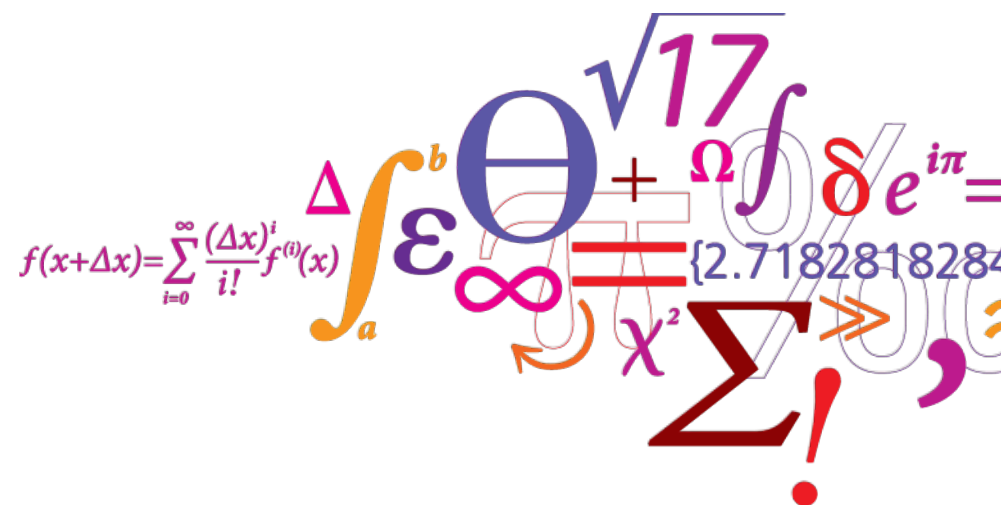


# Environmental sustainability assessment of urban systems applying coupled urban metabolism and life cycle assessment

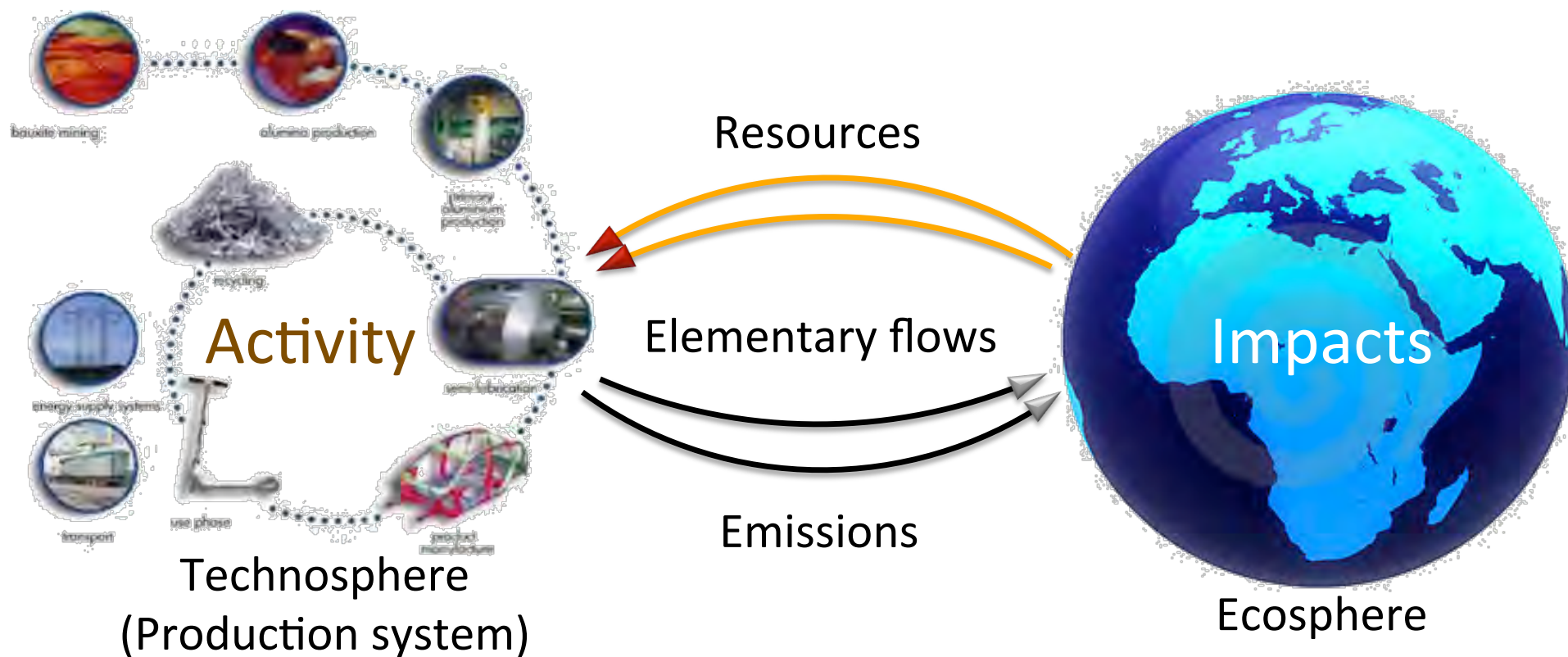
Illustration of quantification of the (absolute) sustainability of urban systems

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DTU Management Engineering

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DTU Management Engineering



# Life Cycle Assessment (LCA)





Substance	CAS.no.	Emission to air g	Emission to water g
2-hydroxy-ethanacrylate	816-61-0	0,0348	
4,4-methylenbis cyclohexylamine	1761-71-2	5,9E-02	
Ammonia	7664-81-7	3,7E-05	4,2E-05
Arsenic ( As )	7440-38-2	2,0E-06	
Benzene	71-43-2 (cur)	5,0E-02	
Lead ( Pb )	7439-92-1	8,5E-06	
Butoxyethanol	111-76-2	6,6E-01	
Carbondioxide	124-38-9	2,6E+02	
Carbonmonoxide ( CO )	630-08-0	1,9E-01	
Cadmium (Cd)	7440-46-9	2,2E-07	
Chlorine ( Cl2 )	7782-50-5	4,6E-04	
Chromium ( Cr VI )	7440-47-3	5,3E-06	
Dicyclohexane methane	86-73-6	5,1E-02	
Nitrous oxide( N2O )	10024-97-2	1,7E-02	
2,4-Dinitrotoluene	121-14-2	9,5E-02	
HMDI	5124-30-1	7,5E-02	
Hydro carbons (electricity, stationary combustion)	-	1,7E+00	
Hydrogen ions (H+)	-		1,0E-03
i-butanol	78-83-1	3,5E-02	
i-propanol	67-63-0	9,2E-01	
copper ( Cu )	7740-50-8	1,8E-05	
Mercury ( Hg )	7439-97-6	2,7E-06	
Methane	74-82-8	5,0E-03	
Methyl i-butyl ketone	108-10-1	5,7E-02	
Monoethyl amine	75-04-7		7,9E-06
Nickel ( Ni )	7440-02-0	1,1E-05	
Nitrogen oxide ( NOx )	10102-44-0	1,1E+00	
NM/VOC, diesel engine (exhaust)	-	3,9E-02	
NM/VOC, power plants (stationary combustion)	-	3,9E-03	
Ozone ( O3 )	10028-15-6	1,8E-03	
PAH	ikke specifikt	2,4E-08	
Phenol	108-95-2		1,3E-05
Phosgene	75-44-5	1,4E-01	
Polyeter polyol	ikke specifikt	1,6E-01	
1,2-propylenoxide	75-56-9	8,2E-02	
Nitric acid	7782-77-6 (cur)	8,5E-02	
Hydrochloric acid	7647-01-0 (cur)	1,9E-02	
Selenium ( Se )	7782-49-2	2,6E-05	
Sulphur dioxide( SO2 )	7446-09-5	1,3E+00	
Toluene	108-88-3	4,8E-02	
Toluene-2,4-diamine	95-80-7	7,9E-02	
Toluene diisocyanat ( TDI )	26471-62-5	1,6E-01	
Total-N	-		2,6E-05
Triethylamine	121-44-8	1,6E-01	
Unspecified aldehydes	-	7,5E-04	
Unspecified organic compounds	-	1,5E-03	
Vanadium	7440-62-2	1,8E-04	
VOC, diesel engine (exhaust)	-	6,4E-05	
VOC, stationary combustion (coal fired)	-	4,0E-05	
VOC, stationary combustion (natural gas fired)	-	2,2E-03	
VOC, stationary combustion (oil fired)	-	1,4E-04	
Xylene	1330-20-7	1,4E-01	
Zinc ( Zn )	7440-66-6	8,9E-05	

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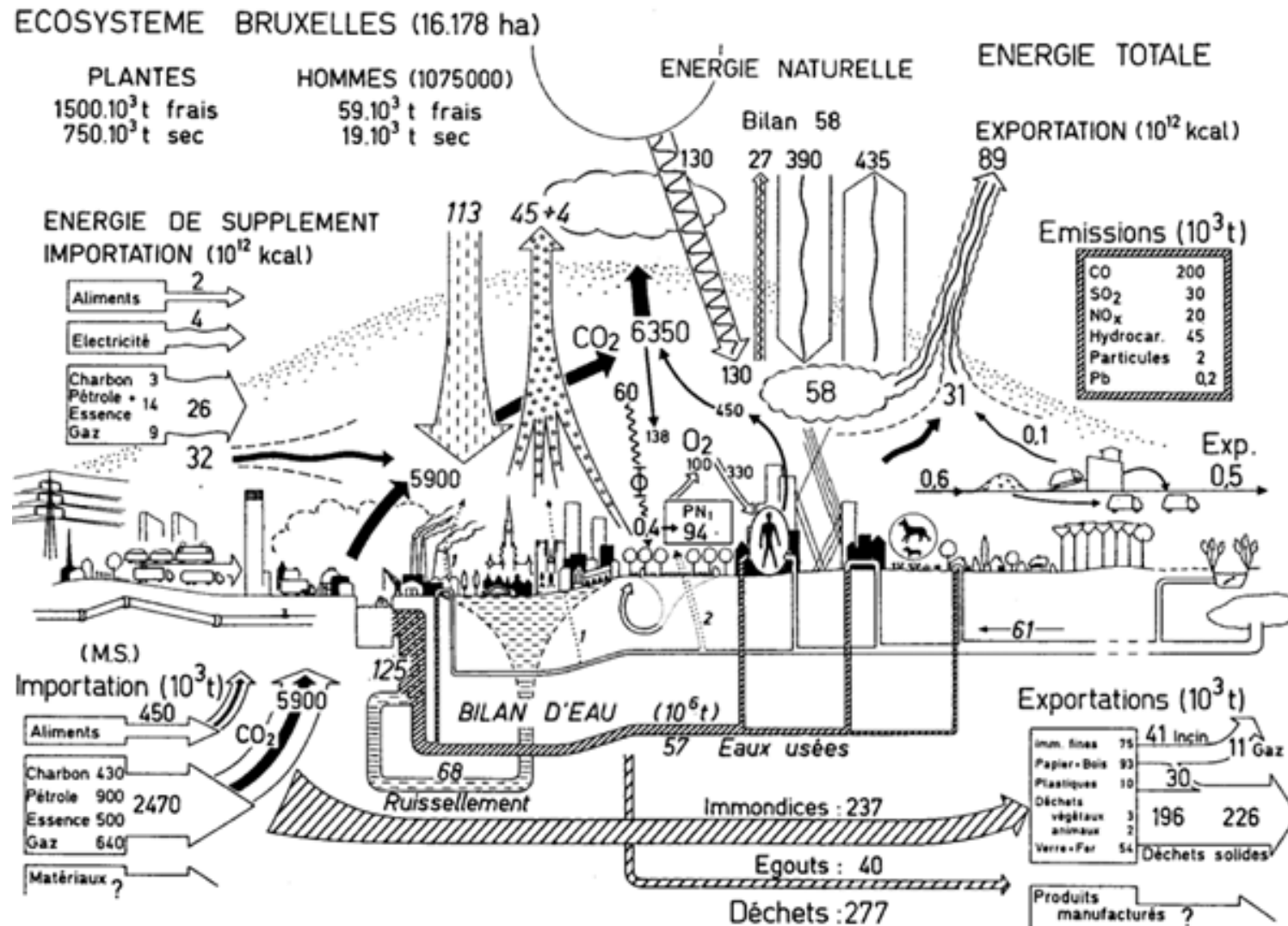
graph TD
    A[Farming of vegetables] --> B[Raw materials]
    B --> C[Truck transport]
    C --> D[Raw materials]
    D --> E[Meal processing step 1]
    E --> F[Vegetables]
    E --> G[Meal product]
    F --> H[Power]
    H --> I[Grid power]
    I --> J[Truck distribution]
    J --> K[Truck distribution step 1]
    K --> L[Meal product]
    L --> M[Customer 1]
    M --> N[Power]
    N --> O[Grid power]
    O --> P[Truck distribution]
    P --> Q[Truck distribution step 2]
    Q --> R[Meal product]
    R --> S[Customer n]
    S --> T[Power]
    T --> U[Grid power]
    U --> V[Truck distribution]
    V --> W[Truck distribution step 1]
    W --> X[Meal product]
    X --> Y[Customer 1]
    Y --> Z[Power]
    Z --> AA[Grid power]
    AA --> AB[Truck distribution]
    AB --> AC[Truck distribution step 2]
    AC --> AD[Meal product]
    AD --> AE[Customer n]
    AE --> AF[Power]
    AF --> AG[Grid power]
    AG --> AH[Truck distribution]
    AH --> AI[Truck distribution step 1]
    AI --> AJ[Meal product]
    AJ --> AK[Customer 1]
    AK --> AL[Power]
    AL --> AM[Grid power]
    AM --> AN[Truck distribution]
    AN --> AO[Truck distribution step 2]
    AO --> AP[Meal product]
    AP --> AQ[Customer n]
    AQ --> AR[Power]
    AR --> AS[Grid power]
    AS --> AT[Truck distribution]
    AT --> AU[Truck distribution step 1]
    AU --> AV[Meal product]
    AV --> AW[Customer 1]
    AW --> AX[Power]
    AX --> AY[Grid power]
    AY --> AZ[Truck distribution]
    AZ --> BA[Truck distribution step 2]
    BA --> BB[Meal product]
    BB --> BC[Customer n]
    BC --> BD[Power]
    BD --> BE[Grid power]
    BE --> BF[Truck distribution]
    BF --> BG[Truck distribution step 1]
    BG --> BH[Meal product]
    BH --> BI[Customer 1]
    BI --> BJ[Power]
    BJ --> BK[Grid power]
    BK --> BL[Truck distribution]
    BL --> BM[Truck distribution step 2]
    BM --> BN[Meal product]
    BN --> BO[Customer n]
    BO --> BP[Power]
    BP --> BQ[Grid power]
    BQ --> BR[Truck distribution]
    BR --> BS[Truck distribution step 1]
    BS --> BT[Meal product]
    BT --> BU[Customer 1]
    BU --> BV[Power]
    BV --> BW[Grid power]
    BW --> BX[Truck distribution]
    BX --> BY[Truck distribution step 2]
    BY --> BZ[Meal product]
    BZ --> C1[Customer 1]
    C1 --> C2[Power]
    C2 --> C3[Grid power]
    C3 --> C4[Truck distribution]
    C4 --> C5[Truck distribution step 1]
    C5 --> C6[Meal product]
    C6 --> C7[Customer 1]
    C7 --> C8[Power]
    C8 --> C9[Grid power]
    C9 --> C10[Truck distribution]
    C10 --> C11[Truck distribution step 2]
    C11 --> C12[Meal product]
    C12 --> C13[Customer n]
    C13 --> C14[Power]
    C14 --> C15[Grid power]
    C15 --> C16[Truck distribution]
    C16 --> C17[Truck distribution step 1]
    C17 --> C18[Meal product]
    C18 --> C19[Customer 1]
    C19 --> C20[Power]
    C20 --> C21[Grid power]
    C21 --> C22[Truck distribution]
    C22 --> C23[Truck distribution step 2]
    C23 --> C24[Meal product]
    C24 --> C25[Customer n]
    C25 --> C26[Power]
    C26 --> C27[Grid power]
    C27 --> C28[Truck distribution]
    C28 --> C29[Truck distribution step 1]
    C29 --> C30[Meal product]
    C30 --> C31[Customer 1]
    C31 --> C32[Power]
    C32 --> C33[Grid power]
    C33 --> C34[Truck distribution]
    C34 --> C35[Truck distribution step 2]
    C35 --> C36[Meal product]
    C36 --> C37[Customer n]
    C37 --> C38[Power]
    C38 --> C39[Grid power]
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    C40 --> C41[Truck distribution step 1]
    C41 --> C42[Meal product]
    C42 --> C43[Customer 1]
    C43 --> C44[Power]
    C44 --> C45[Grid power]
    C45 --> C46[Truck distribution]
    C46 --> C47[Truck distribution step 2]
    C47 --> C48[Meal product]
    C48 --> C49[Customer n]
    C49 --> C50[Power]
    C50 --> C51[Grid power]
    C51 --> C52[Truck distribution]
    C52 --> C53[Truck distribution step 1]
    C53 --> C54[Meal product]
    C54 --> C55[Customer 1]
    C55 --> C56[Power]
    C56 --> C57[Grid power]
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    C58 --> C59[Truck distribution step 2]
    C59 --> C60[Meal product]
    C60 --> C61[Customer n]
    C61 --> C62[Power]
    C62 --> C63[Grid power]
    C63 --> C64[Truck distribution]
    C64 --> C65[Truck distribution step 1]
    C65 --> C66[Meal product]
    C66 --> C67[Customer 1]
    C67 --> C68[Power]
    C68 --> C69[Grid power]
    C69 --> C70[Truck distribution]
    C70 --> C71[Truck distribution step 2]
    C71 --> C72[Meal product]
    C72 --> C73[Customer n]
    C73 --> C74[Power]
    C74 --> C75[Grid power]
    C75 --> C76[Truck distribution]
    C76 --> C77[Truck distribution step 1]
    C77 --> C78[Meal product]
    C78 --> C79[Customer 1]
    C79 --> C80[Power]
    C80 --> C81[Grid power]
    C81 --> C82[Truck distribution]
    C82 --> C83[Truck distribution step 2]
    C83 --> C84[Meal product]
    C84 --> C85[Customer n]
    C85 --> C86[Power]
    C86 --> C87[Grid power]
    C87 --> C88[Truck distribution]
    C88 --> C89[Truck distribution step 1]
    C89 --> C90[Meal product]
    C90 --> C91[Customer 1]
    C91 --> C92[Power]
    C92 --> C93[Grid power]
    C93 --> C94[Truck distribution]
    C94 --> C95[Truck distribution step 2]
    C95 --> C96[Meal product]
    C96 --> C97[Customer n]
    C97 --> C98[Power]
    C98 --> C99[Grid power]
    C99 --> C100[Truck distribution]
    C100 --> C101[Truck distribution step 1]
    C101 --> C102[Meal product]
    C102 --> C103[Customer 1]
    C103 --> C104[Power]
    C104 --> C105[Grid power]
    C105 --> C106[Truck distribution]
    C106 --> C107[Truck distribution step 2]
    C107 --> C108[Meal product]
    C108 --> C109[Customer n]
    C109 --> C110[Power]
    C110 --> C111[Grid power]
    C111 --> C112[Truck distribution]
    C112 --> C113[Truck distribution step 1]
    C113 --> C114[Meal product]
    C114 --> C115[Customer 1]
    C115 --> C116[Power]
    C116 --> C117[Grid power]
    C117 --> C118[Truck distribution]
    C118 --> C119[Truck distribution step 2]
    C119 --> C120[Meal product]
    C120 --> C121[Customer n]
    C121 --> C122[Power]
    C122 --> C123[Grid power]
    C123 --> C124[Truck distribution]
    C124 --> C125[Truck distribution step 1]
    C125 --> C126[Meal product]
    C126 --> C127[Customer 1]
    C127 --> C128[Power]
    C128 --> C129[Grid power]
    C129 --> C130[Truck distribution]
    C130 --> C131[Truck distribution step 2]
    C131 --> C132[Meal product]
    C132 --> C133[Customer n]
    C133 --> C134[Power]
    C134 --> C135[Grid power]
    C135 --> C136[Truck distribution]
    C136 --> C137[Truck distribution step 1]
    C137 --> C138[Meal product]
    C138 --> C139[Customer 1]
    C139 --> C140[Power]
    C140 --> C141[Grid power]
    C141 --> C142[Truck distribution]
    C142 --> C143[Truck distribution step 2]
    C143 --> C144[Meal product]
    C144 --> C145[Customer n]
    C145 --> C146[Power]
    C146 --> C147[Grid power]
    C147 --> C148[Truck distribution]
    C148 --> C149[Truck distribution step 1]
    C149 --> C150[Meal product]
    C150 --> C151[Customer 1]
    C151 --> C152[Power]
    C152 --> C153[Grid power]
    C153 --> C154[Truck distribution]
    C154 --> C155[Truck distribution step
```

A horizontal bar chart comparing the environmental impact scores for two scenarios, A and B, across nine categories. The x-axis represents a score from 0 to 120. Scenario B is represented by dark red bars and Scenario A by light blue bars. The categories are listed on the y-axis. The scores for each category are as follows:

Category	Scenario B (Dark Red)	Scenario A (Light Blue)
Global warming	55	22
Acidification	35	12
Photochemical ozone formation	30	10
Nutrient enrichment	45	30
Human toxicity	45	110
Ecotoxicity	20	45
Land use	10	35
Volume waste	30	8
Hazardous waste	10	12

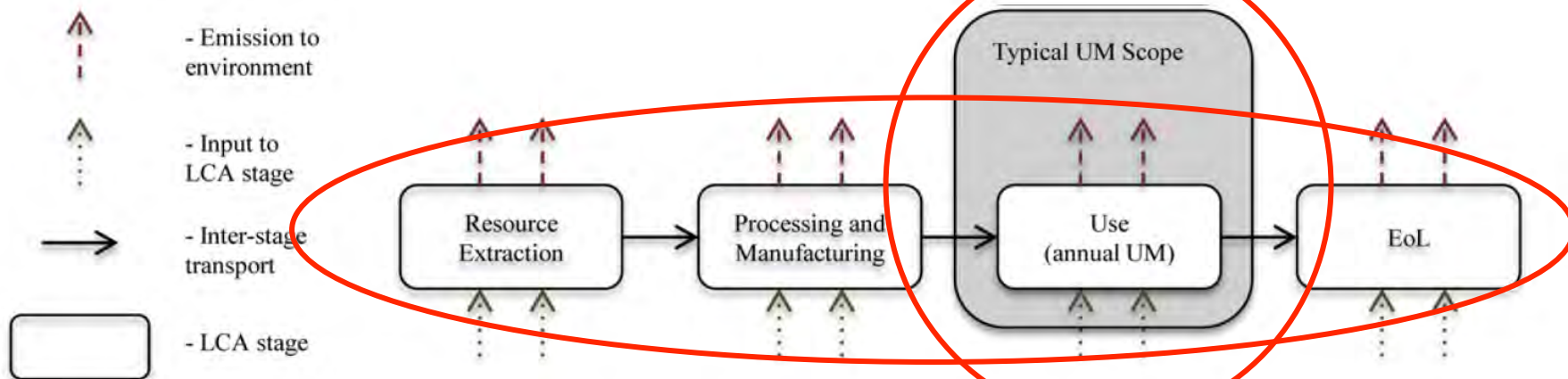
PEweu94

# Classic Urban Metabolism (UM)



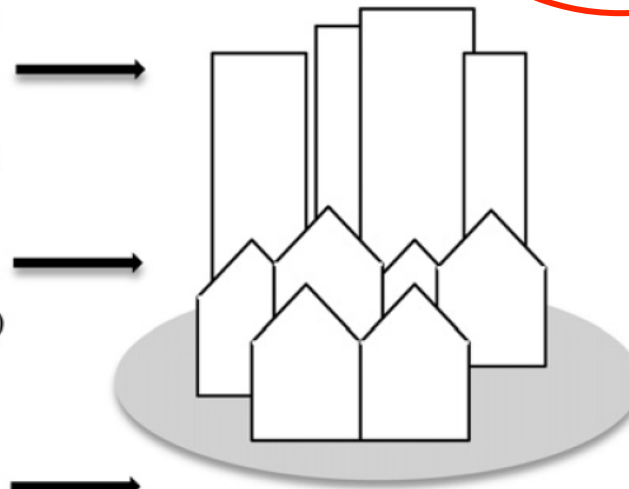
*Duvigneaud and Denaeyer-De Smet (1977)*

# Coupling of Urban Metabolism and LCA (UM-LCA)



**Food:** vegetables, fruits, meat, fish, oils, sugar, tea, dairy, grains  
**Water:** residential, commercial, industrial  
**Transport Fuels:** gasoline, diesel  
**Building Energy:** electricity, thermal energy: coal, coke, kerosene, natural gas, fuel oil (heavy and light)  
**Metals:** steel, aluminum  
**Plastics:** polyethylene terephthalate, polystyrene, polypropylene, polyethylene (high and low density)  
**Paper:** newsprint, cardboard  
**Glass:** clear, green, brown packaging  
**Rubber:** natural and synthetic  
**Electronics:** white goods (stoves, fridges, etc.), consumer electronics (laptops, stereos, etc.), batteries  
**Construction Materials:** wood, concrete

*Metabolic Flows*



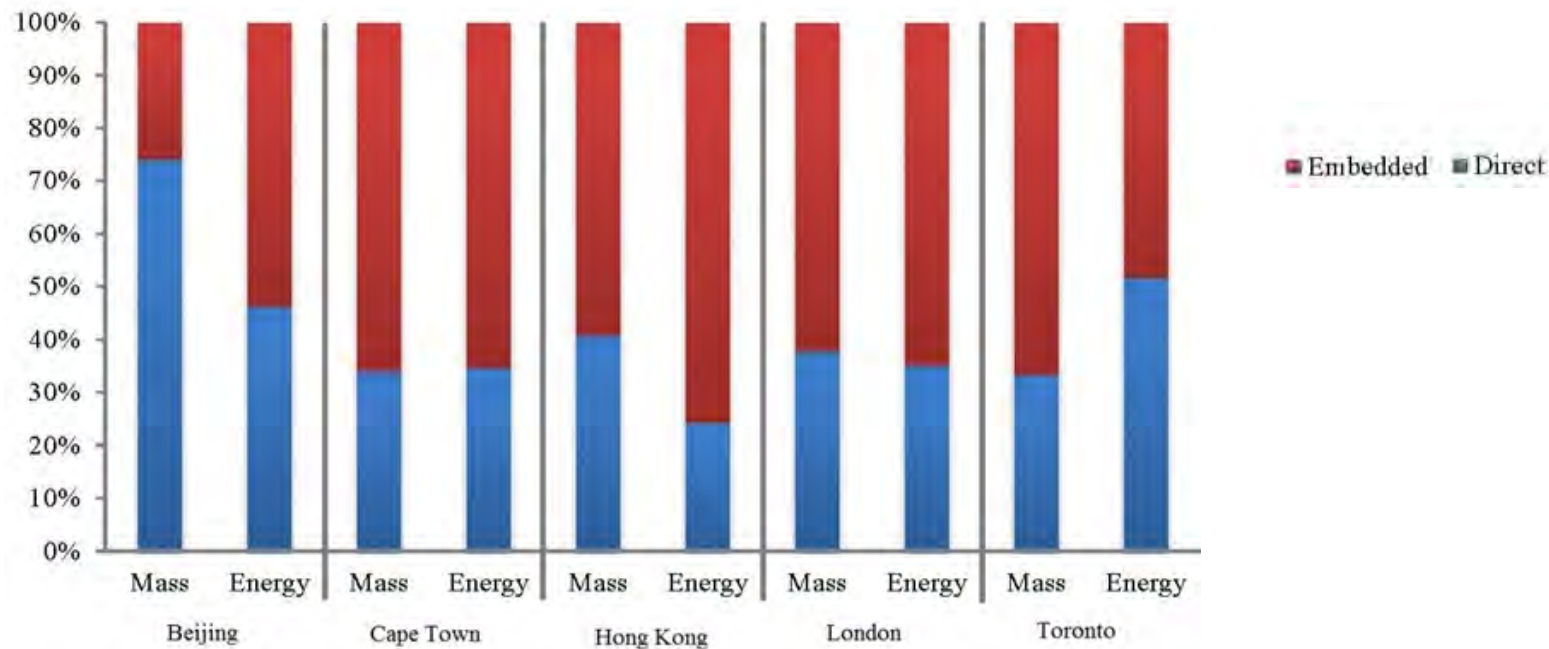
*Urban Area*

**Global Warming Potential**  
**Freshwater Ecotoxicity**  
**Agricultural Land Occupation**  
**Particulate Matter Formation**

*Environmental Stresses (midpoint indicators)*

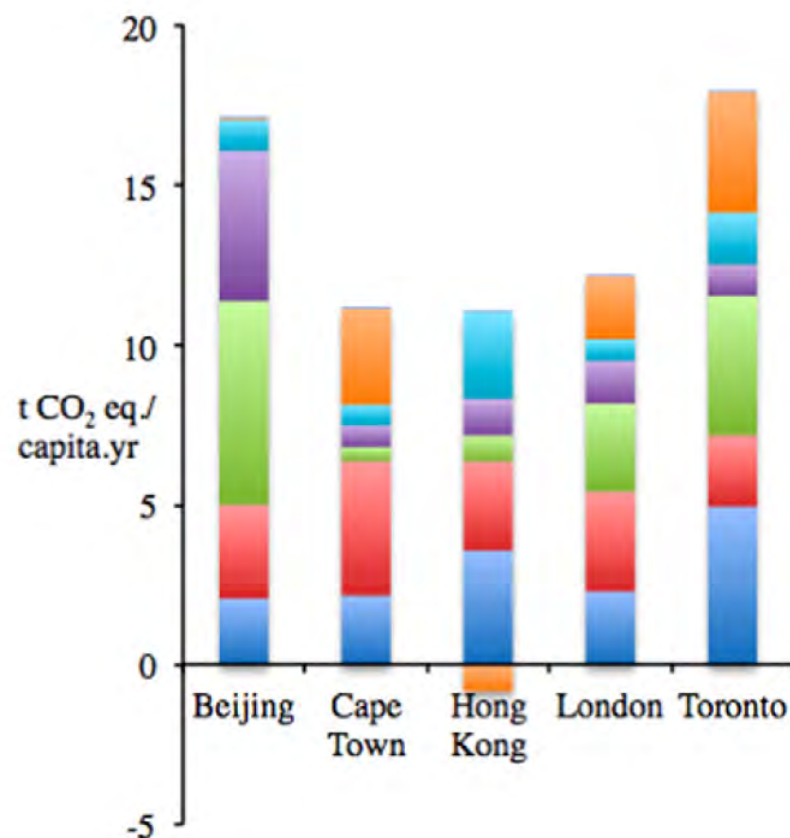
# UM-LCA – Case cities and mass flows

City (year modeled)	Beijing (2006)	Cape Town (1997)	Hong Kong (1997)	London (2000)	Toronto (1999)
Population ( $10^6$ )	17.07	3.04	6.62	7.40	5.07
Population density (residents/km <sup>2</sup> )	1016	1239	6480	4978	858
Gross domestic product ( $10^9$ Year 2000 United States Dollars)	85.2	18.9	169	211	165
Human development index	0.633	0.616	0.824	0.833	0.879
Average daily temperature (°C)	12	17	23	11	9



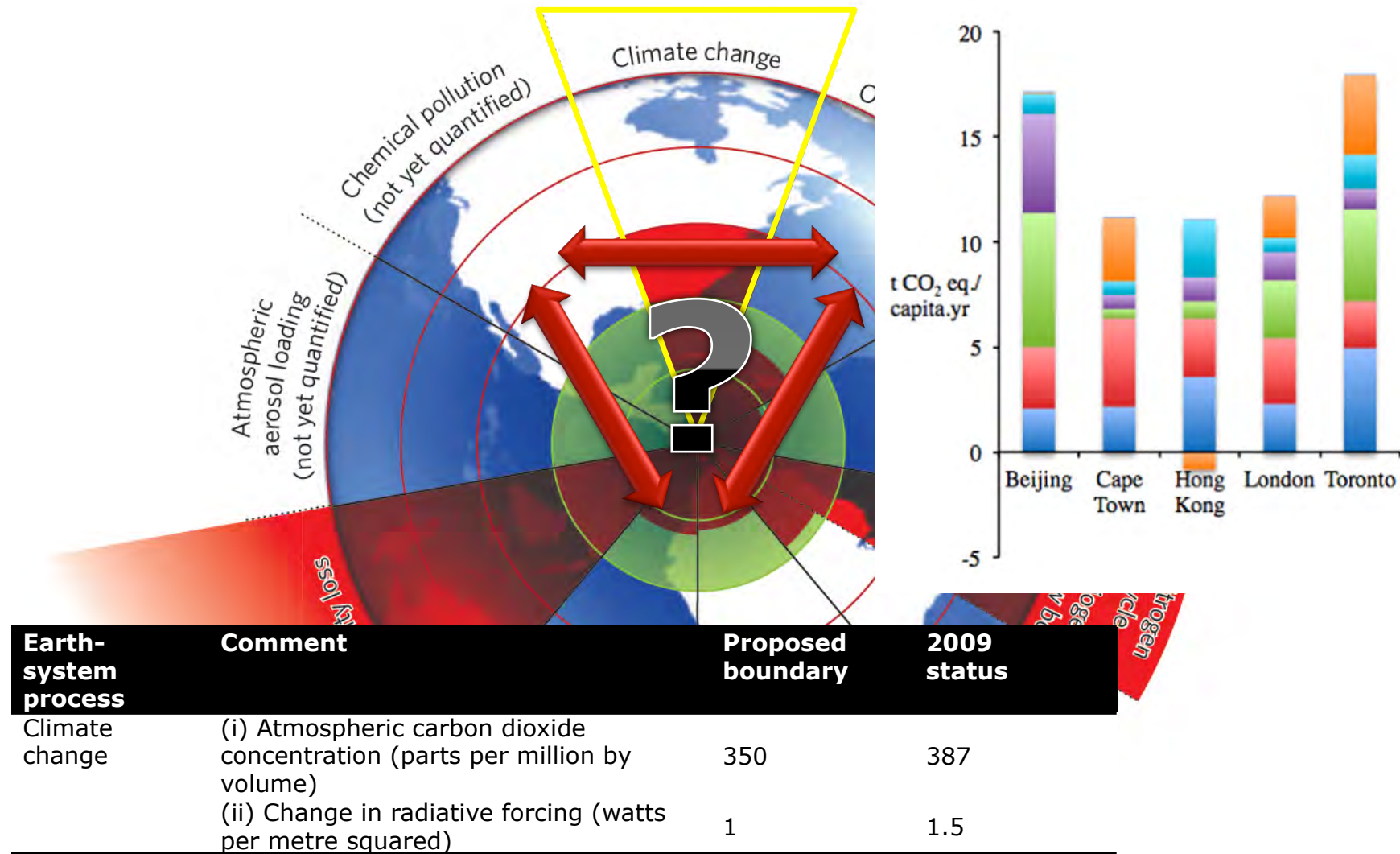
From: Goldstein et al. (2013)

# UM-LCA – Impact indicators



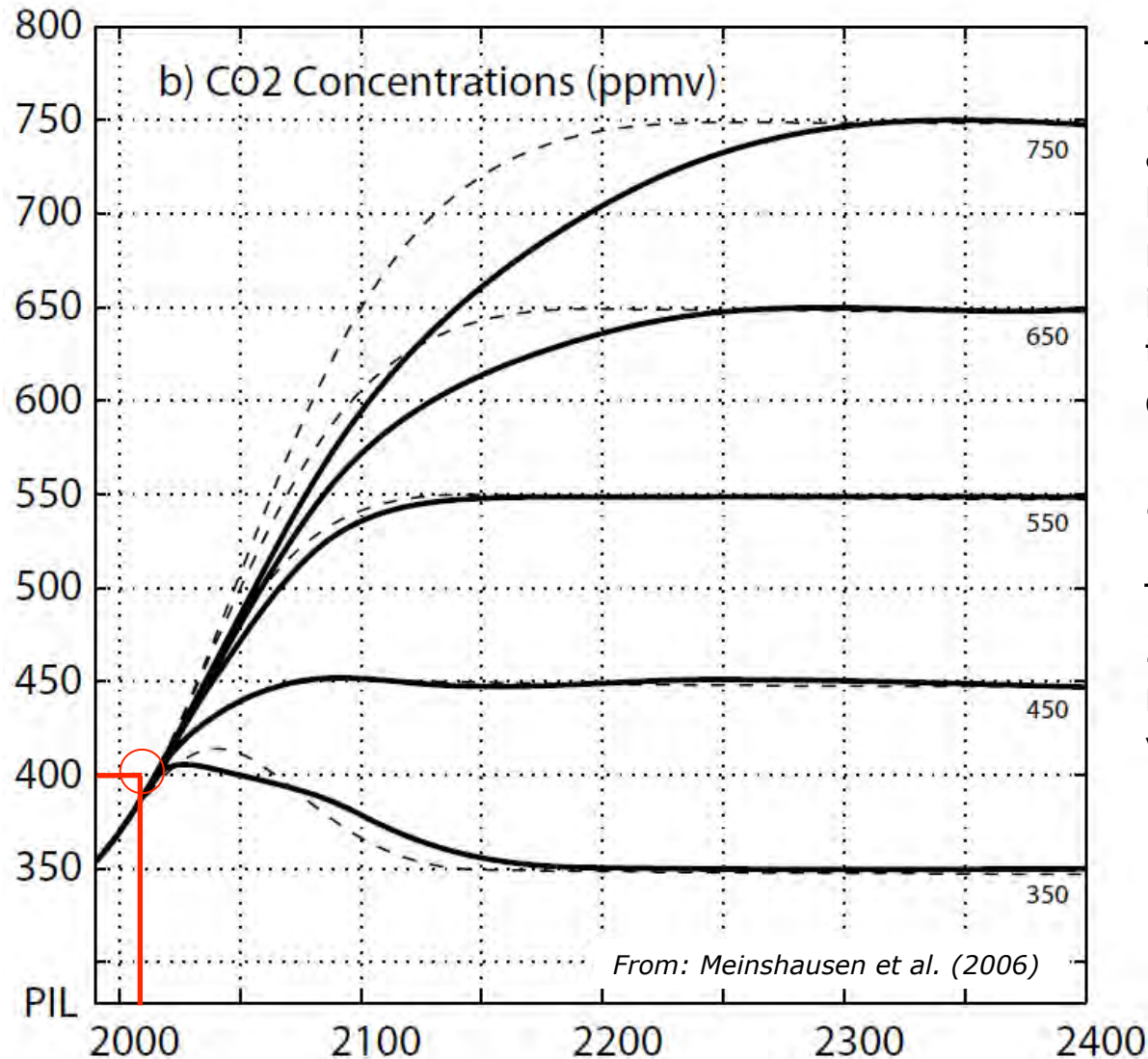
From: Goldstein et al. (2013)

# Absolute sustainability



From: Rockström et al. (2009)

# Relating CO<sub>2</sub> emissions to atmospheric CO<sub>2</sub> concentrations



To reach below 350 ppm (again) around 2100 with app. 75 % propability and hence keeping the global mean-temperature increase below 2C° realtive to PIL means cutting emissions to 60 % of the 1990 emissios levels by 2050

The global emissions in 2050 should amount to maximum 14.4 GtCO<sub>2</sub>-eq/ year

# Urban sustainability performance relative to planetary boundaries



City	Population (millions)	GDP (billions Year 2000 USD)
Beijing (2006)	17.1	85.2
Cape Town (1997)	3.0	18.9
Hong Kong (1997)	6.6	169
London (2000)	7.4	211
Toronto (1999)	5.07	160

Allocation of CO<sub>2</sub> emissions 14.4 GtCO<sub>2</sub>-eq/year assuming unaltered population and GDP development trends:

**Egalitarian:** Equal allocation per person (world population 6.188 billion people in 2000)

**Individualist:** Equal allocation per dollar GDP (world GDP in 2000 of 32,334 billion US \$ )

	Beijing	Cape Town	Hong Kong	London	Toronto
Contribution to GWP [Mt CO <sub>2</sub> -eq/year]	291.9	34.1	67.5	90.3	91.3
Emission reduction needed by 2050 - egalitarian allocation of CO <sub>2</sub> boundary quotas (%)	86.2	79.0	76.9	80.7	86.9
Emission reduction needed by 2050 - individualist allocation of CO <sub>2</sub> boundary quotas (%)	87.0	75.3	-11.5	-4.1	21.9

# Conclusions

- Fusing urban metabolism and life cycle assessment enables and facilitates inclusion of up- and downstream processes in the assessment of urban systems
- Fusing urban metabolism and life cycle assessment enables comparison of sustainability performance of urban systems by relying on a ISO standardized assessment methodology and a wide pallet of impact/performance indicators
- Relying on a broad/holistic set of impact indicators lowers the chance of shuffling impacts among impact categories
- Recent published absolute measures for sustainable development can be applied in combination with the fused UM-LCA approach
- The absolute sustainability performace of urban cities are not solely controlled by the actual environmental performance of the cities but also the way the absolute sustainability measures are distributed