effekt på denne parameter.

ECO. 2.1 som drejer sig om fleksibilitet og tilpasningsevne omhandler i ligeså høj grad designet af bygningen. Alt efter betonens udformning (søjle/bjælke system vs. Skiver) såvel som dimensionering kan det have indflydelse på denne parameter.

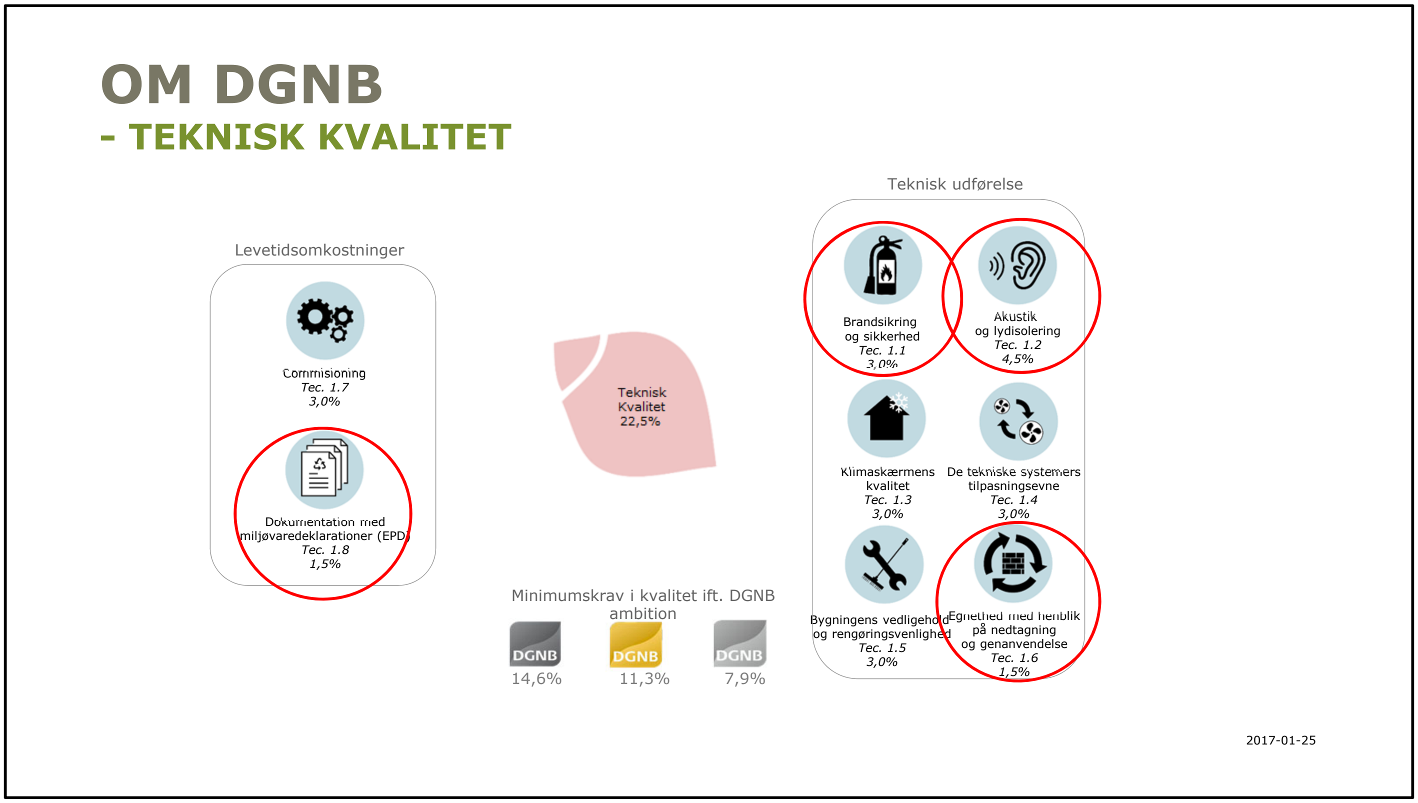
ECO. 2.2 beskæftiger sig med bygningens robusthed og lægger især vægt på komponenternes levetider, byggeteknisk udførelse og overholdelse af tidsfrister.

# OM DGNB
## - SOCIAL KVALITET




2017-01-25

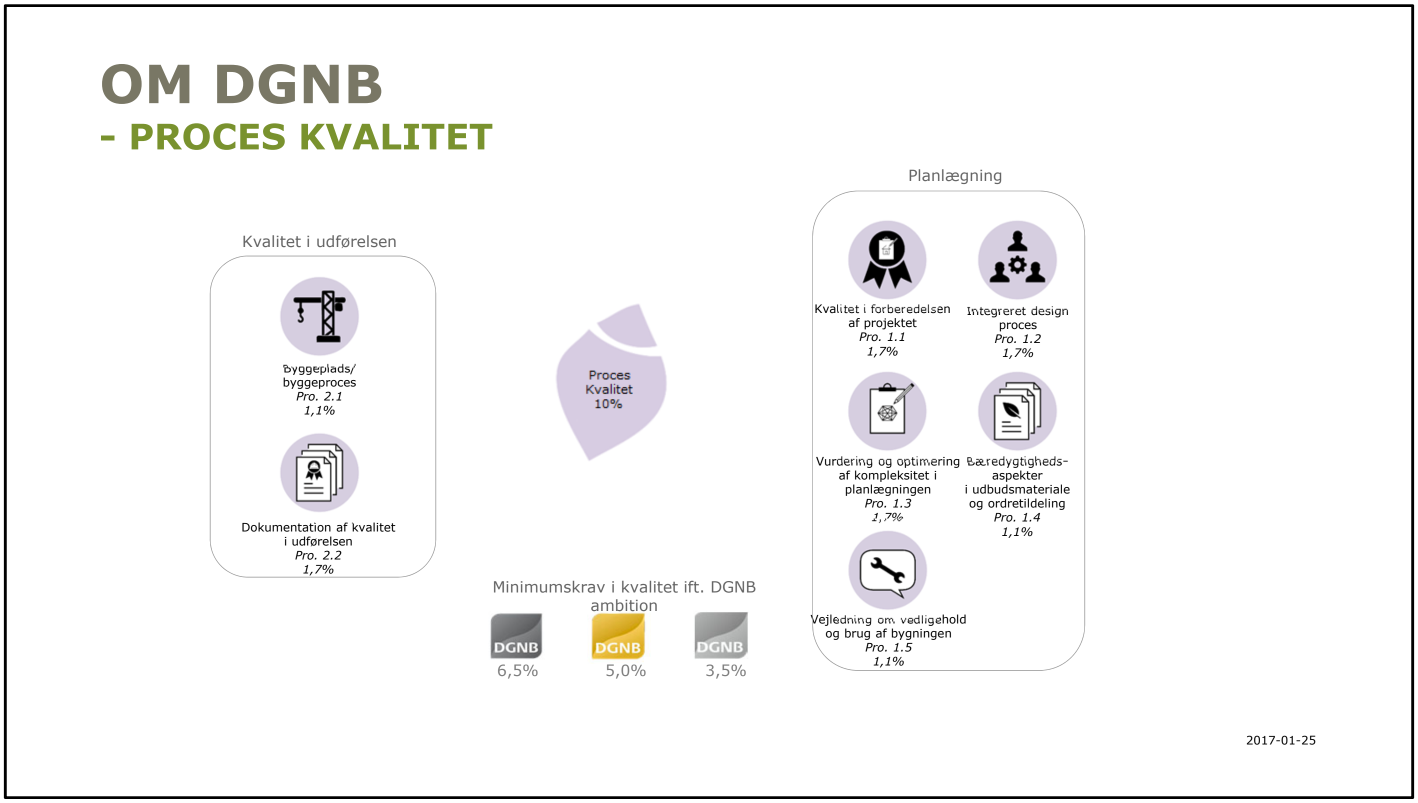
Beton har indflydelse på parametrene SOC. 1.1 Termisk komfort og SOC. 1.2 Indendørs luftkvalitet via fx dets termiske masse.




Beton har indflydelse på de markerede parametre fx TEC. 1.1 brandsikring og sikkerhed idet det ikke kræver brandisoleringsmateriale som fx stål.

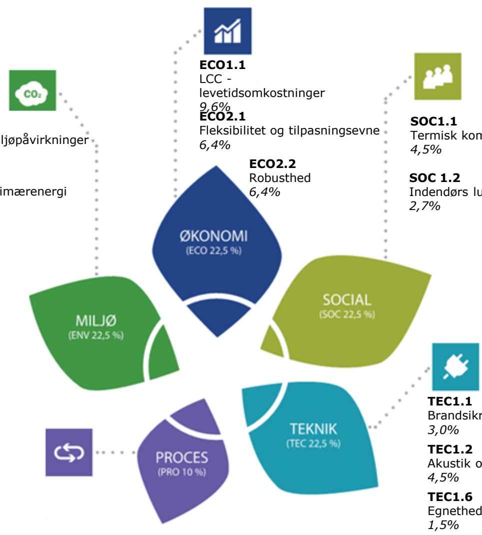
I TEC. 1.2 Akustik og lydisolering lægges fx vægt på luftlydsisolation mellem boliger og rum uden for boliger eksempelvis elevatorer og gangarealer såvel som andre boliger.

I TEC. 1.6 lægges der vægt på ensartethed i materialevalg for at undgå mange forskelligartede bortskaffelsesscenarier, samt at bygningskomponenterne let kan adskilles og genanvendes.




Beton og andre byggematerialer har ingen eller minimal indflydelse på kvaliteten i processen, da denne kvalitet handler om processen fra forberedelsen, design og projektering til selve byggeprocessen og vedligehold af det færdige byggeri.

# OM DGNB
## - OPSUMMERING




**ENV1.1**
LCA - Miljøpåvirkninger
*7,9%*

**ENV2.1**
LCA - Primærenergi
*5,6%*

**ECO1.1**
LCC - levetidsomkostninger
*9,6%*

**ECO2.1**
Fleksibilitet og tilpasningsevne
*6,4%*

**ECO2.2**
Robusthed
*6,4%*

**SOC1.1**
Termisk komfort
*4,5%*

**SOC 1.2**
Indendørs luftkvalitet
*2,7%*

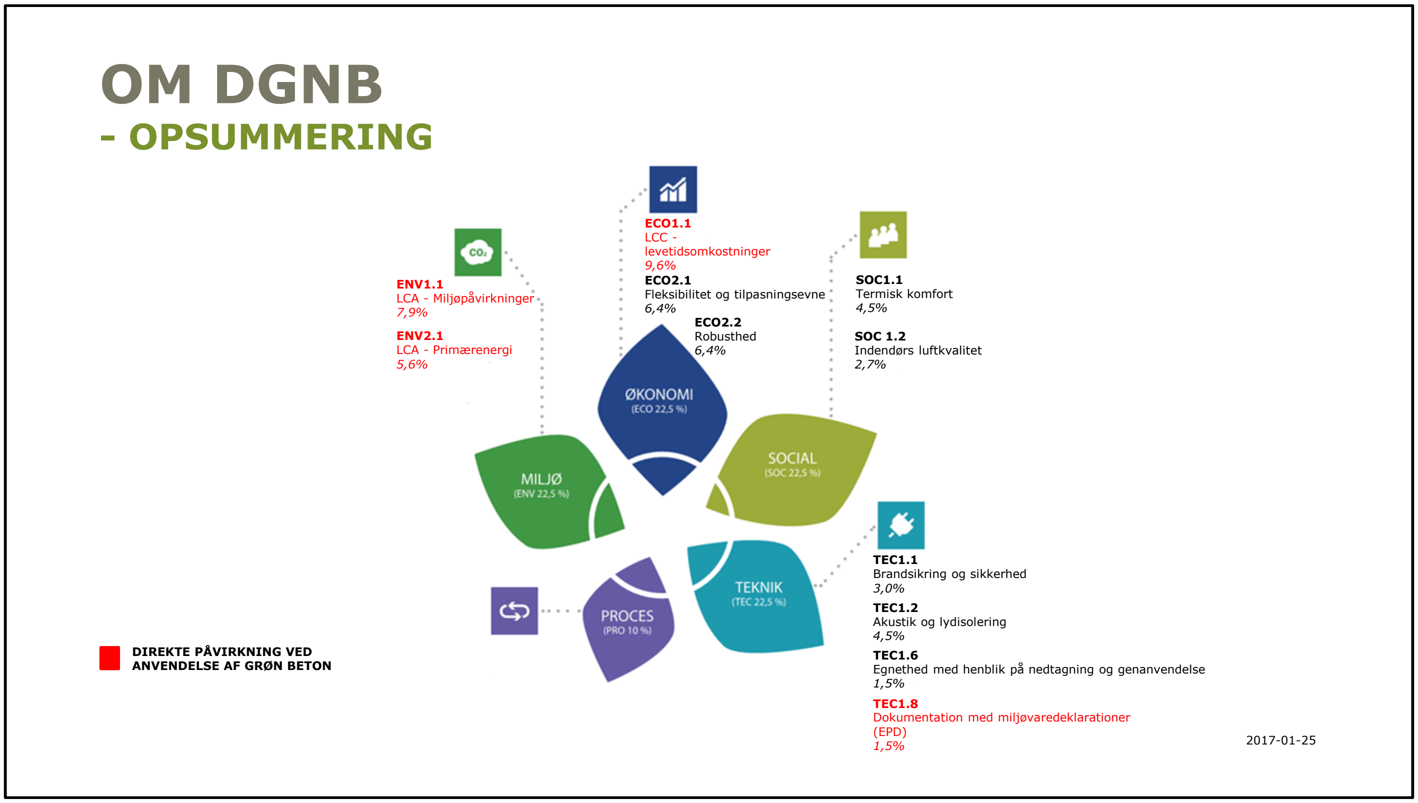
**TEC1.1**
Brandsikring og sikkerhed
*3,0%*

**TEC1.2**
Akustik og lydisolering
*4,5%*

**TEC1.6**
Egnethed med henblik på nedtagning og genanvendelse
*1,5%*

**TEC1.8**
Dokumentation med miljøvaredeklarationer (EPD)
*1,5%*

2017-01-25




Kriterierne markeret med rød viser, hvor grøn beton vil have en indflydelse på byggeriet. Ved at anvende grøn beton fremfor konventionel beton vil disse kriterier performe bedre og dermed påvirke byggeriet positivt. Grøn Beton vil altså have direkte indflydelse på 24,6 % af DGNB certificeringen.

# OM DGNB

## - OPSUMMERING

| Nr. | Kriterium | Indikator | Checklist-point (TLP - Auditor) | | | Evaluerings point (EVP) | | vægtnings-faktor | Max. DGNB-point |
|---|---|---|---|---|---|---|---|---|---|
| | | | TLP Kriterium | TLP Indikatorer | Max | EVP score | Max | | |
| ENV1.1 | Livscyklusvurdering (LCA) - Miljøpåvirkninger | | 87,63 | | 100 | 8,76 | 10 | 7 | 7,9% |
| | 1. | Global opvarming (GWP) | | 85,00 | 100 | | | | |
| | 2. | Ozonnedbrydning (ODP) | | 68,00 | 100 | | | | |
| | 3. | Fotokemisk ozondannelse (POCP) | | 97,00 | 100 | | | | |
| | 4. | Forsuring (AP) | | 100,00 | 100 | | | | |
| | 5. | Næringssaltbelastning (EP) | | 92,50 | 100 | | | | |
| ENV1.2 | Miljøricisi relateret til byggevarer | | 65,00 | | 100 | 6,50 | 10 | 3 | 3,4% |
| ENV1.3 | Miljøvenlig indvinding af materialer | | 100,00 | | 100 | 10,00 | 10 | 1 | 1,1% |
| | 1. | Anvendelse af træ og træmateriale | | 45,00 | 45 | | | | |
| | 1.1 | forskallingstræ | | 5,00 | 5 | | | | |
| | 2. | Anvendelse af natursten | | 50,00 | 50 | | | | |
| ENV2.1 | Livscyklusvurdering (LCA) - Primærenergi | | 88,80 | | 100 | 8,88 | 10 | 5 | 5,6% |
| | 1. | Forbrug af ikke-vedvarende primærenergi (PEnr) | | 100,00 | 100 | | | | |
| | 2. | Samlet forbrug af primærenergi (Petot) | | 53,00 | 100 | | | | |
| | 3. | Andel af vedvarende primærenergi | | 38,00 | 50 | | | | |
| ENV2.2 | Drikkevandsforbrug og spildevandsudledning | | 48,50 | | 100 | 4,85 | 10 | 2 | 2,3% |
| ENV2.3 | Effektiv arealanvendelse | | 60,00 | | 100 | 6,00 | 10 | 2 | 2,3% |
| | 1.1 | Anvendelse af "genbrugsarealer" vs. anvendelse af ubebyggede arealer | | 20,00 | 40 | | | | |
| | 1.2 | Bebyggelsestætheden | | 40,00 | 40 | | | | |
| | 2 | Miljømæssige forbedringer af arealet | | 0,00 | 5 | | | | |
| | 2.1 | Oprensning af forurenet jord. | | 0,00 | 5 | | | | |
| | 2.2 | Positiv indflydelse på grundens biofaktor | | 0,00 | 10 | | | | |
| ECO1.1 | Bygningsrelaterede levetidsomkostninger | | 84,00 | | 100 | 8,40 | 10 | 3 | 11,2% |
| ECO2.1 | Fleksibilitet og omstillingsevne | | 56,30 | | 100 | 5,63 | 10 | 2 | 7,5% |
| | 1. | arealudnyttelse | | 8,30 | 10 | | | | |
| | 2. | Rumhøjde | | 10,00 | 10 | | | | |
| | 3. | Bygningsdybde | | 0,00 | 10 | | | | |
| | 4. | Vertikale adgangsveje | | 0,00 | 10 | | | | |
| | 5. | Fleksible planløsninger | | 10,00 | 10 | | | | |
| | 6. | Konstruktion | | 5,00 | 10 | | | | |
| | 7.1 | Tekniske installationer - indeklima | | 7,00 | 10 | | | | |
| | 7.2 | Tekniske installationer - køling | | 7,50 | 10 | | | | |
| | 7.3 | Tekniske installationer - varme | | 7,50 | 10 | | | | |
| | 7.3 | Tekniske installationer - afløb | | 1,00 | 10 | | | | |

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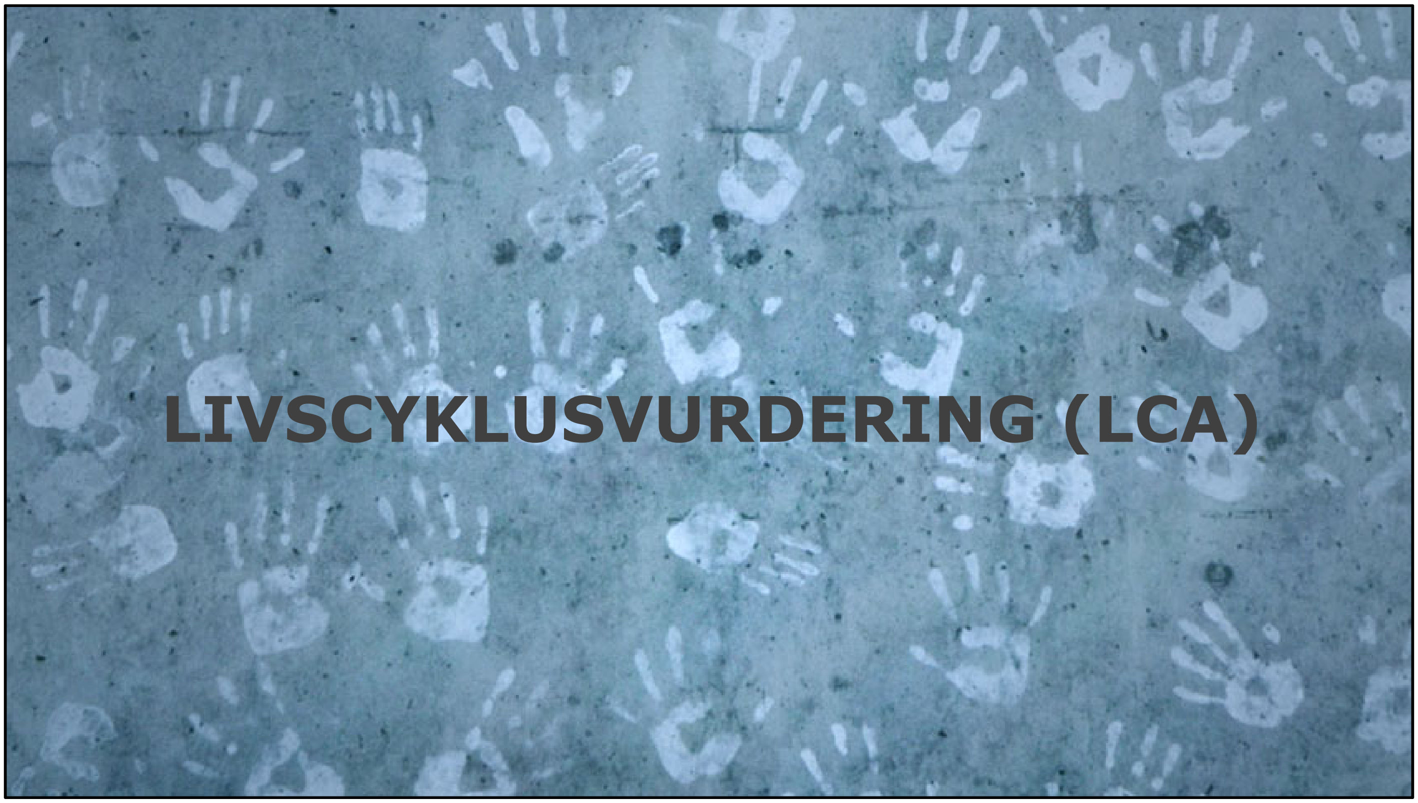
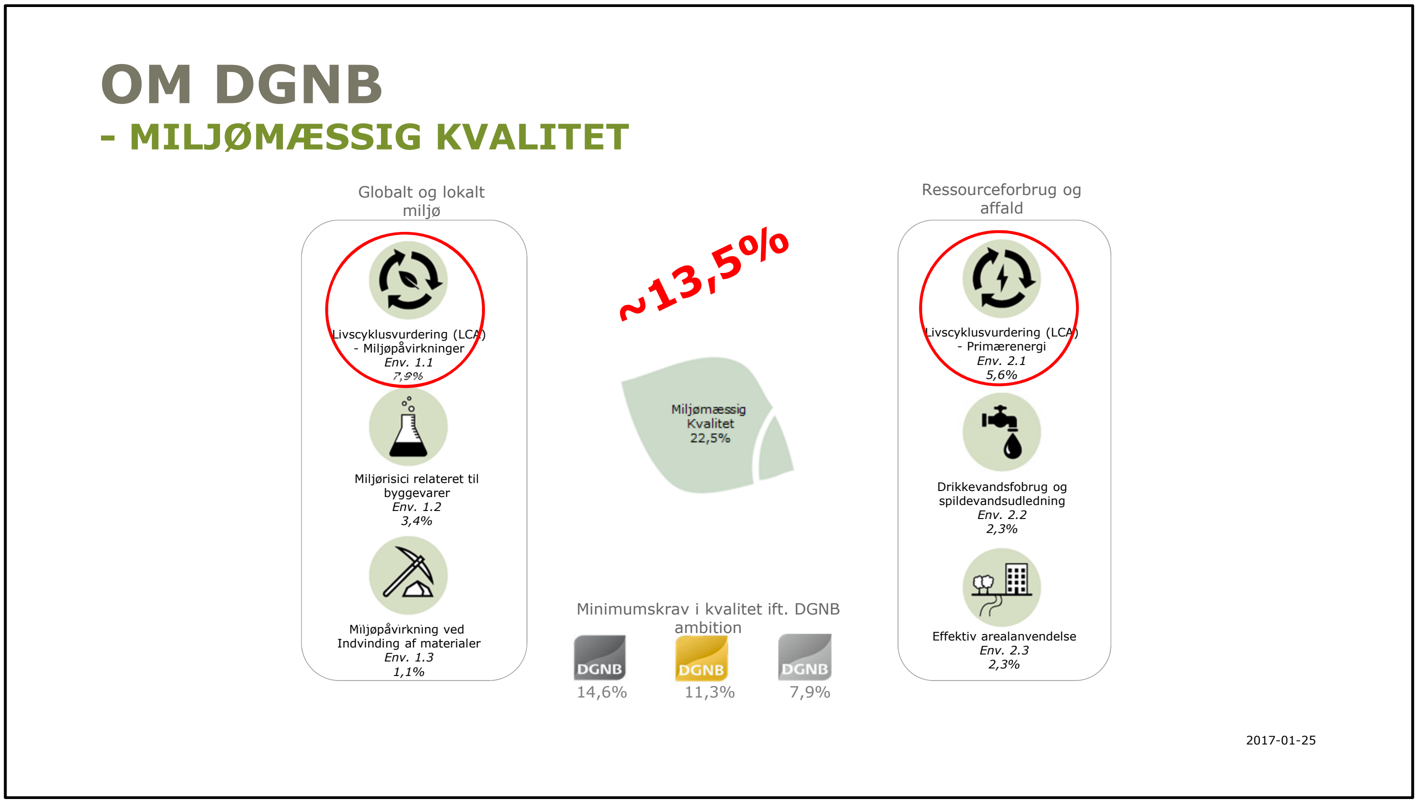
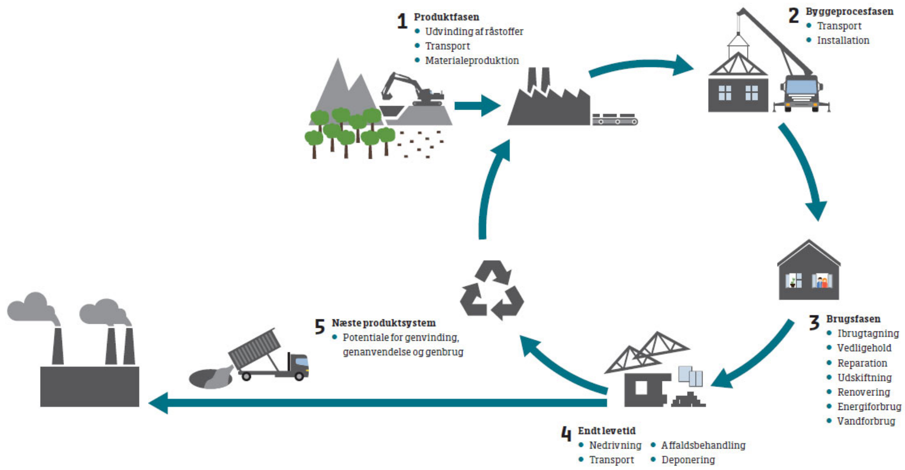
Slide slettes?


LIVSCYKLUSVURDERING (LCA)




Selv små forbedringer kan have stor betydning for den samlede vurdering. Især materialevalg spiller en afgørende rolle i DGNB certificeringen på grund af vægtningen af parametrene. Tidligere var energioptimering en lavt hængende frugt og fokus har i høj grad været på energibesparelser i byggeriet via fx bedre isolering, vinduesrammer/glas m.m. Nu er fokus især flyttet til materialeforbruget igennem byggeriets livscyklus da der bl.a. er store mængder $CO_2$ at spare her.

# LIVSCYKLUSANALYSE
## - MILJØPÅVIRKNINGER

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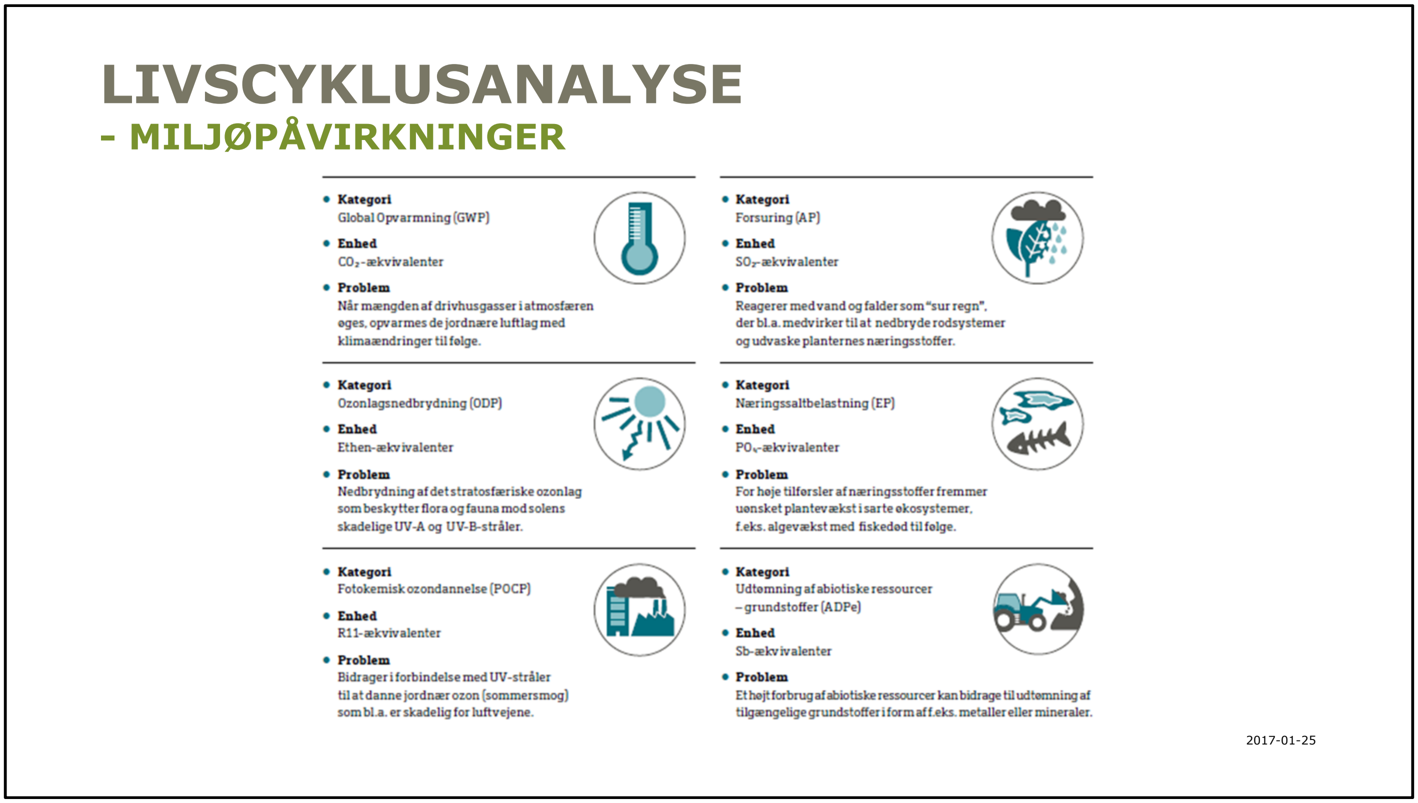
En livscyklusvurdering ser på alle aspekter af et produkts livscyklus, helt fra udvindingen af råstoffet og transporten derfra til materialeproduktionen. Derfra den videre transport af det færdige produkt til byggepladsen og installationen af produktet. Herfra ses på brugsfasen hvor produktet skal vedligeholdes og eventuelt udskiftes. Slutteligt ses på endt levetid for produktet i forhold til nedrivning eller adskillelse samt transport til enten genanvendelse eller deponering. Byggematerialer som har potentiale for genvinding, genanvendelse eller direkte genbrug indgår derefter direkte i en ny livscyklus.




Miljøpåvirkningerne beregnes for 5 forskellige indikatorer:

1. GWP: Global Warming Potential. Har til formål at reducere de emissioner, som bidrager til global opvarmning.

2. ODP: Ozone Depletion Potential. Har til formål at reducere de emissioner, som bidrager til nedbrydelsen af ozonlaget.

3. POCP: Photochemical Ozone Creation Potential: Har til formål at reducere den fotokemiske ozondannelse nær jordoverfladen (sker fx når nitrogenoxid eller hydrocarbon udsættes for UV-stråling.)

4. AP: Acidification Potential. Har til formål at reducere forsuring af miljøet (syreregn).

5. EP: Eutrophication potential. Har til formål at reducere belastningen af de næringssalte, der opstår når jord og vandområder overgår fra næringsfattig til næringsrig tilstand. (Herved øges fx dannelsen af alger i vandområder som fører til større fiskedødelighed)

# SCOPE
## - LIVSCYKLUSANALYSE I DGNB

**Produktfasen (A1, A2, A3)**

Udvinding af ressourcer og produktion af materialer

**Drift og vedligeholdelse (B4, B6)**

Energiforbrug + fornyelse af materialer og end-of-life af udskiftede materialer

**End-of-life (C3, C4)**

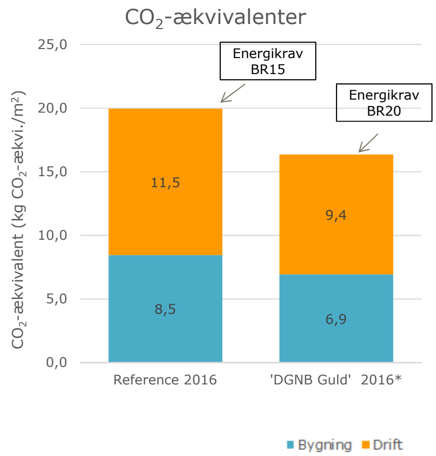
Affaldsbehandling, genanvendelse, bortskaffelse

**Livscyklusanalyse:**

Beregningsperiode hhv.
50/80/120 år

**Materialedata, prioritering**

1. Miljøvaredeklarationer EPD/MVD, EN15804
2. ESUCO database (EU)
3. Ökobau.dat database (Tysk)




*Baseret på erfaringstal

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### Livscyklus for Grøn Beton:

Produktfasen: Udvinding af ressourcer og produktion af cement og betonelementer sker lokalt (DK).

Drift & vedligehold: Grøn beton skal ikke udskiftes og kræver et minimum af vedligehold i driftsfasen.

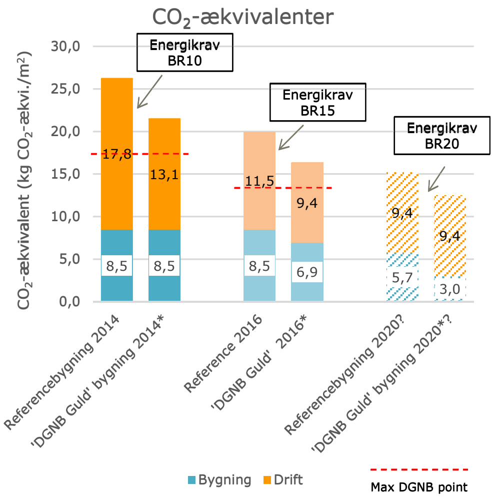
End-of-life: Slutscenariet for bygningselementer er svære at spå om 100 år ud i fremtiden. I dag bliver beton nedknust og genanvendt som tilslag i bl.a. vejanlæg og store konstruktionsanlæg som fyld. At kunne genanvende betonelementer direkte kræver en anden tilgang til samlingen af bygningskomponenterne og et produktions paradigme skift som følger Design-for-disassembly.

Der har indtil nu været mest at vinde ved at reducere CO2, ved at mindske energiforbruget, fx ved at øge isolering. I det nye BR20 er energikravet strammet op, og det er svært udelukkende at optimere vha. mindre energiforbrug. Der kommer derfor fremover mere fokus på at reducere energiforbruget i forbindelse med de anvendte materialer i byggeriet og i byggeprocessen. Det vil derfor fremover blive endnu mere relevant at anvende grøn beton fremfor konventionel beton.

Af grafen ses det tydeligt, med BR20's stramme krav til energiforbrug i driften af byggeriet, at bygningens opførsel har større betydning end tidligere. Mængden af CO2-ækvivalenter udledt ved byggeriet i referenceprojektet (BR15) er næsten lige så stor som de udledte CO2-ækvivalenter ved driften i BR20 byggeriet. Da man ikke hidtil har haft fokus på materialeudvinding og forbrug er der et stort optimeringspotentiale her.

# LØBENDE UDVIKLING AF DGNB

## - LIVSCYKLUSVURDERINGER




- Skærpet energikrav fra BR10 til BR15
- Skærpet referencebygning i DGNB 2016
- Det er ikke privat eller samfundsøkonomisk at gå længere ned i energiforbrug
- Så hvad sker der? Fokus skifter fra energiforbrug til materialer for at opretholde samme DGNB score

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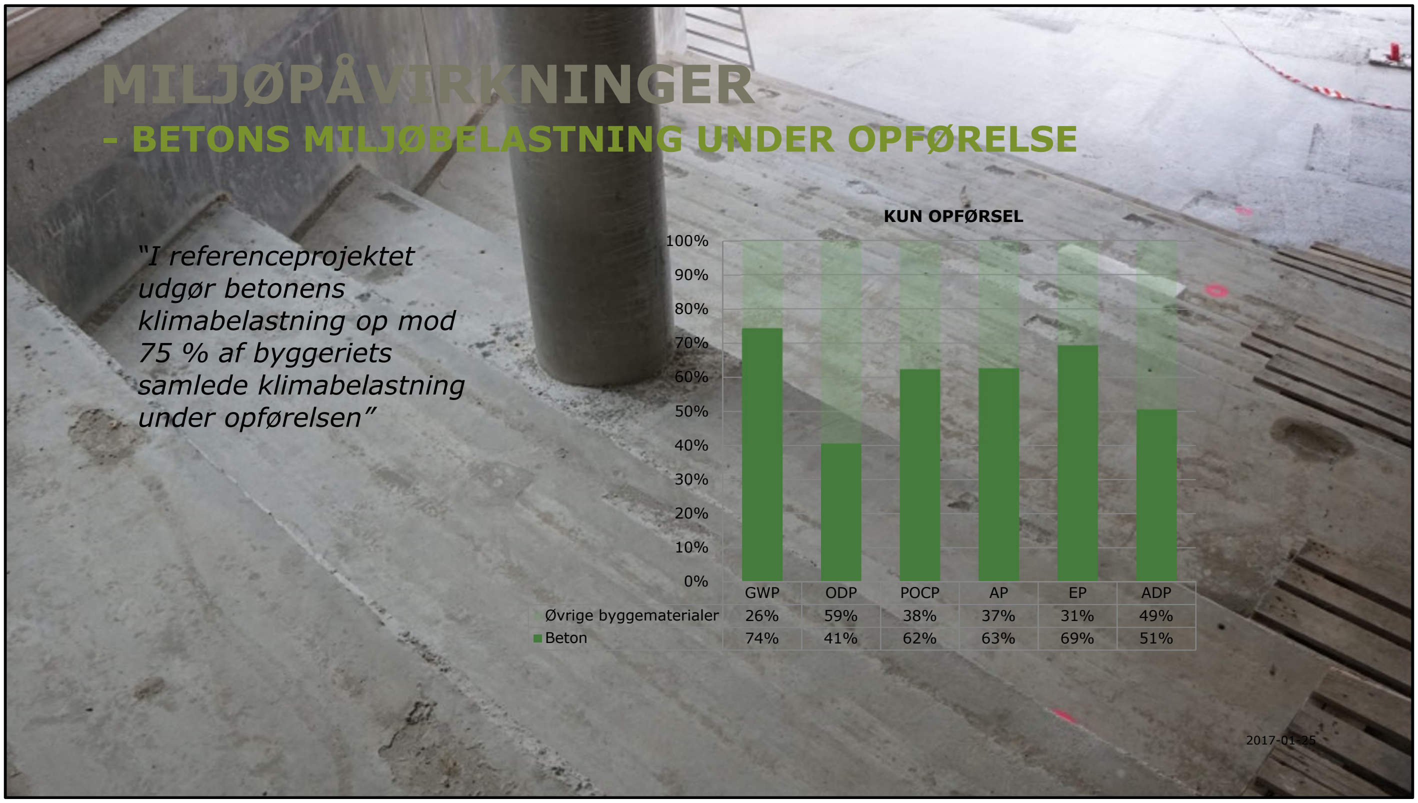
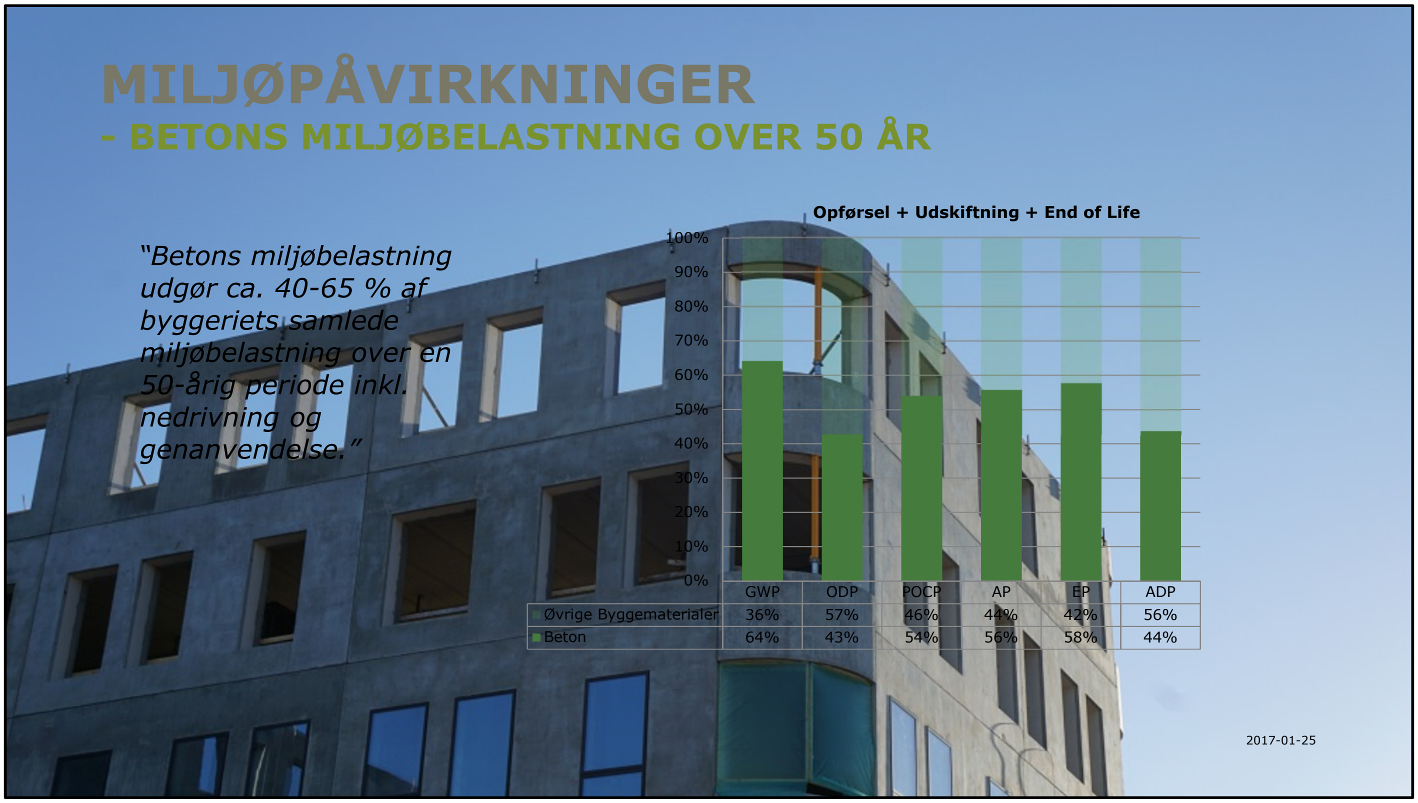
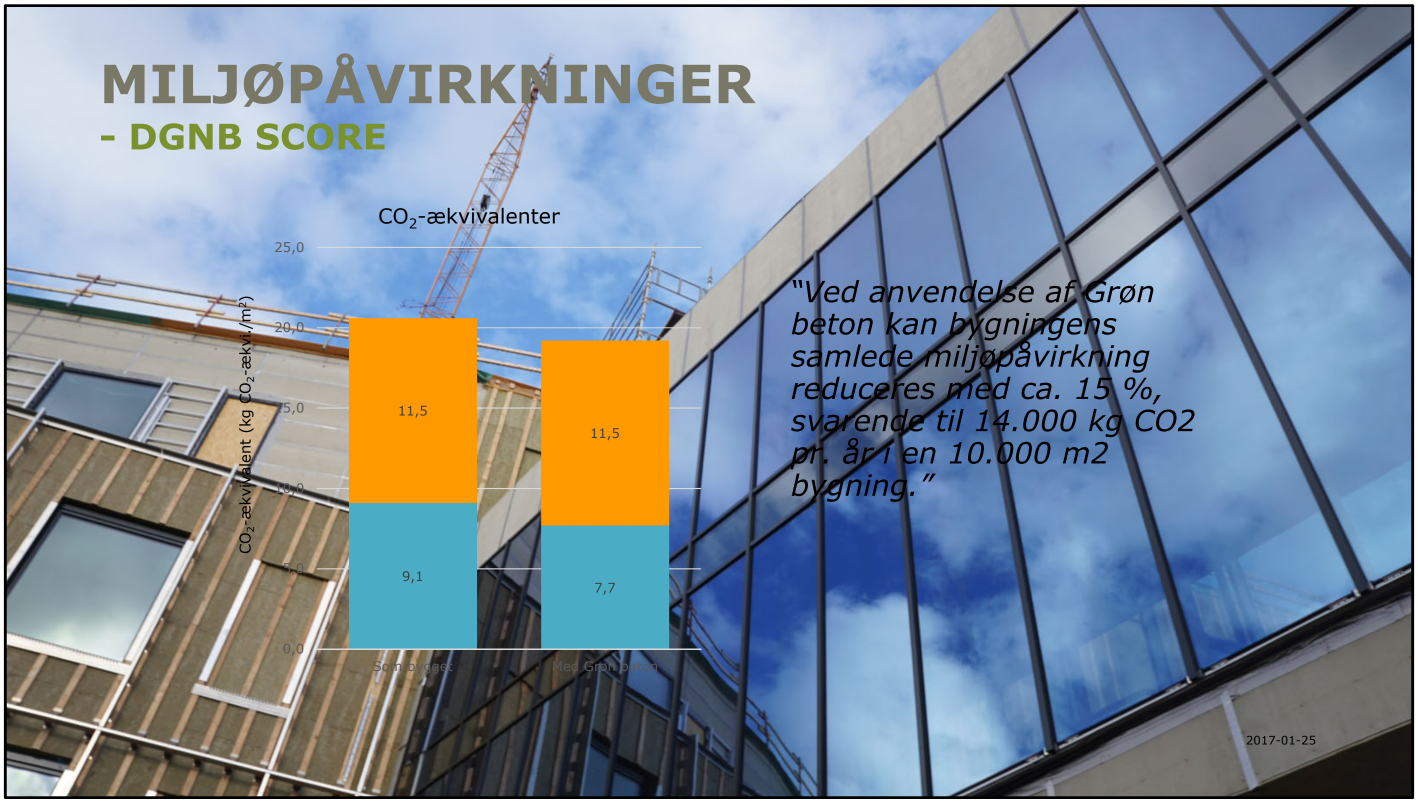
Der er et uforløst potentiale i at optimere på bygningens materialemasse, da der ikke tidligere har været fokus herpå eller stillet krav hertil. DGNB er med til at sætte fokus på dette gennem krav om LCA.




Det ses af grafen at betons miljøbelastning under opførslen af byggeriet for et reference byggeri udgør mellem 40 % og 75 % af bygningens samlede miljøbelastning.



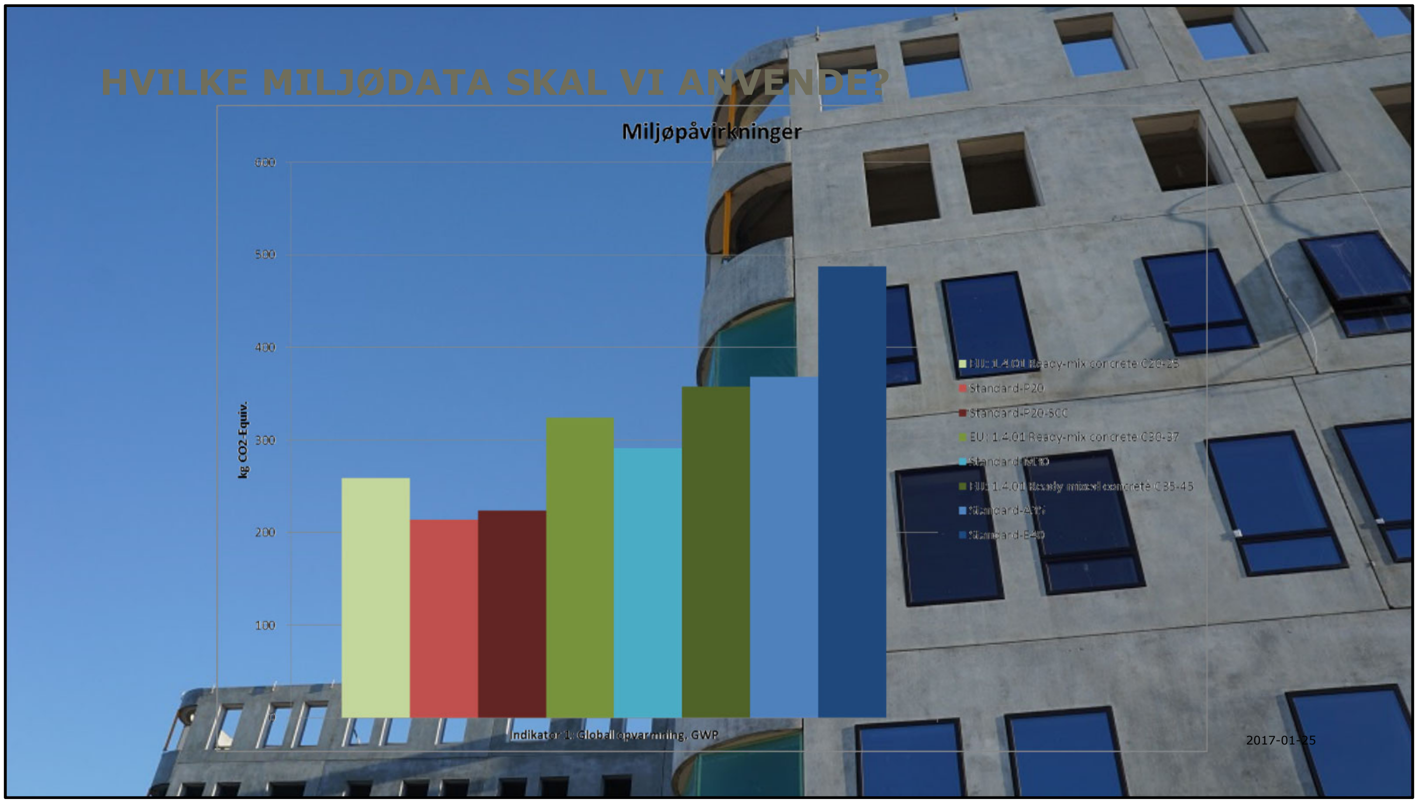

Det ses af grafen at betons miljøbelastning over 50 år for reference byggeriet udgør mellem 40 % og 65 % af bygningens samlede miljøbelastning i perioden.




Grøn Beton, er beton, hvor der anvendes nye CO2-reducerede cementer, der er baseret på naturligt forekommende råmaterialer og som er produceret gennem mere energieffektive metoder, der vil medvirke til, at reducere CO2-udledningen fra cementproduktion med 0,5 mia. tons på verdensplan og 0,5 mio. tons i Danmark inden 2050.


Da beton udgør en stor del af bygningsmassen er der store besparelser at hente samlet set selv med små justeringer i betonsammensætningen.


Miljøvaredeklarationen (EPD) dokumenterer byggevarers miljømæssige egenskaber, og udvikles iht. anerkendte europæiske og internationale standarder. EPD’er anvendes bl.a. ved DGNB-certificering.



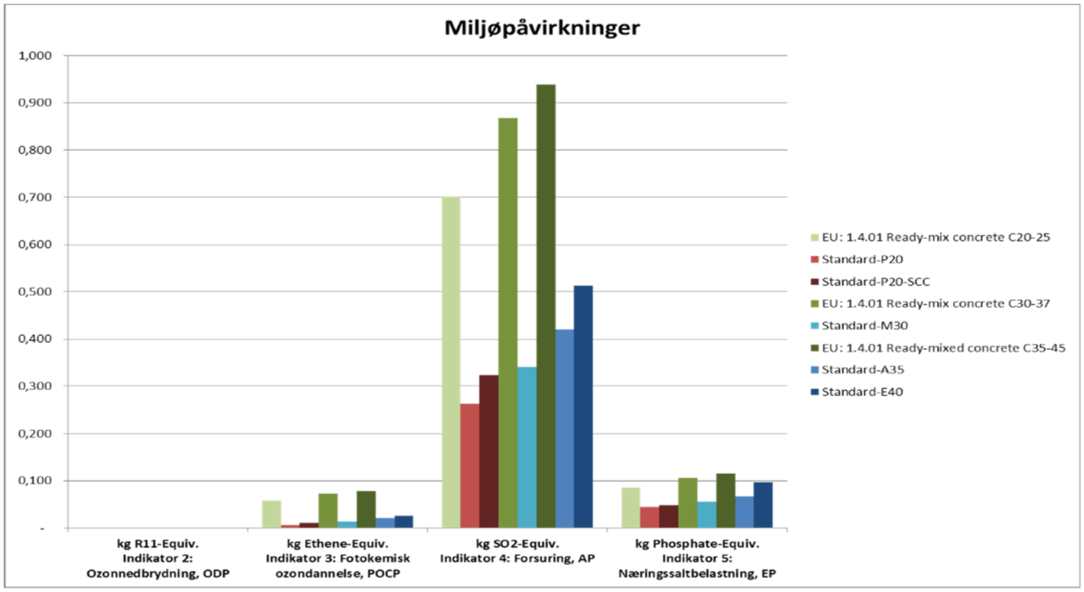

Ready-mixed concrete er et udtryk for en standard angivet i ESUCO.

"Standard" er et udtryk for Dansk Betonforenings (DBF) gennemsnitlige målinger fra betonfabrikanter som er medlem af DBF.

Af grafen ses det at højere betonstyrker giver højere CO2 udledning. (GWP)

Dette skyldes at der anvendes mere cement, og det er cementen der giver det markant største bidrag til CO2 udledningen. Dette betyder at hvis man skal spare CO2, må man enten spare på cementen ved at gå ned i styrkeklasse (hvis dette er muligt, konstruktionsmæssigt, evt. ved in-situ-støbning), erstatte dele af cementen med andre tilsætninger der kan bidrage til styrkeudviklingen eller ved at udvikle cementtyper der udleder mindre CO2 – som er det Grøn Beton projektet arbejder med.

## HVILKE MILJØDATA SKAL VI ANVENDE?

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Ready-mixed concrete er et udtryk for en standard angivet i ESUCO.

"Standard" er et udtryk for Dansk Betons gennemsnitlige målinger fra betonfabrikanter som er medlem af fabriksbetongruppen i Dansk Beton

Det ses at dansk beton generelt klarer sig bedre end betonen i den generiske database.

# KONKLUSION FOR GRØN BETON

## FRA DGNB ARBEJDSGRUPPE

- Stigende efterspørgsel på bæredygtigt byggeri
- Materialer og bunden energi får større fokus pga. den grønne omstilling
- Grøn beton har en betydelig effekt på DGNB score
- Designløsningen vil altid have en betydning for bæredygtigheden og i en bæredygtighedscertificering
- Udarbejdelse af EPD´er er positivt for gennemsigtigheden i branchen og tæller op i en DGNB certificering
- Fabriksbetonforeningen arbejder på at udarbejde et EPD-regneark til forskellige betonsammensætninger

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Se slide

# PROCESSER DER INDGÅR I LIVSCYKLUSVURDERINGEN I DGNB

Der ses i det følgende nærmere på livscyklusvurdering i DGNB (kriterierne ENV1.1 og ENV2.1).

En livscyklusvurdering for et materiale eller et produkt, er et udtryk for, hvor stor miljøpåvirkning det enkelte materiale/produkt har på miljøet i hele dets levetid.

En livscyklusvurdering af et materiale indeholder optimalt set alle faser af hele materialets levetid. Dvs. helt fra anskaffelse af råstoffer til og med bortskaffelse af materialet. Alle faser ses i figuren til højre.

I livscyklusvurderingen i DGNB fokuseres på faserne hvor der er sat "x" i figuren til højre.

Der er nogle af de andre elementer, som bliver behandlet andre steder i DGNB-certificeringen, f.eks. vandforbrug til drift.

Figur 1. Bygningens livscyklusfaser og definition af hvilke processer der indgår i livscyklusvurderingen.

| LIVSCYKLUSFASER | A 1-3 | | | A 4-5 | | B 1-7 | | | | | | | C 1-4 | | | | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FREMSTILLINGS-FASE | | | OPFØR-ELSES-FASE | | BRUGSFASE | | | | | | | AFSLUTNING AF LEVETIDEN | | | | FORDELE OG BELASTNINGER UDEN FOR SYSTEM-GRÆNSEN |
| | Anskaffelse af råstoffer | Transport | Produktion | Transport | Opførelse/montering | Ibrugtagning | Vedligeholdelse | Istandsættelse | Udskiftning | Modernisering | Energiforbrug til drift | Vandforbrug til drift* | Nedtagning/nedrivning | Transport | Genvinding af affald | Bortskaffelse | Potentiale for genanvendelse, genvinding og genbrug |
| MODULER IHT. DS EN 15978 | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| DEKLAREREDE MODULER | x | x | x | | | | | | x[1] | | X[2] | | | | x | x | x |

1) Omfatter kun fremstilling og bortskaffelse af det udskiftede produkt og ikke selve udskiftningsprocessen (iht. byggeproces).
2) Inkluderes i del 1 men ikke del 2 af vurderingen.
* Bygningens vandforbrug anføres i ENV2.2. Ikke indeholdt i bygningens livscyklusvurdering.

GREEN BUILDING COUNCIL DENMARK

2017-01-25


SPØRGSMÅL?