Ecole polytechnique fédérale de Lausanne EPFL
School of Architecture, Civil and Environmental Engineering ENAC
ENAC - Environmental Science and Engineering Section ENAC-SSIE

Dynamic MFA Modelling Background and Examples

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Socio-economic metabolism

Energy and material use of society

Why bother about energy and materials?

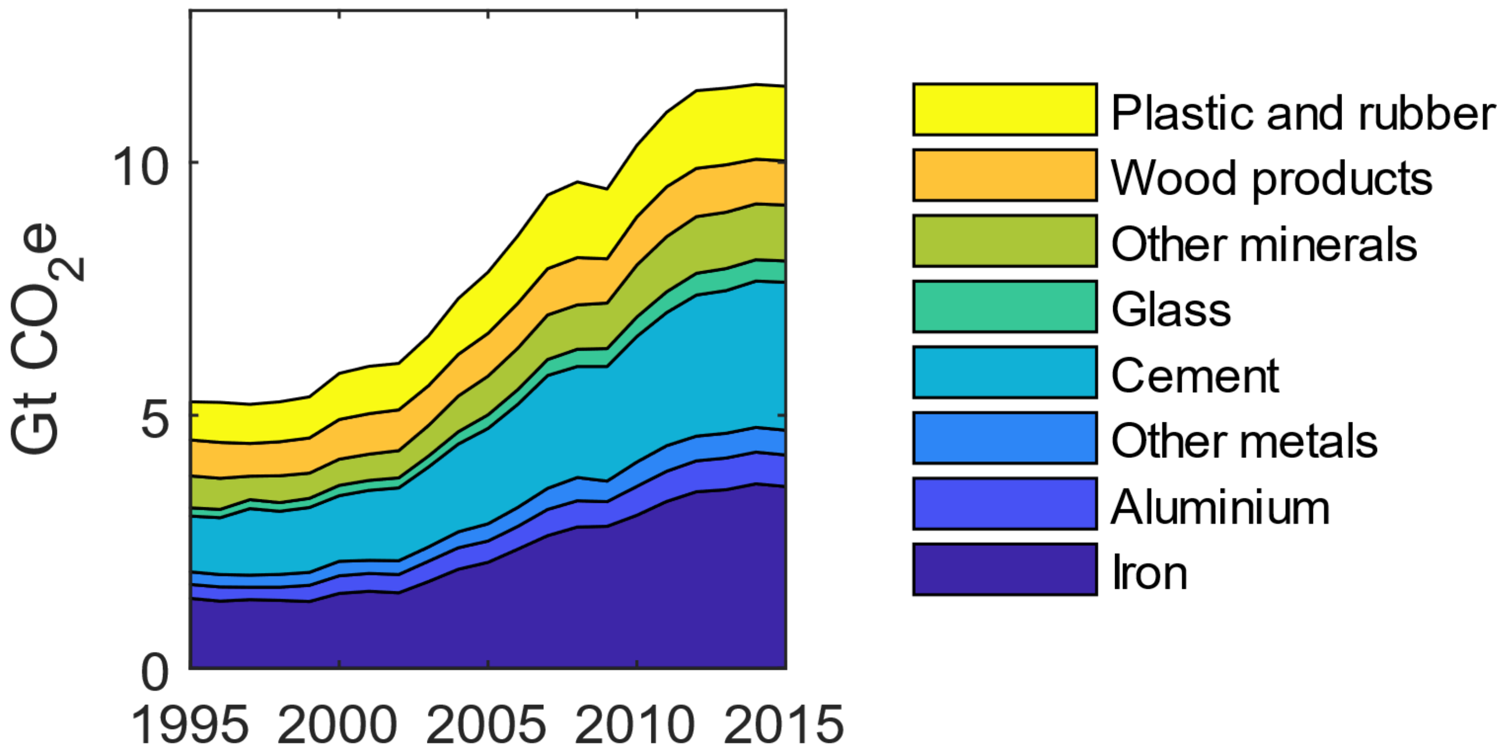
- They provide services to people (thermal comfort, transportation, nutrition, …).
- Thus, they are prerequisites for human well-being (social dim. of sustainability)
- Are related to resource depletion and emissions into the environment (environmental dimension of sustainability).
- Are the components of all material economic goods and processes (economic dim.)





→ **No sustainability withouth proper management of materials and energy!**

Emissions from material production emerge as major bottleneck to curbing global warming to well below 2°C



- Emissions from producing materials have increased from 5 billion tons CO_2eq in 1995 to 12 Gt in 2015
- With their share in global emissions rising from 15% to 23%.
- Iron&steel, cement, and plastics are three largest contributors

Source: Hertwich, 2019, DOI 10.31235/osf.io/n9ecw

Services need physical input: energy, materials, land, …

Supply chains and environmental impacts

Supply chains and environmental impacts

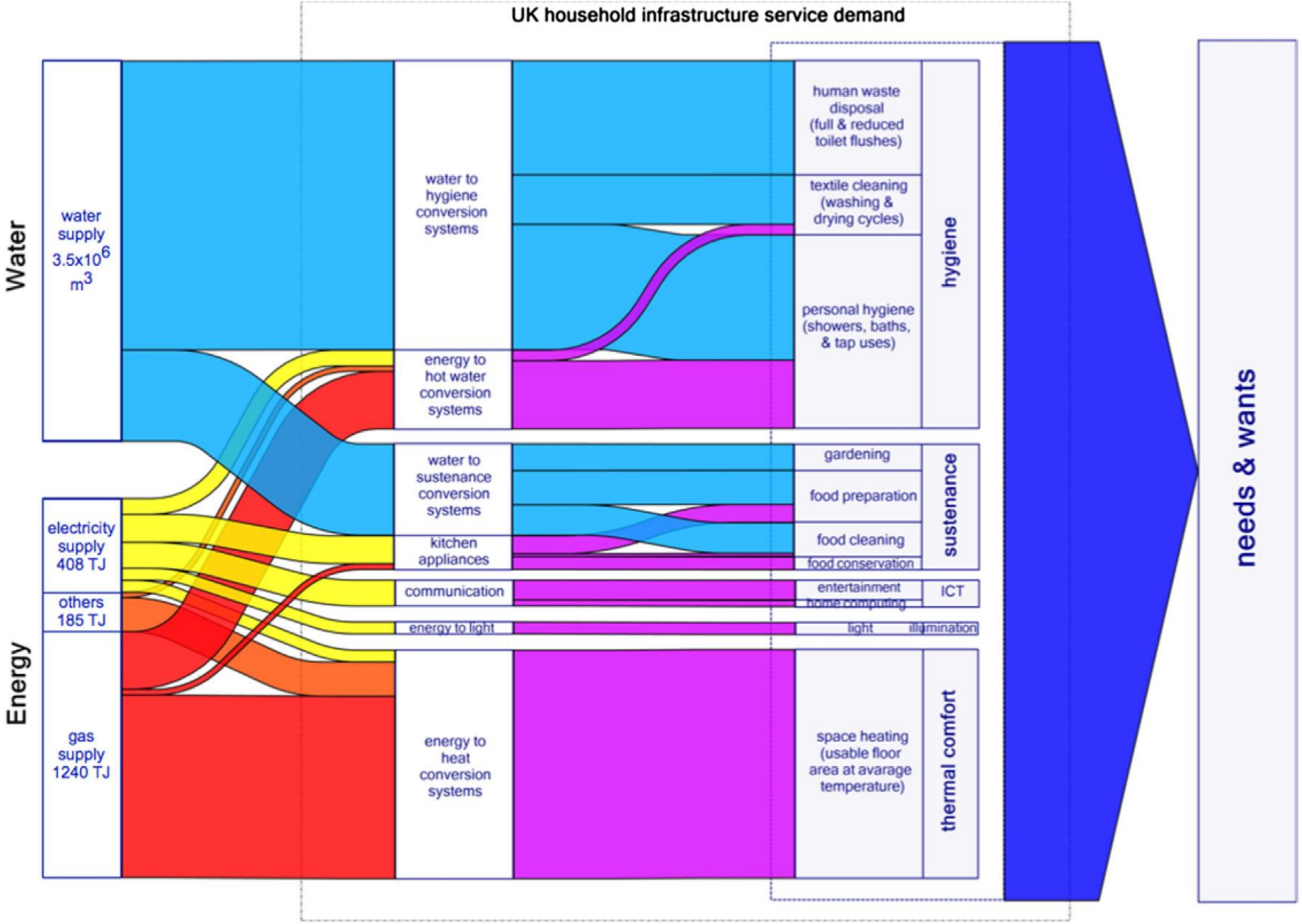
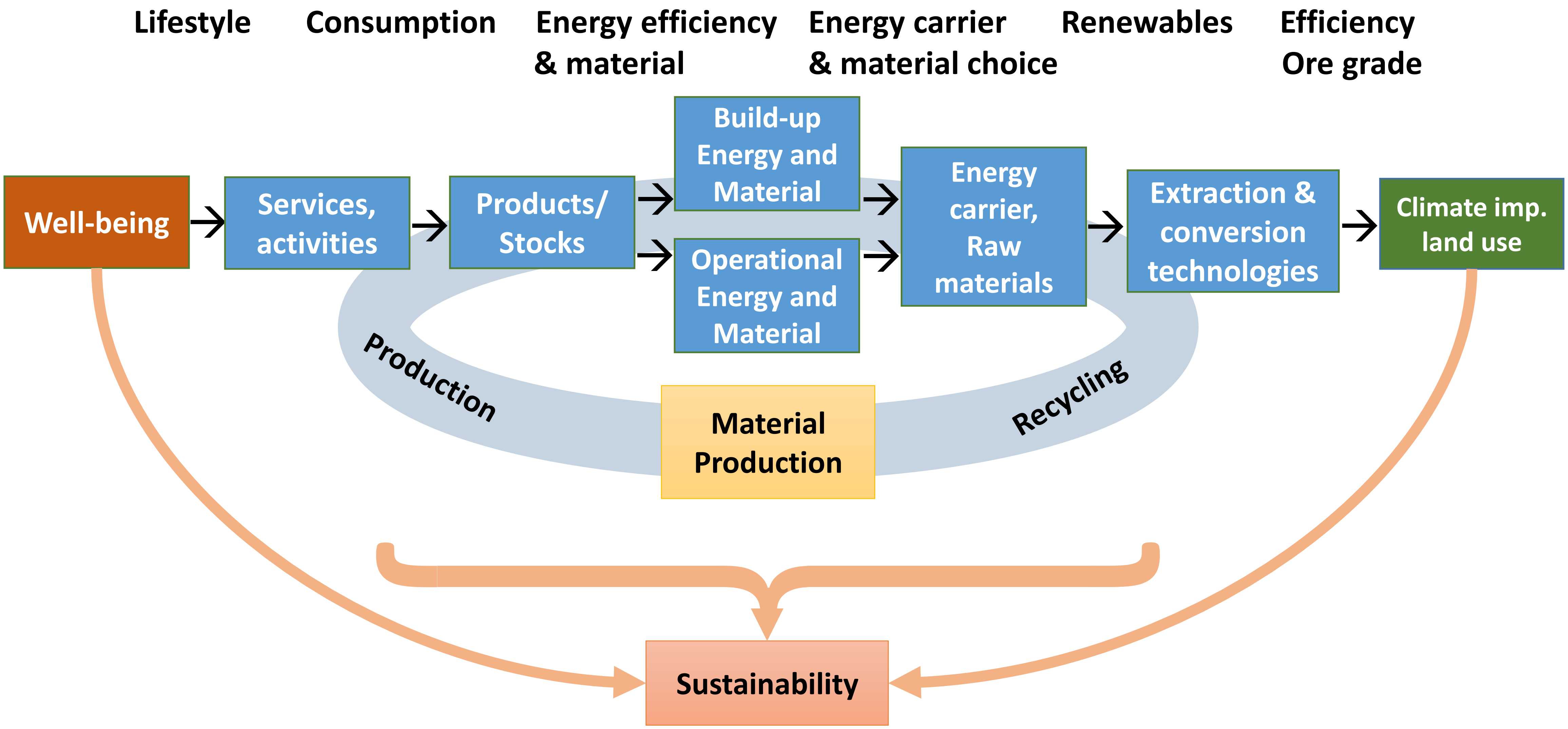


Figure shows household-based services only, scope: UK (e.g., no cooling for thermal comfort).

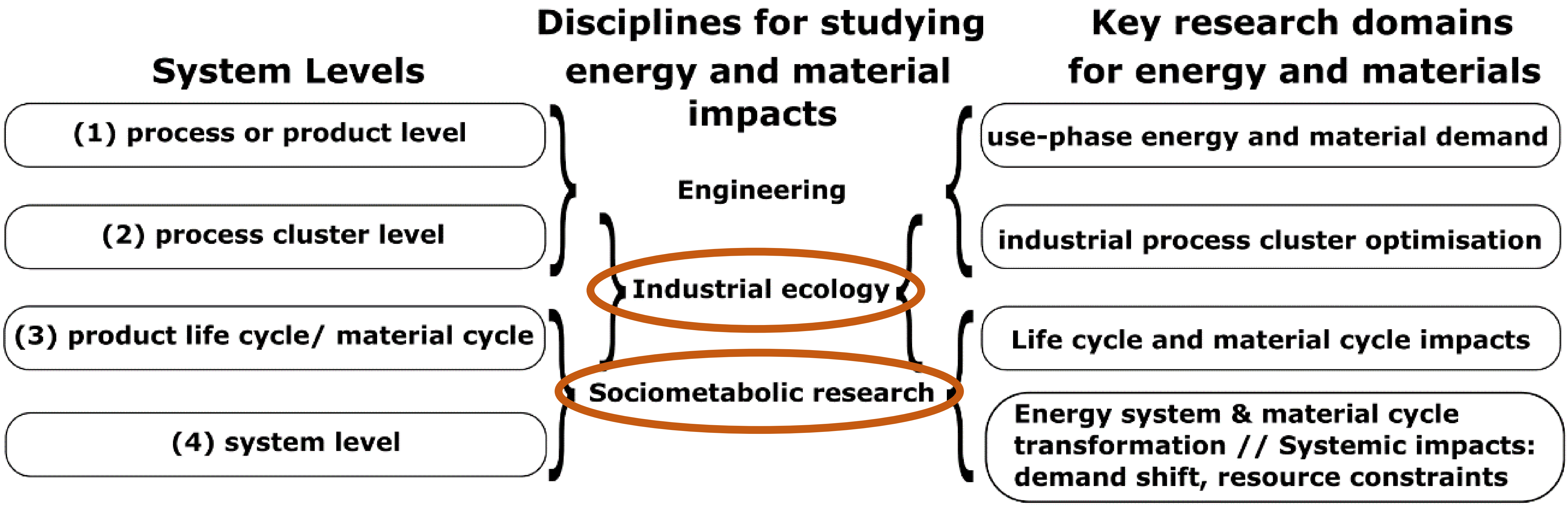
Source: Knoeri, Steinberger, and Roelich, 2016, DOI: 10.1016/j.jclepro.2015.08.079

Overarching framework: The material and energy service cascade (ESC) and the service-stock-flow nexus (SFSN)



Source: Bergsdal et al. (2007), DOI 10.1080/09613210701287588; Kalt et al. (2019), DOI 10.1016/j.erss.2019.02.026; Haberl et al. (2017), DOI 10.3390/su9071049

Scientific fields to study energy and material impacts of the sustainability transformation



Many solutions at the product/technology level … We study the system effects!

Source: Pauliuk et al. 2022, https://doi.org/10.1016/j.jclepro.2022.130997

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Dynamic MFA
Basic principles

Principle I: The Service-Stock-Flow Nexus

Human well-being (hedonic/eudaimonic)

↓

Services (physical) (shelter, mobility, communication, …)

↓

In-use stocks (homes, cars, infrastructure, …)

↓

Operational flows (energy to operate, maintenance materials)

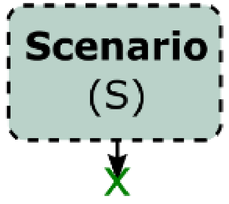
Build-up flows (New products to expand stock and replace old products)

↓

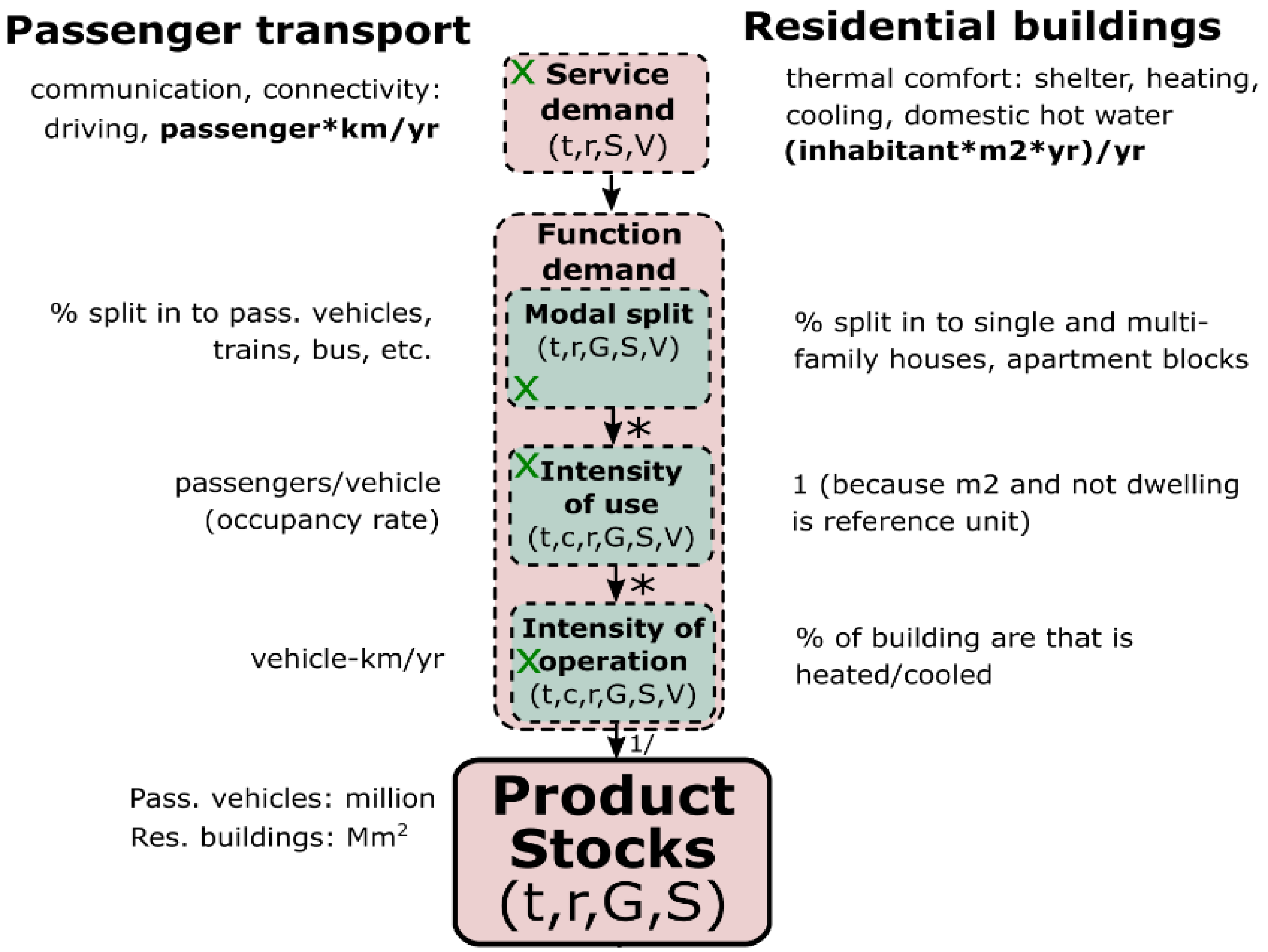
Energy & material supply

Source: Haberl et al. (2017), DOI 10.3390/su9071049

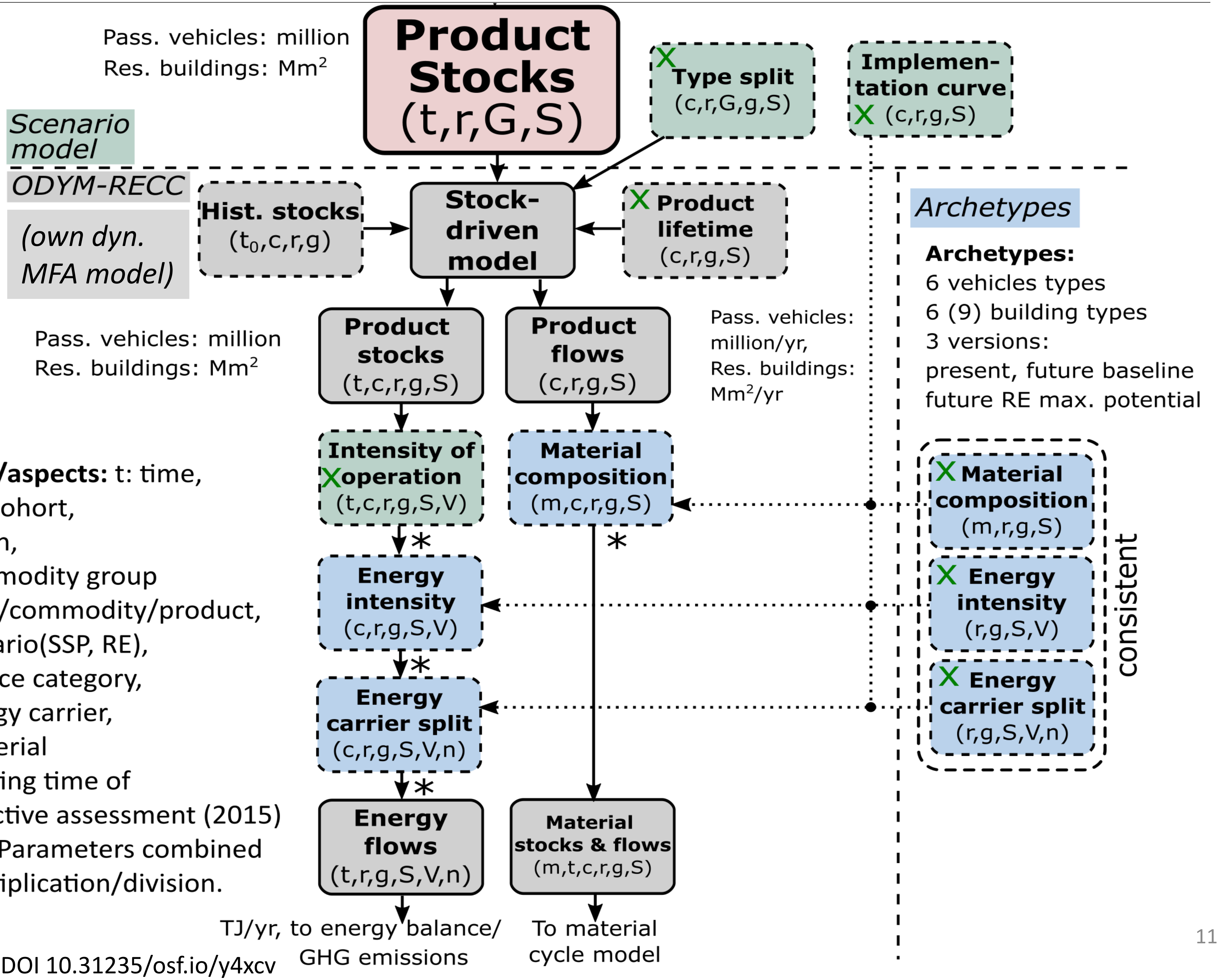
Central Linkage: The Service-Stock-Flow Nexus as part of the Energy Service Cascade



- Services are linked to wellbeing
- Stocks provide services
- Materials are needed to build up and maintain product stocks



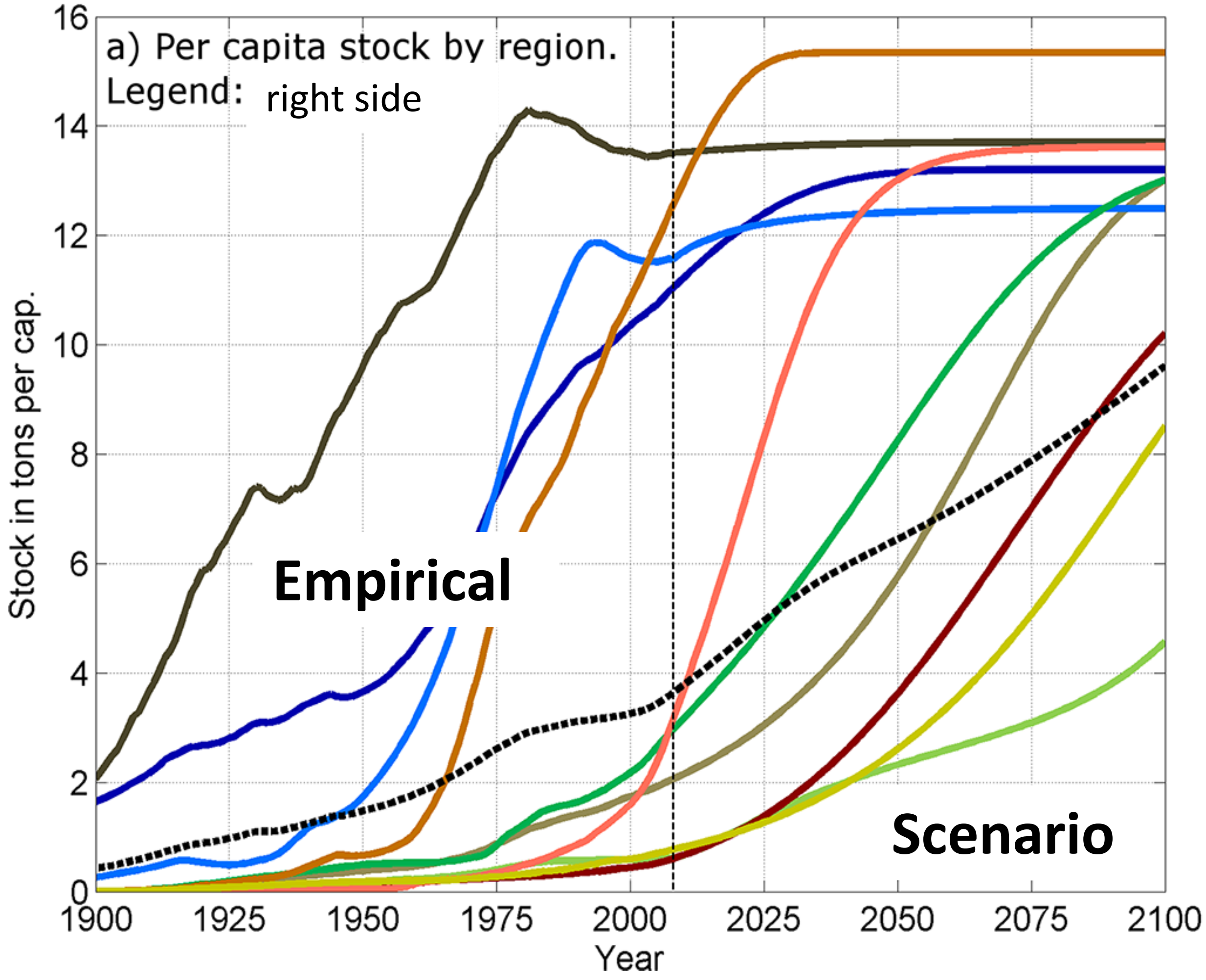
Product stocks -> material Cycles -> energy demand

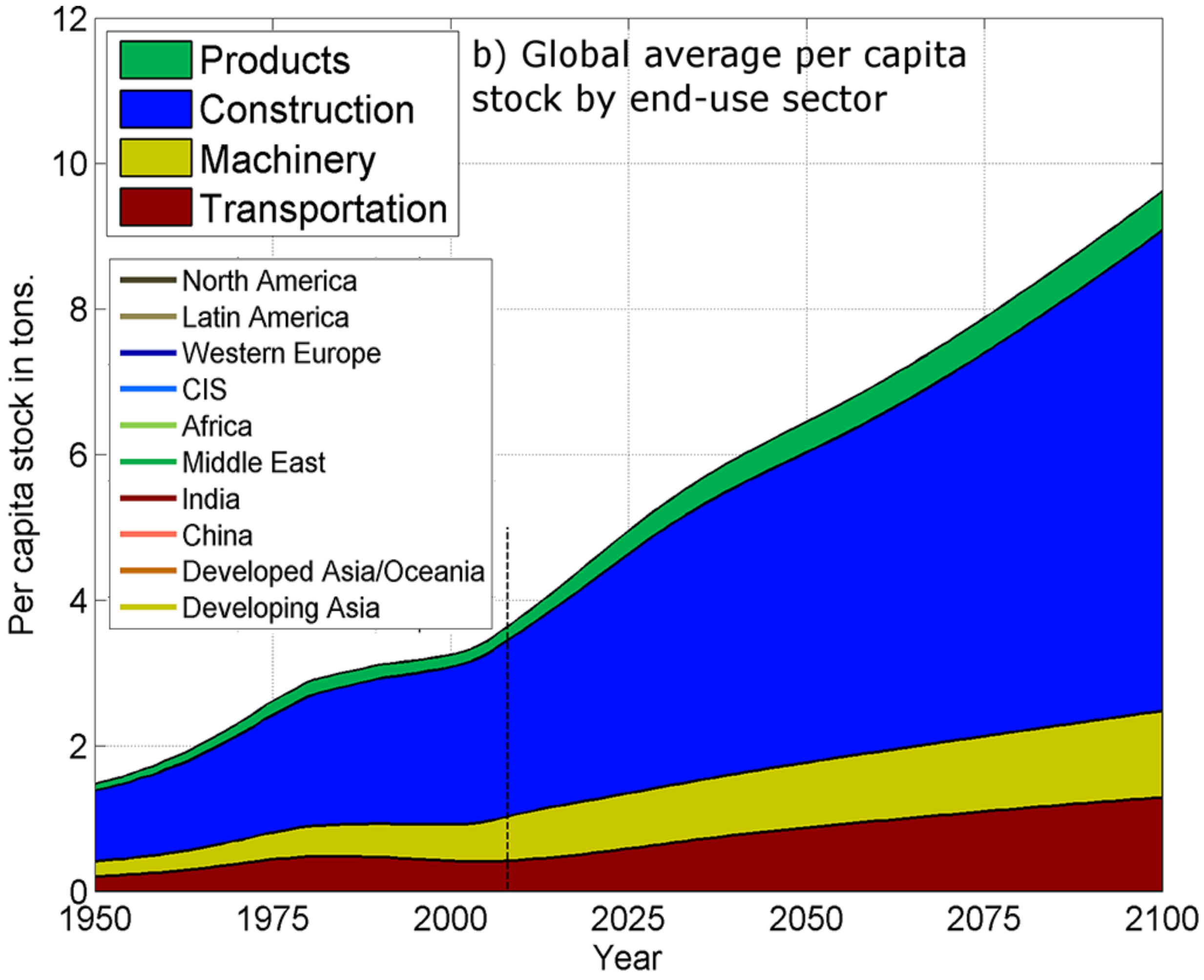


Indices/aspects: t: time,
c: age-cohort,
r: region,
G: commodity group
g: good/commodity/product,
S: scenario(SSP, RE),
V: service category,
n: energy carrier,
m: material
t_0: starting time of prospective assessment (2015)
(*, 1/): Parameters combined by multiplication/division.

Source: ODYM-RECC v2.2 model docu, DOI 10.31235/osf.io/y4xcv

Historic and suggested future per capita stocks based on stock saturation hypothesis





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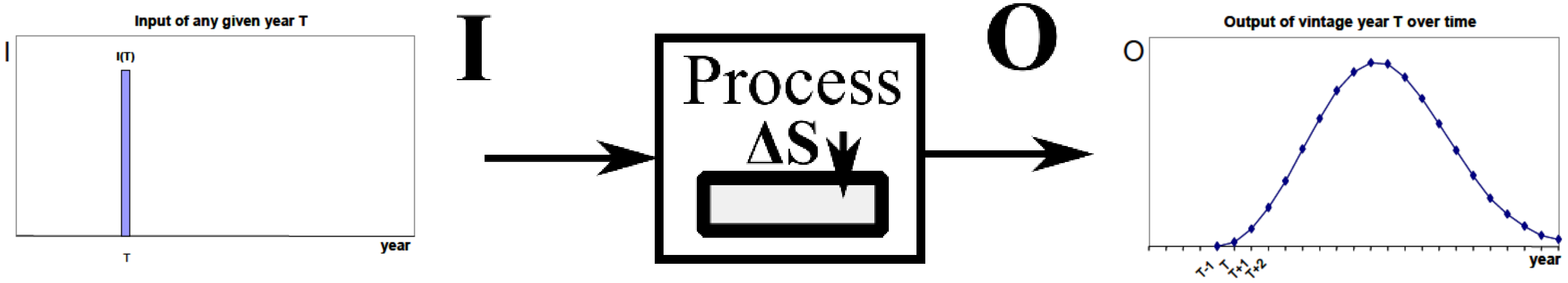
Principle II: In-Use-Stock Dynamics – Three Central Equations



1. Lifetime model: $$O(t) = \sum_{t_0}^{t} I(\tau) \cdot pf(t-\tau)$$

2. Use phase mass balance: $$I(t) = \Delta S(t) + O(t)$$

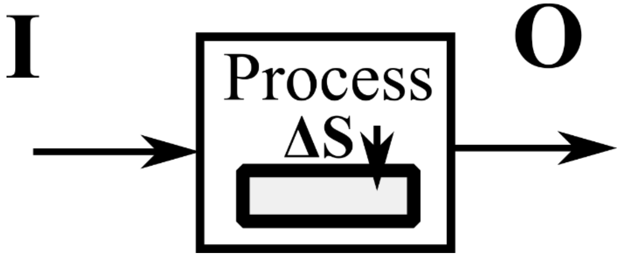
3. System mass balance: Primary production $P(t) = \Delta S(t) + L(t)$

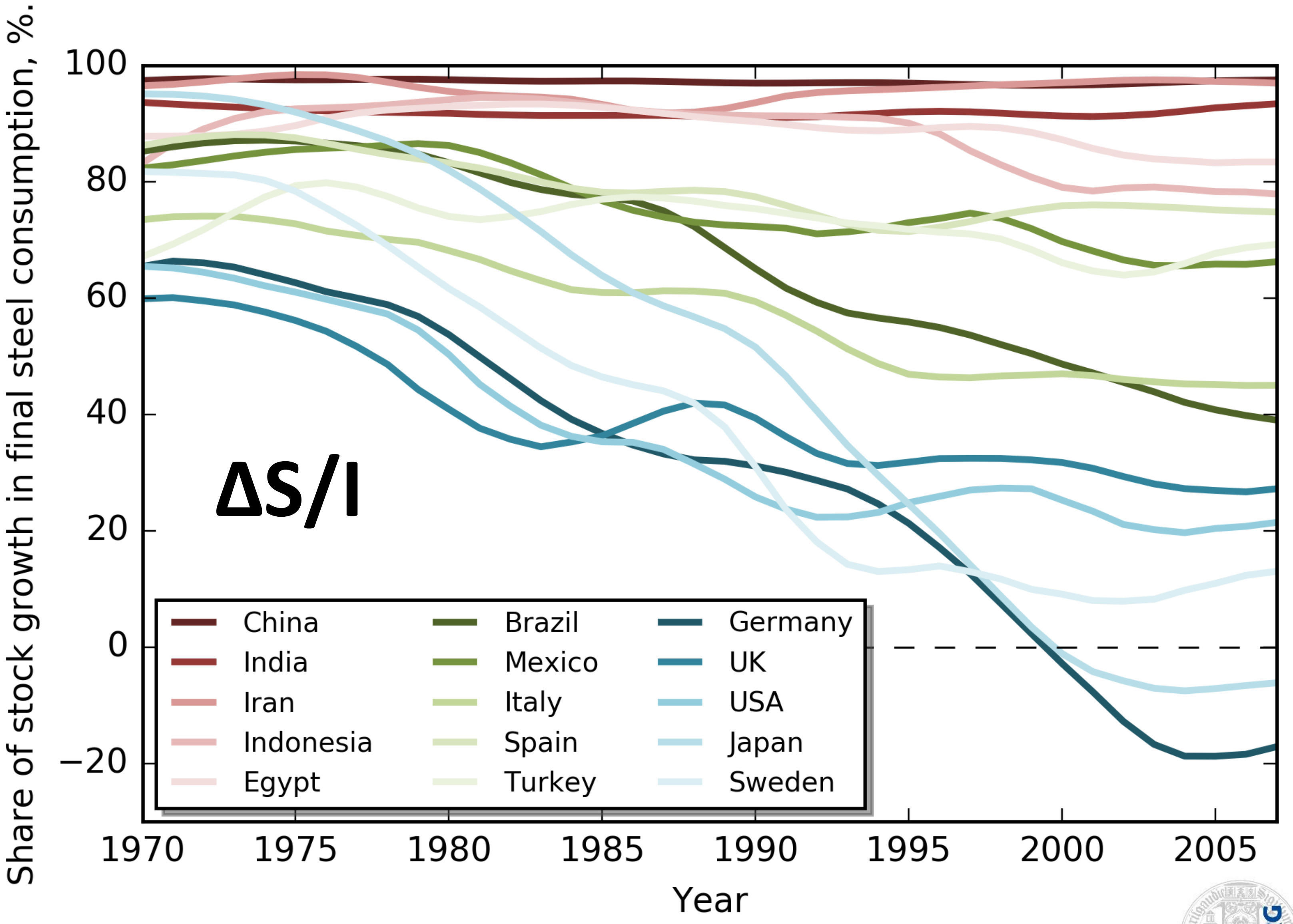
(L: total losses)

Circular economy - Material consumption and stock expansion

From the mass balance of the use phase, one finds that the final material consumption I always has two components: replacement of outflow O and stock expansion ΔS:

I = ΔS + O





Source: Pauliuk (2018), DOI 10.1016/j.resconrec.2017.10.019

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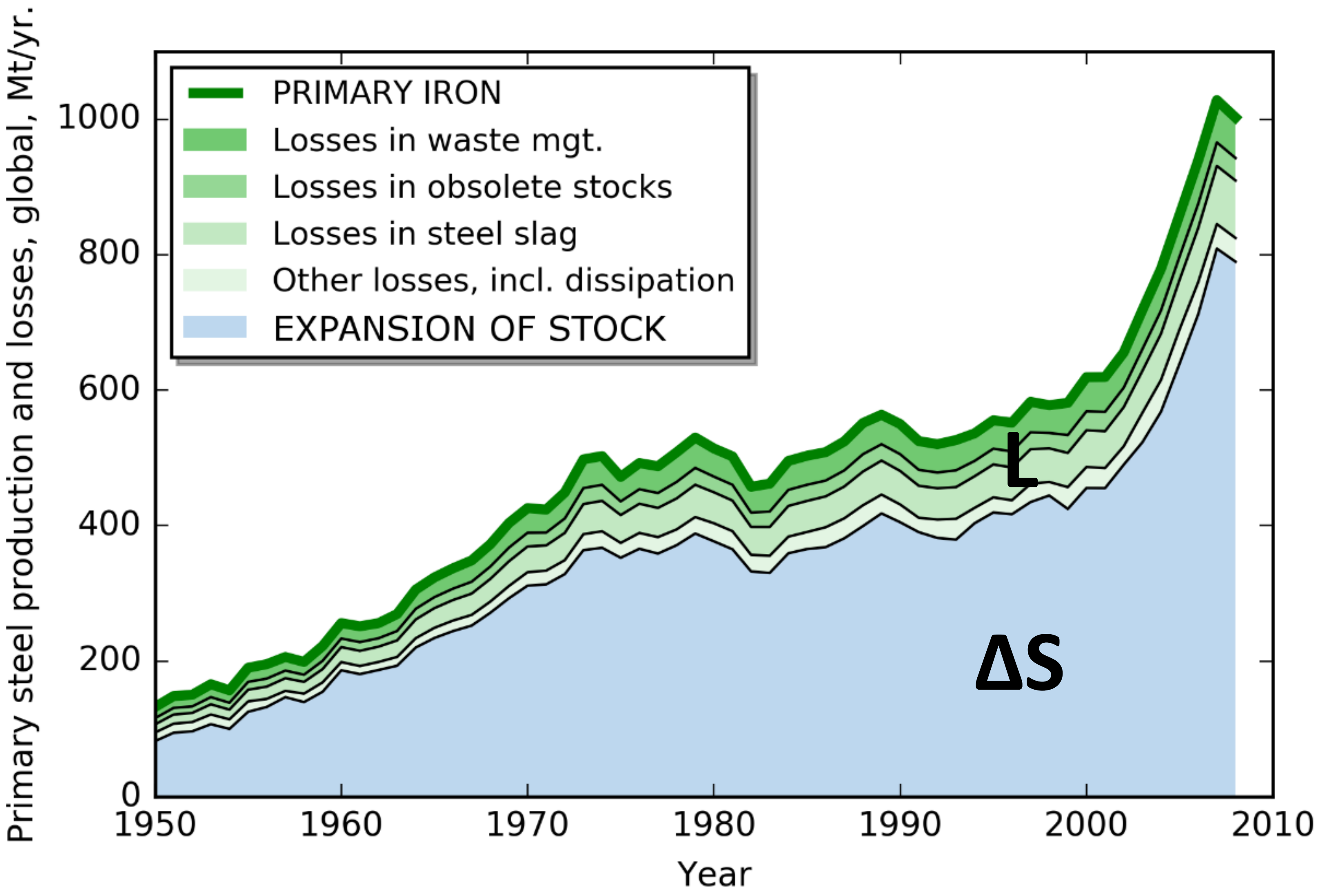
Circular economy - Primary production and stock growth

At the global scale, a entire material cycle has the following mass balance:

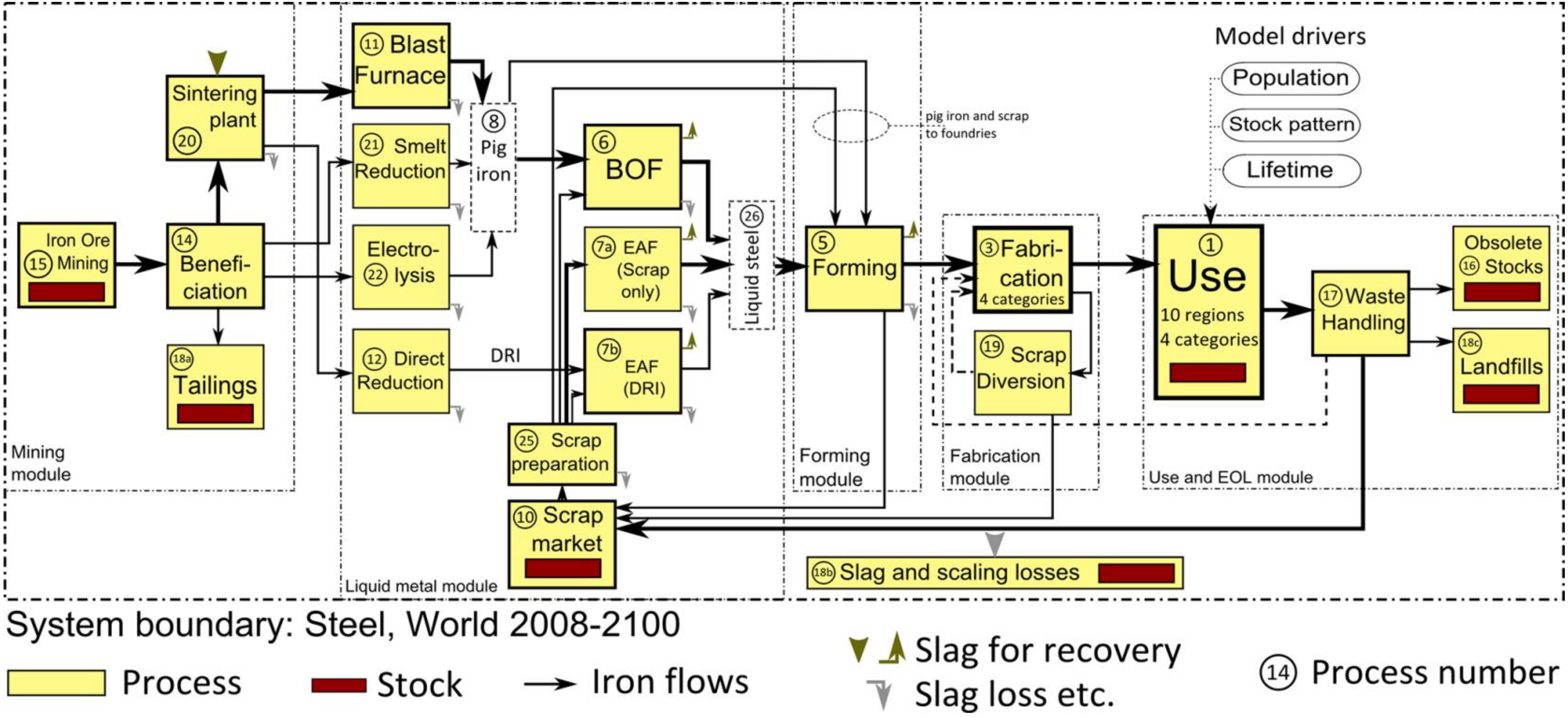
$$P = \Delta S + L$$

Primary production P is either replacing system-wide losses L or contributing to stock expansion ΔS.



Source: Pauliuk (2018), DOI 10.1016/j.resconrec.2017.10.019

Principle III: Mass-balanced material cycle modelling



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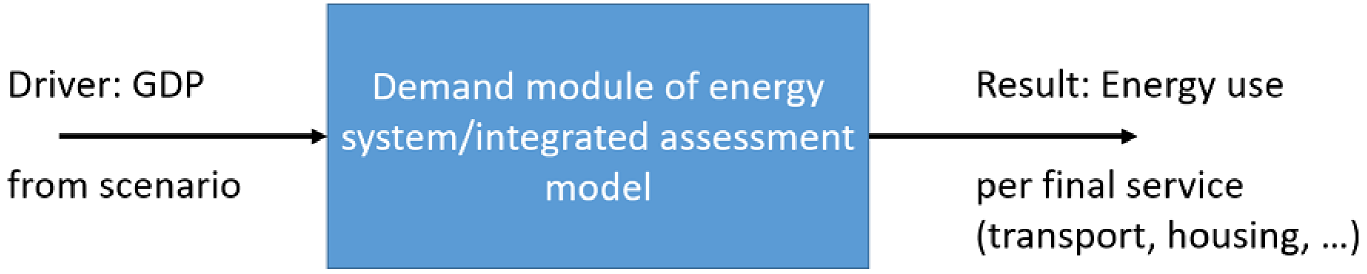
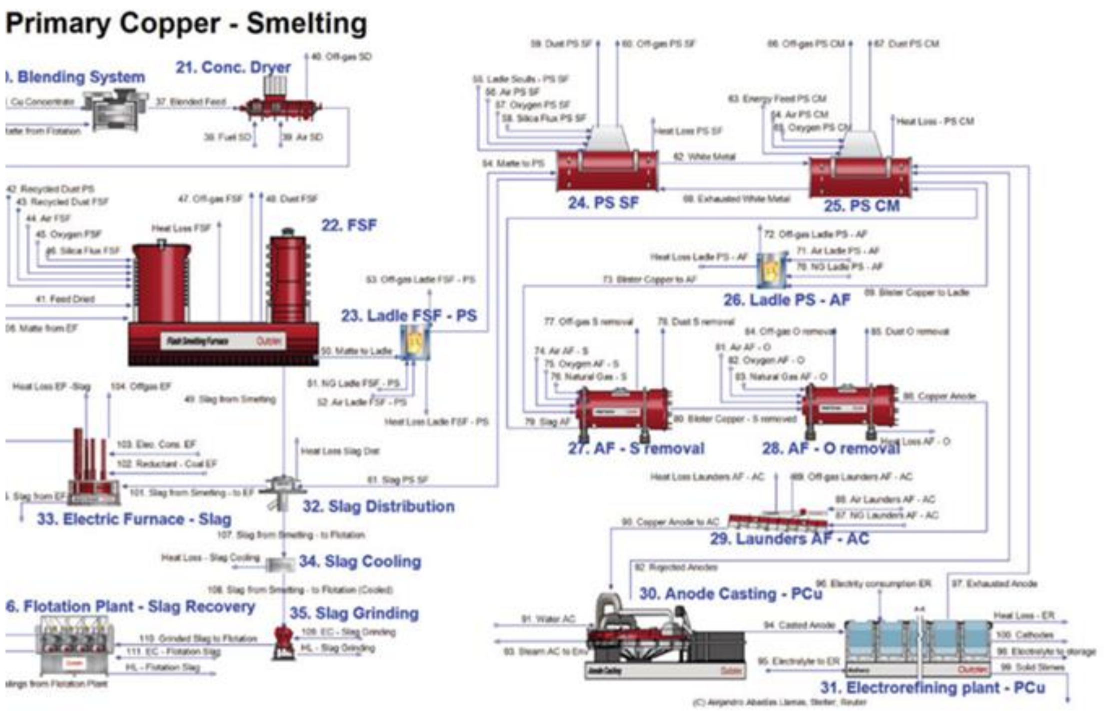
Which level of detail?

So-called ‚aggregate demand modelling‘ translates proxies for wellbeing, e.g., GDP, directly into energy demand via parameter equations.



High-resolution process modelling

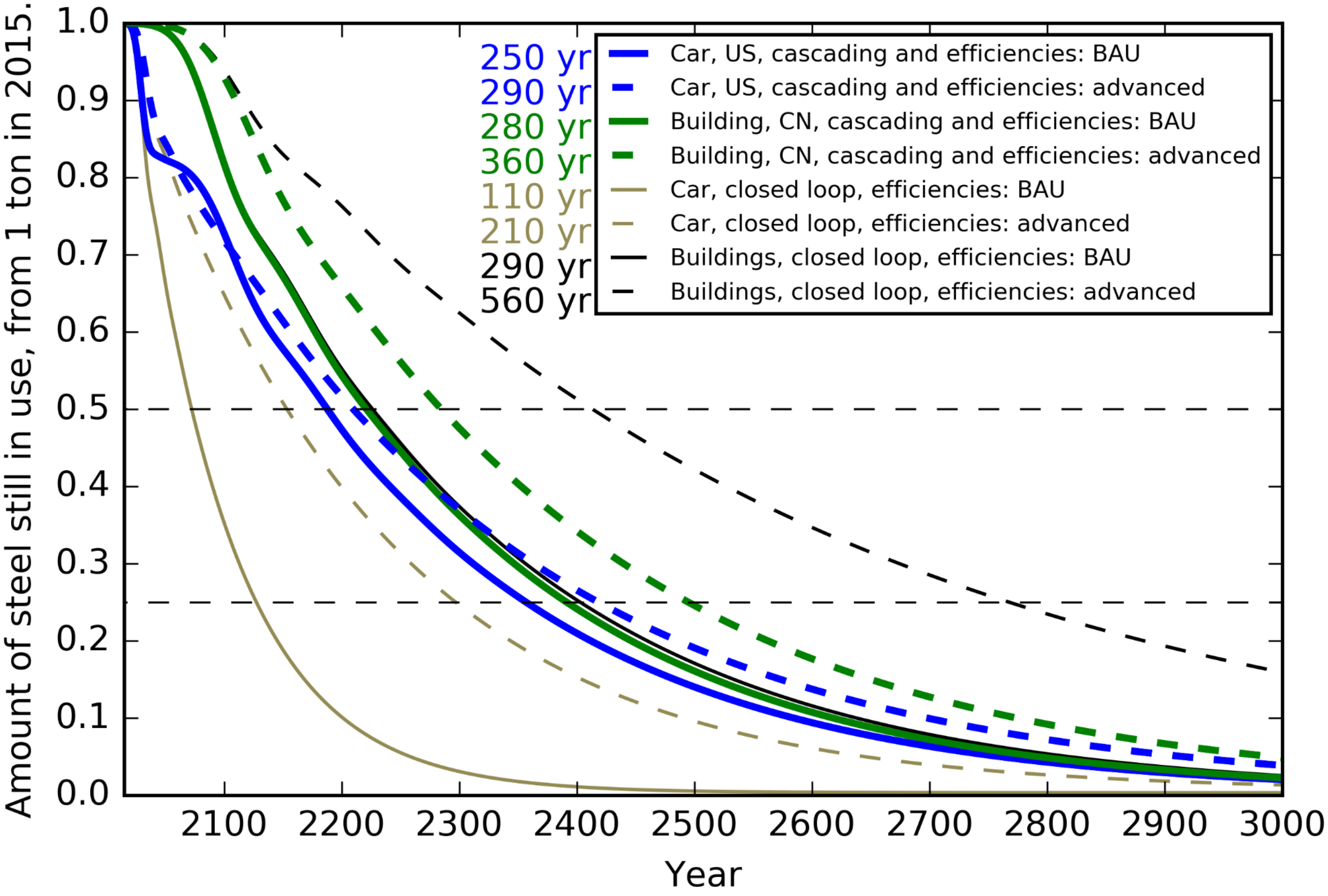


Compromise in material flow analysis (MFA):

- Consider aggregate processes and conversion parameters (see example above)
- Respect mass balance for all relevant chemical elements individually

Source right side: Reuter, M.A., Schaik, A. Van, Gutzmer, J., Bartie, N., Abadías-llamas, A., 2019. Challenges of the Circular Economy : A Material , Metallurgical , and Product Design Perspective 253–274.

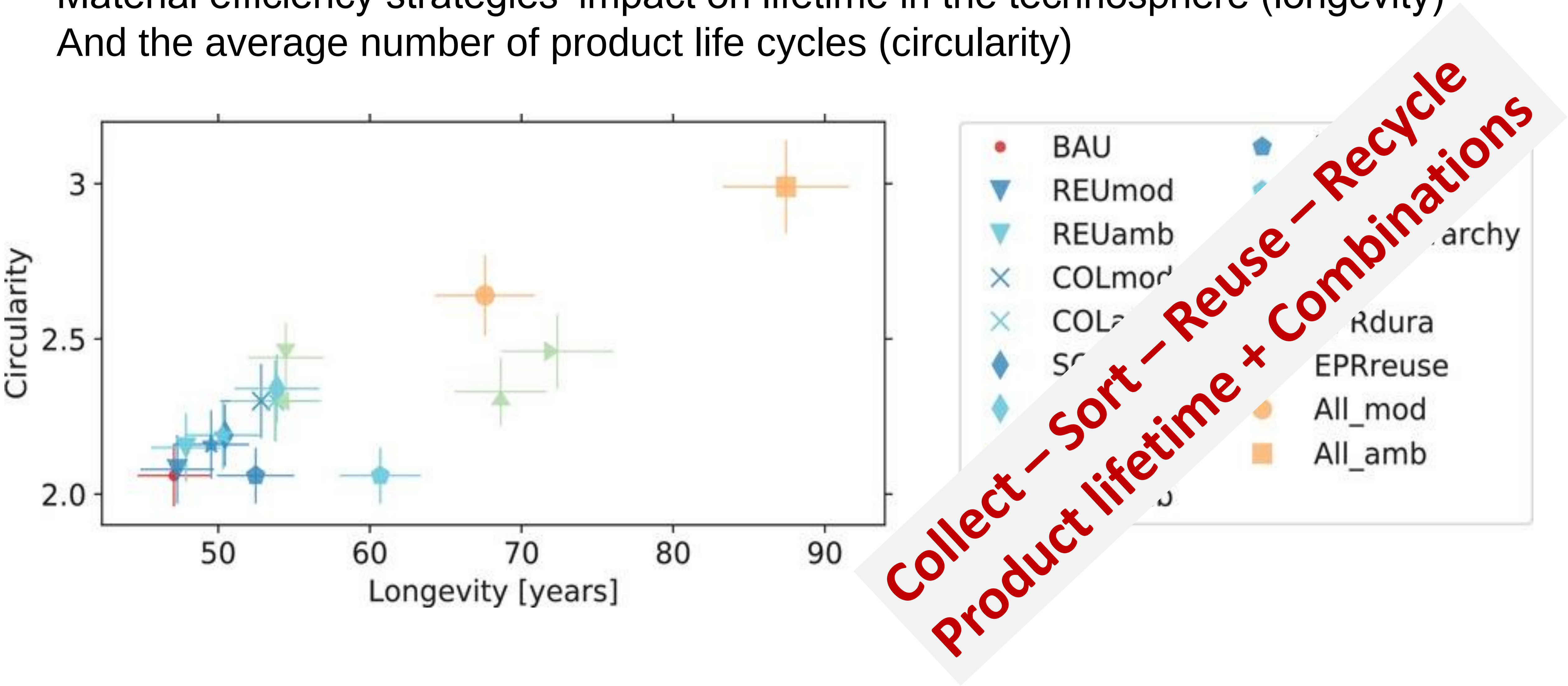
Lifetime of steel in the techno-sphere: 250-300 years



Source: Pauliuk (2018), DOI 10.1016/j.resconrec.2017.10.019

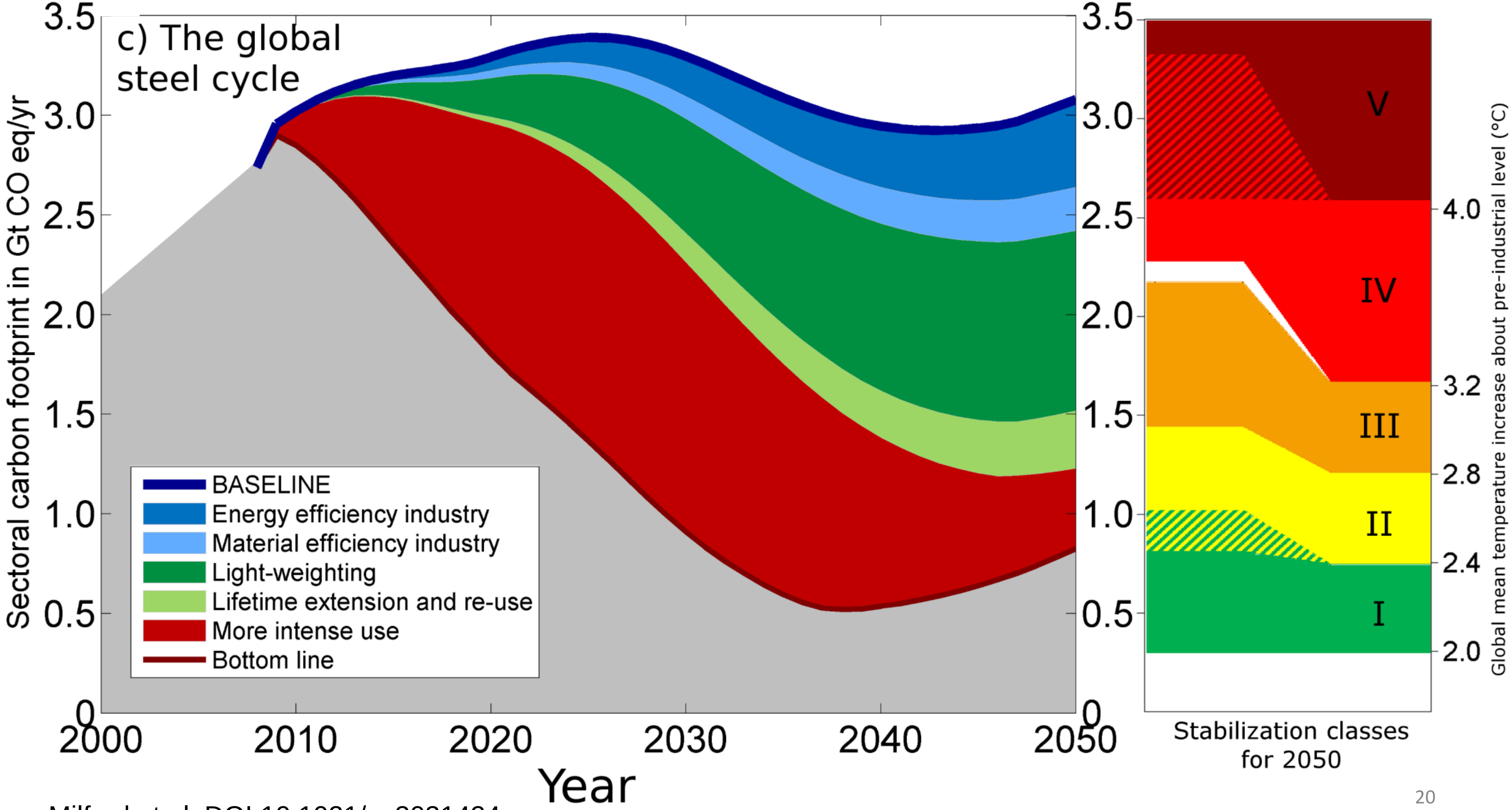
Life cycle perspective: The example of copper

Material efficiency strategies‘ impact on lifetime in the technosphere (longevity)
And the average number of product life cycles (circularity)



Source: Klose and Pauliuk (2021), DOI 10.1111/jiec.13092

System-wide material and energy efficiency in global steel cycle

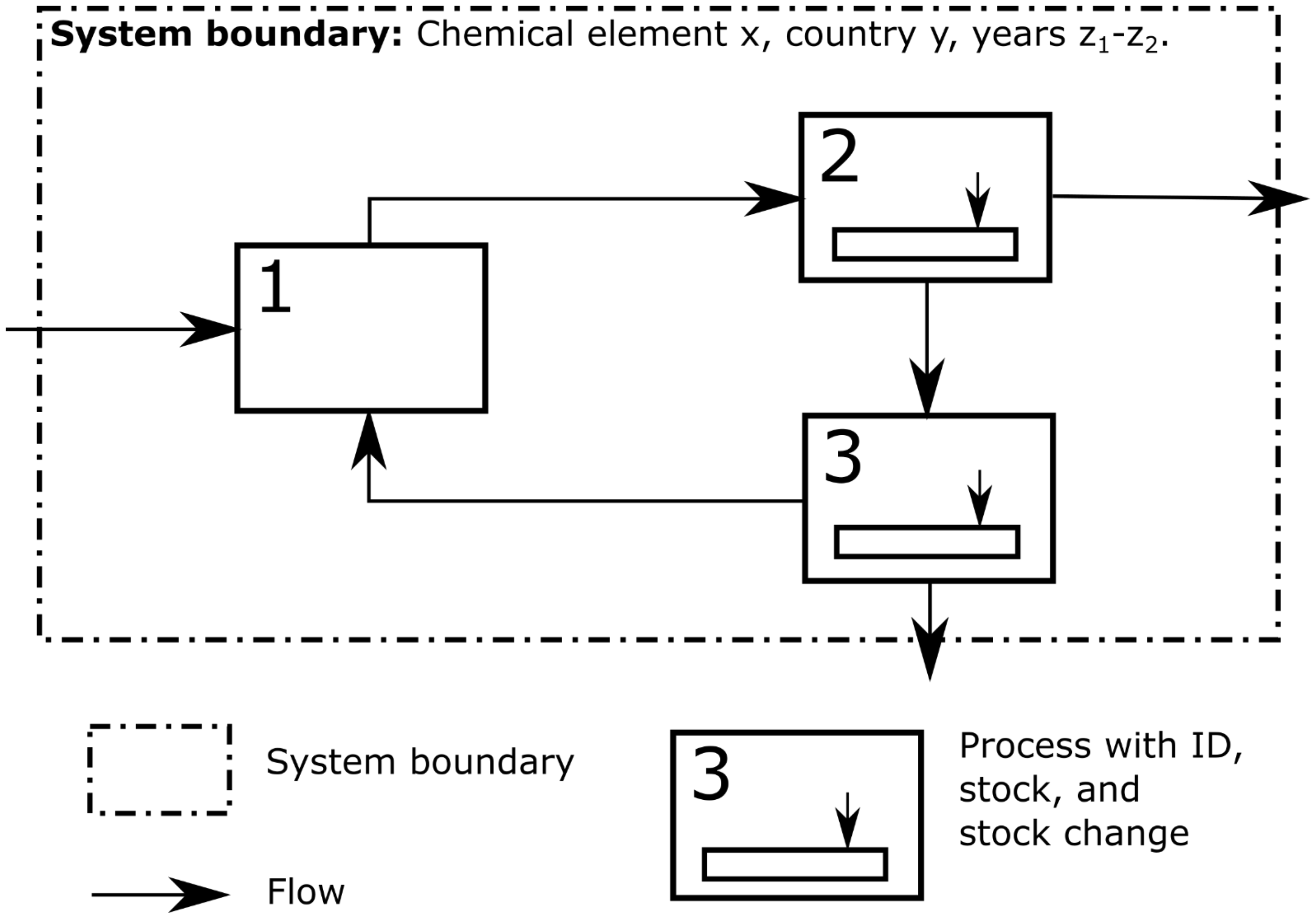


Source: Milford et al. DOI 10.1021/es3031424

Dynamic MFA

Dynamic stock modelling: Basics

System variables and parameters



Stocks, stock changes, and flows together form the **system variables.**

Stocks: $S_1(t)$, $S_3(t)$.

Stock changes (net addition to stock): $\Delta S_1(t)$, $\Delta S_3(t)$.

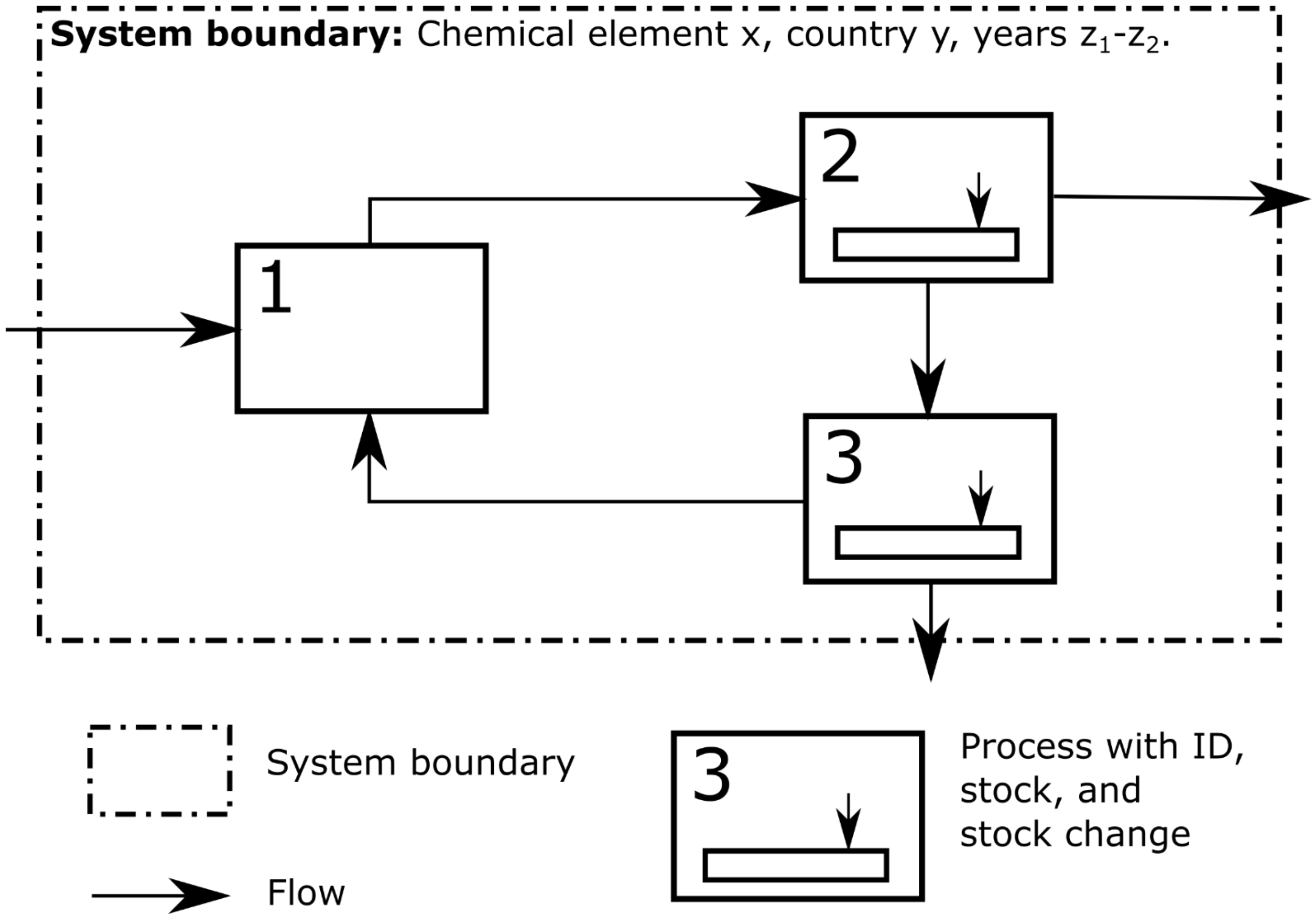
Flows: $F_{01}(t)$, $F_{12}(t)$, $F_{20}(t)$, $F_{23}(t)$, $F_{31}(t)$, $F_{30}(t)$

A **parameter** is an additional variable that couples different system variables through equations:

For example:

$F_{23}(t) = k(t) \cdot F_{12}(t)$
$\Delta S_1(t) = (0.15 + 0.01 \cdot t) \cdot F_{12}(t)$
$\Delta S_3(t) = 0$

Process and system balances



For mass, energy, sometimes monetary values, the process and system-wide balance holds:

Input – Output = Net Stock Change

Process 1: $F_{01}(t) + F_{31}(t) - F_{12}(t) = \Delta S_1(t)$

Process 2: $F_{12}(t) - F_{23}(t) - F_{20}(t) = 0$

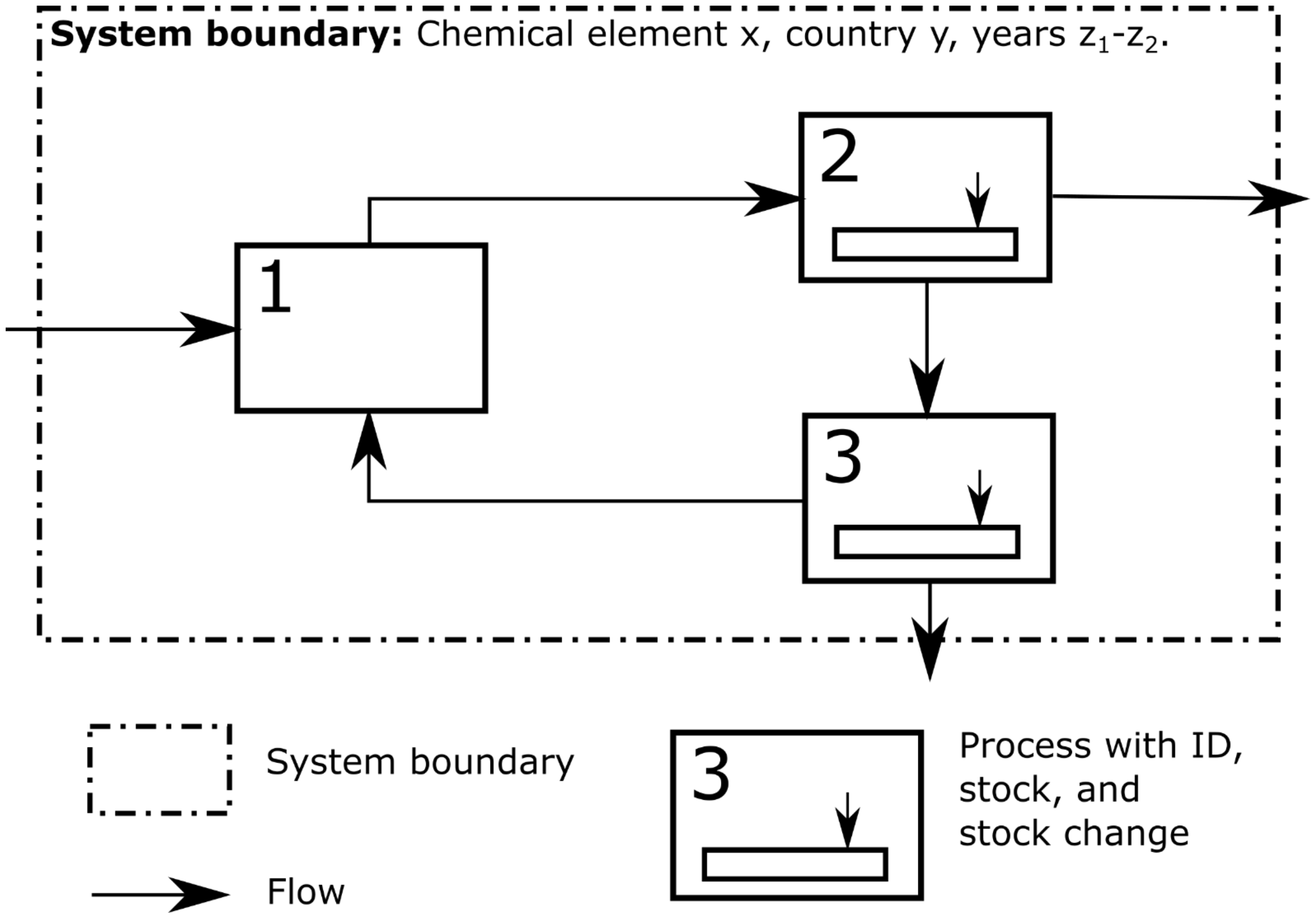
Process 3: $F_{23}(t) - F_{31}(t) - F_{30}(t) = \Delta S_3(t)$

System: $F_{01}(t) - F_{20}(t) - F_{30}(t) = \Delta S_1(t) + \Delta S_3(t)$

For a fully quantified system:

#System variables = #balance equations
+ #parameters
+ #Measurements

Performance indicators



A major advantage of an explicit system definition is the clear definition of performance indicators.

Efficiency η(t) *= useful output* (t) */ total input* (t)

Process 2: $\eta_2(t) = F_{20}(t) / F_{12}(t)$

Process 1: $\eta_1(t) = F_{12}(t) / F_{01}(t)$ OR $\eta_1(t)$

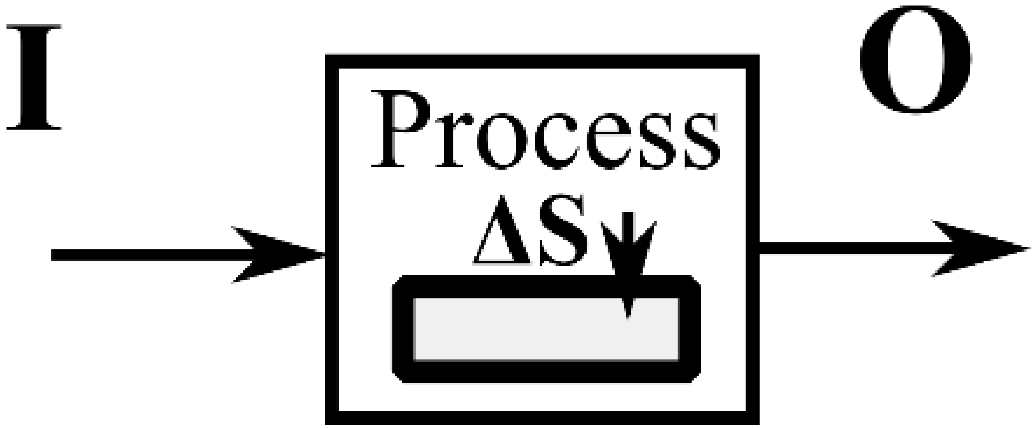
$= F_{12}(t) / (F_{01}(t) + F_{31}(t))$

System: $\eta_S(t) = F_{20}(t) / F_{01}(t)$

Emissions/waste intensity b = waste / useful output

OR waste / total input

Population balance model



$$\frac{dS(t)}{dt} = I(t) - O(t)$$

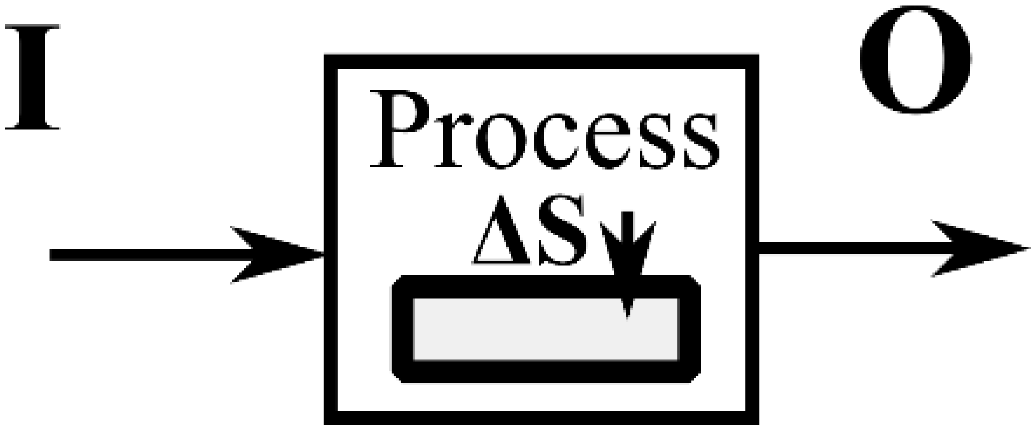
$$S(t) = \int_{t_0}^{t} \frac{dS(\tau)}{d\tau} d\tau$$

The mass balance equation dictates
The following relation between
Inflow, outflow, and stock change
of a process:

This relation applies to all processes
with a conservation law.

Non-conserved quantities can be
adopted: For a population of
individuals, I is the birth rate
and O is the death rate.

The leaching model



$$O(t) = c \cdot S(t)$$

At any given time, the outflow is proportional to the total stock present.

If no further inflow (I(t) = 0), the stock decays exponentially: $S(t) = S_0 \cdot \exp(-c \cdot t)$

Applications:

- Radioactive decay
- Leaching from deposits of pollutants or nutrients (landfills, tailings, soil)
- Simple to apply
- Only works for processes with no 'internal memory': probability of an item leaving the stock is independent of its residence time.

Van der Voet, Kleijn, et al. (2002): "Predicting future emissions based on characteristics of stocks", Ecological Economics, DOI 41 (2002) 223–234

https://en.wikipedia.org/wiki/Leaching_model_(soil)

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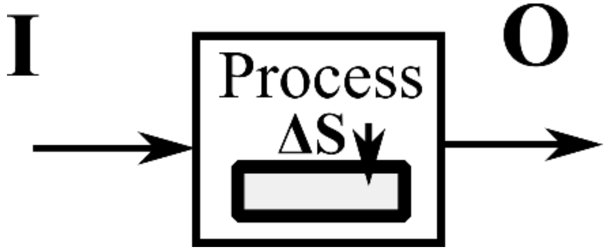
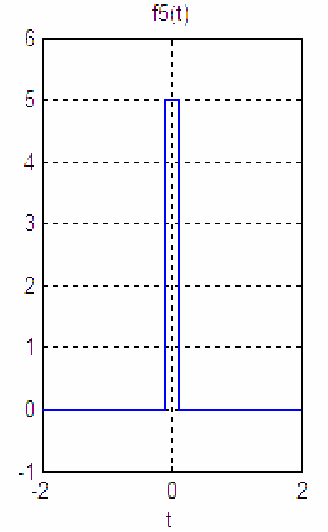
The impulse response function

The **impulse response**, or **impulse response function (IRF)**, of a dynamic system is its output when presented with a brief input signal, called an impulse.

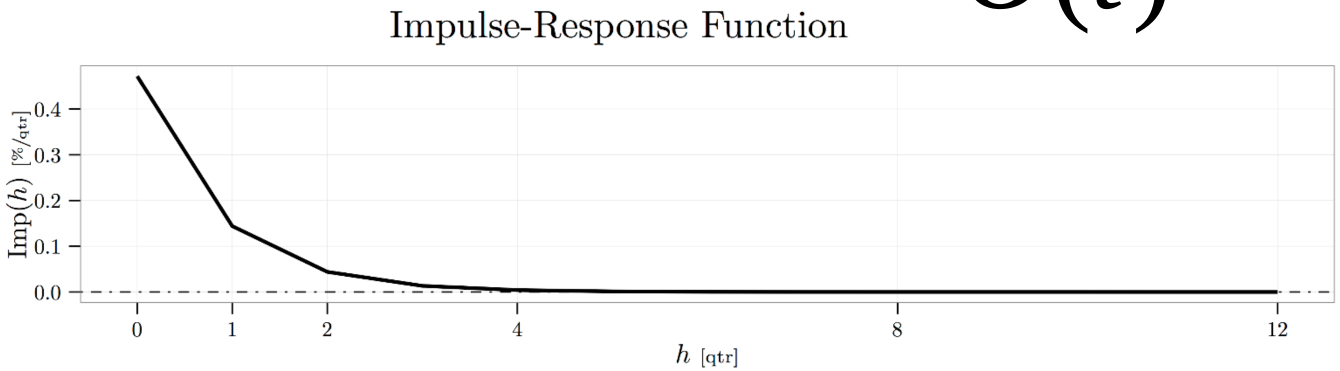


The impulse response function of a process with a stock is the outflow O(t) as response to an instantaneous inflow I(0) = I_0 at time t = 0.

$I(t)$



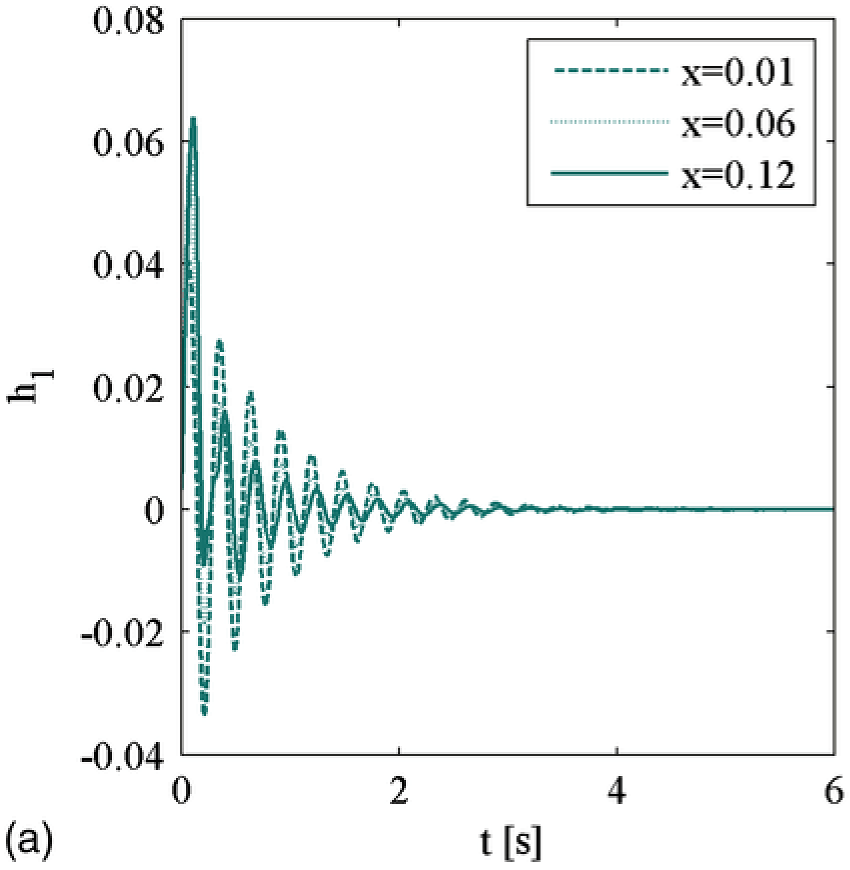
$O(t)$



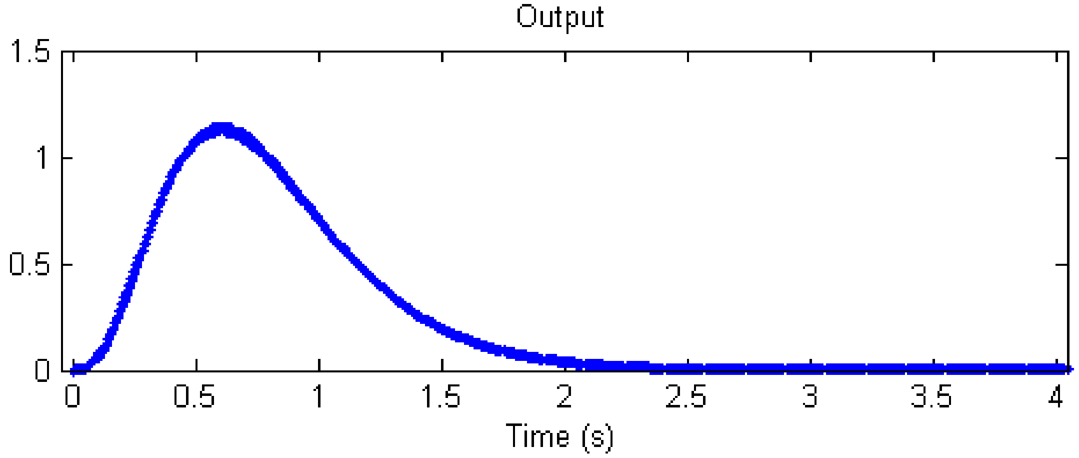
https://en.wikipedia.org/wiki/Impulse_response http://www.thefouriertransform.com/math/fnt2.gif
http://www.alexchinco.com/wp-content/uploads/2015/11/plot-cpi-ar1-irf1.png

Types of impulse responses

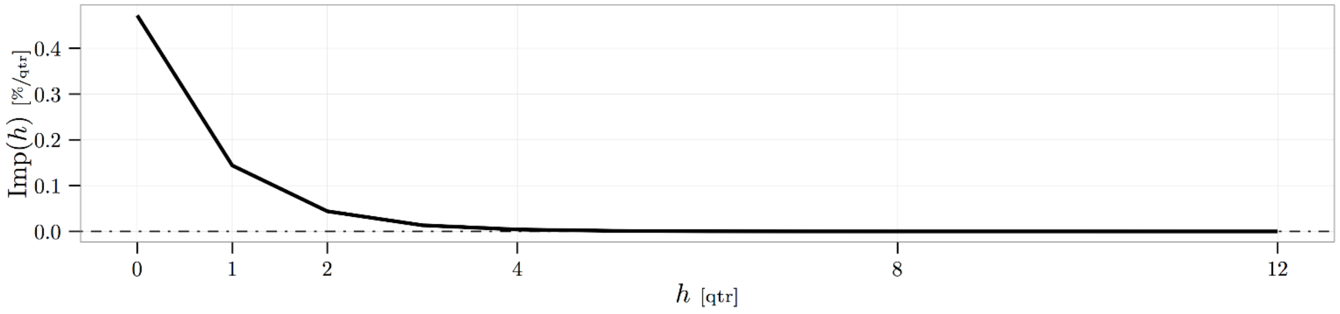
Oscillating



Delayed response



Decaying response



https://www.researchgate.net/profile/Marco_Broccardo2/publication/283683880/figure/fig2/AS:399452046151684@1472248197847/Fig-8-Impulse-response-function-white-noise-input.ppm
http://www.mbfys.ru.nl/~robvdw/DGCN22/PRACTICUM_2011/LABS_2011/ALTERNATIVE_LABS/Lesson_12_18.png
http://www.alexchinco.com/wp-content/uploads/2015/11/plot-cpi-ar1-irf1.png

Response to an addition to stock: Age-cohorts and lifetime

Two types of response are commonly considered in dynamic stock modelling:

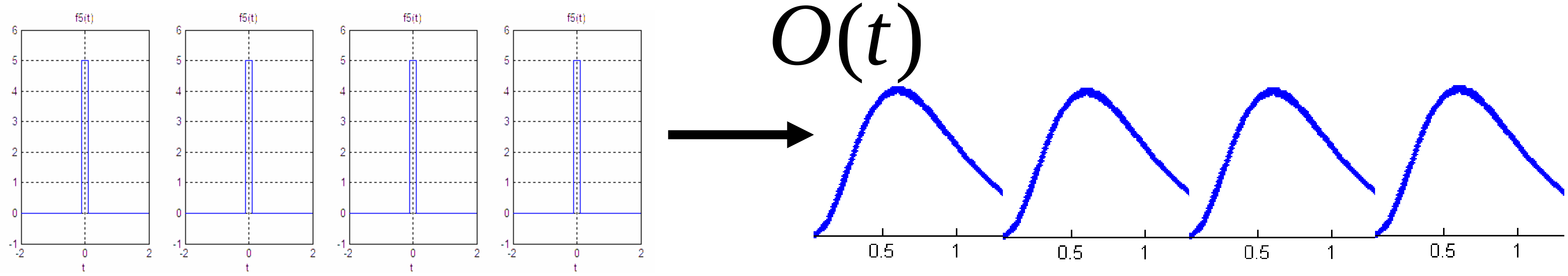
- Delayed response
- Decay

The response of the stock is linear: The responses to different input pulses are simply added up.

(analogy: The sound of an orchestra is the superposition (‘sum’) of the sounds of the different musical instruments.

Contrary: distortions added to guitar sounds in rock music

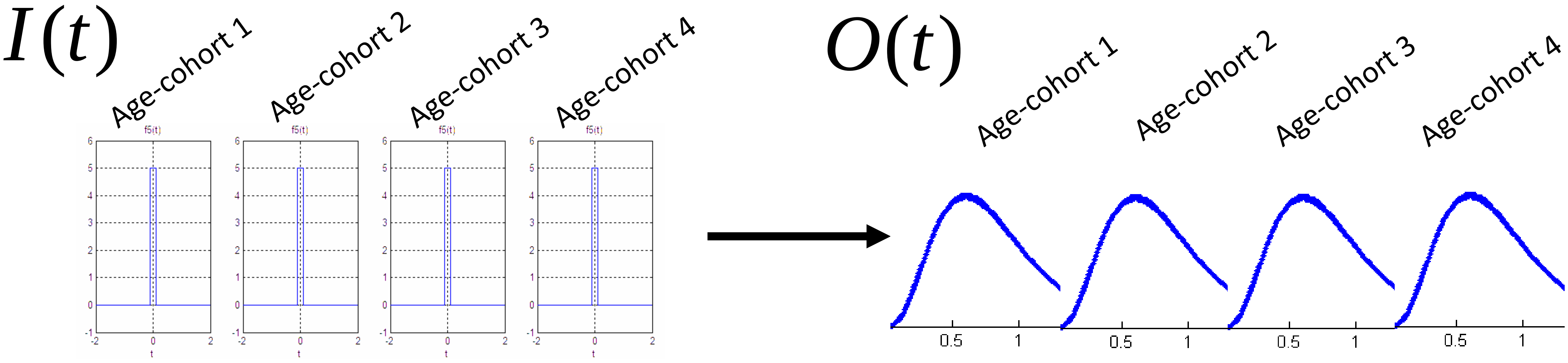
$I(t)$



Response to an addition to stock: Age-cohorts and lifetime

For linear dynamic stock models (standard situation)

- Each input to stock can be traced separately, and the fraction of the stock that origins from a given input at time t is called the *age-cohort* (of) t.
- The different age-cohorts can be traced separately (individually).

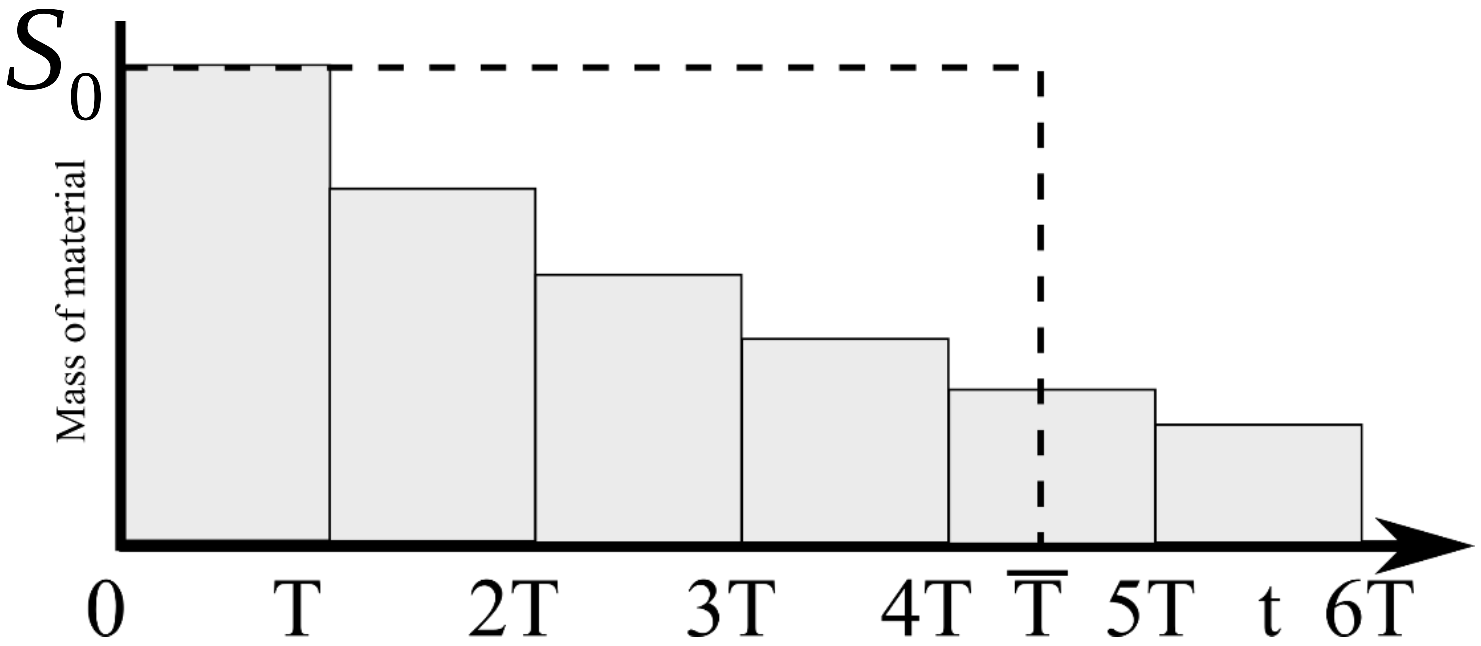


Response to an addition to stock: Age-cohorts and lifetime

The average lifetime $\bar{T}$ of an age-cohort is defined as the average residence time of the age-cohort in the stock.

Plot: Stock (t) after initial inflow at t=0.

$$\bar{T} = \frac{1}{S_0} \cdot \int_0^\infty S(t)dt$$



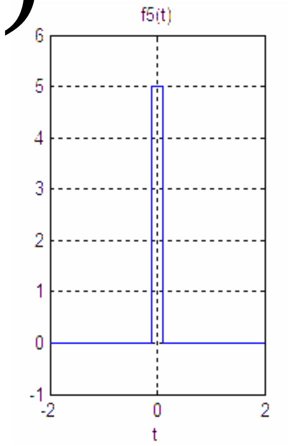
Read plot vertically: for each time t the stock at t is indicated.
Read plot horizontally: for the different fractions of the stock the total lifetime is indicated, sorted from shortest (top) to longest (bottom).
From combining both perspectives the average lifetime can be derived.

Fixed and distributed lifetimes

For a delayed response to an inflow (e.g. duration of product use) to cases are distinguished:

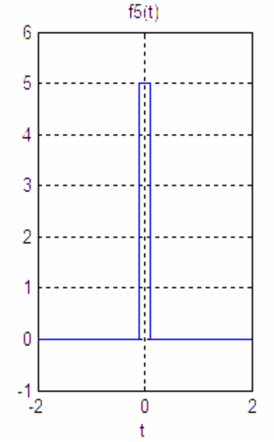
Fixed Product lifetime

$I(t)$



t=0

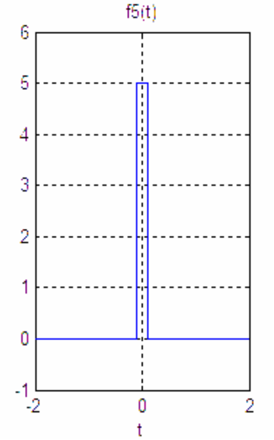
$O(t)$



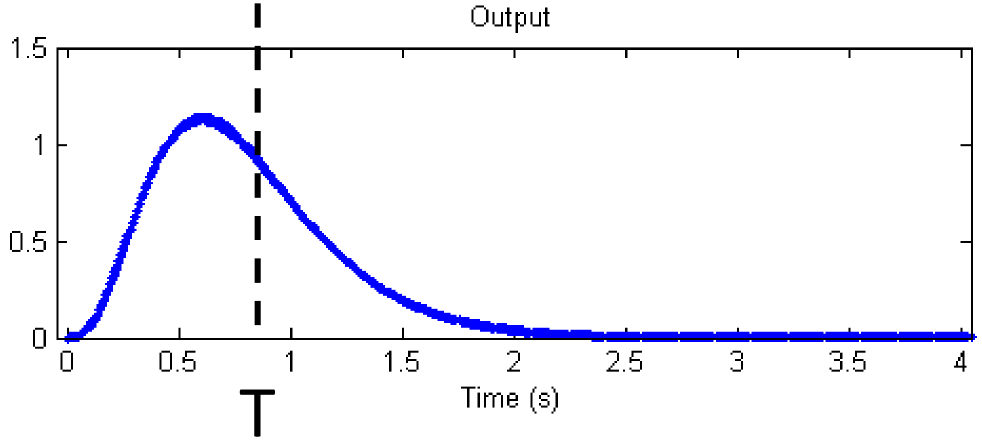
t=T

Distributed Product lifetime

$I(t)$



$O(t)$



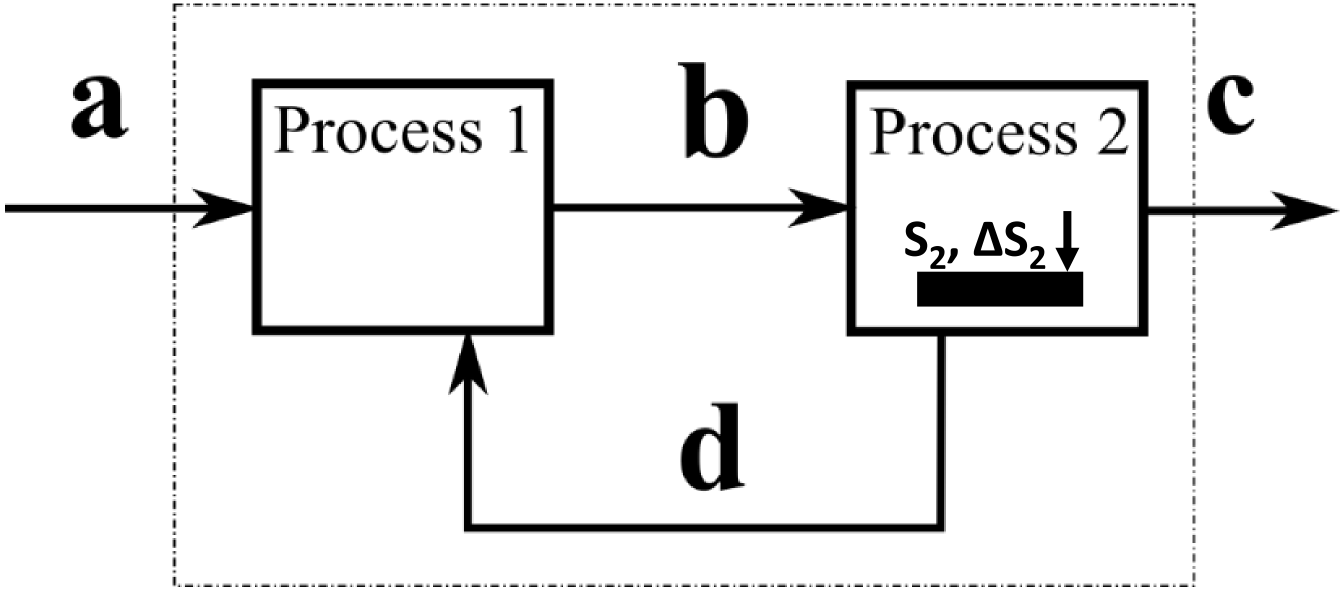
For fixed product lifetimes the entire age-cohort leaves the stock together after the lifetime T has expired. For the distributed lifetime the different fractions of the age-cohorts leave the stock with different Probabilities, so that the average lifetime (expectation value) equals T.

Solving dynamic MFA systems: (Linear) difference equations

Idea: Level of system variable x at time t is determined by previous states:

$$x(t) = a_1 \cdot x(t-1) + a_2 \cdot x(t-2) + \ldots + a_n \cdot x(t-n)$$

Example:



Growth in demand:

$$b(t) = (1+\alpha) \cdot b(t-1)$$

Scrap flow, fixed lifetime T in S_2:

$$d(t) = \beta \cdot b(t-T)$$

https://en.wikipedia.org/wiki/Linear_difference_equation

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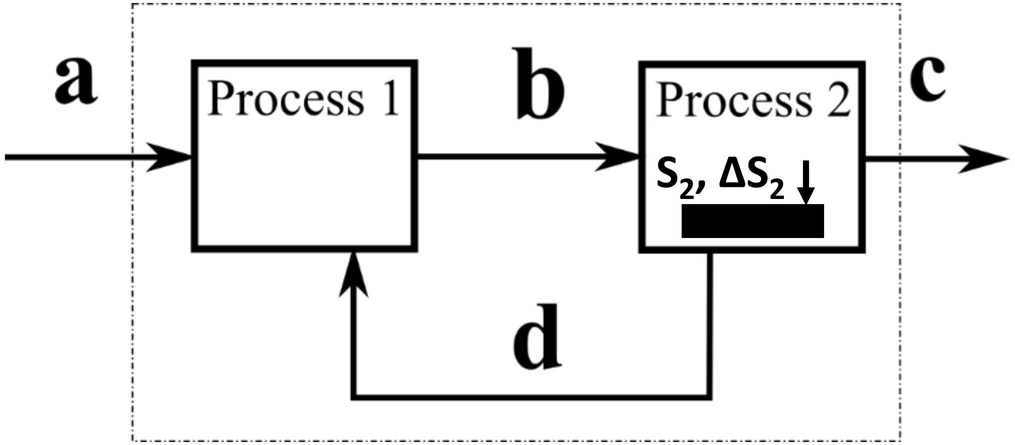
Solving dynamic MFA systems: (Linear) difference equations

To solve the example we need a complete set of starting values for $t = 0$.



System equations:

- Growth in demand:
  $b(t) = (1+\alpha)\cdot b(t-1)$
- Scrap flow, fixed lifetime T in S_2:
  $d(t) = \beta\cdot b(t-T)$
- Mass balances:
  $a(t) + d(t) = b(t)$
  $b(t) = c(t) + d(t)$

Starting values: $b(0) = B$, $b(t < 0) = 0$

Model solution:

$b(t) = (1+\alpha)^t\cdot B$

$d(t) = 0$ (f. $t < T$) and $\beta\cdot(1+\alpha)^{t-T}\cdot B$ else

$a(t) = (1+\alpha)^t\cdot B$ (f. $t<T$) and
$(1+\alpha)^t\cdot B - \beta\cdot(1+\alpha)^{t-T}\cdot B$ else

$c(t) = 0$ (f. $t < T$) and $(1-\beta)\cdot(1+\alpha)^{t-T}\cdot B$ else

$S_2(t) = ((1+\alpha)^t+(1+\alpha)^{t-1}+\ldots+(1+\alpha)^{t-T}) \cdot B$
(for $t >= T$)

https://en.wikipedia.org/wiki/Linear_difference_equation

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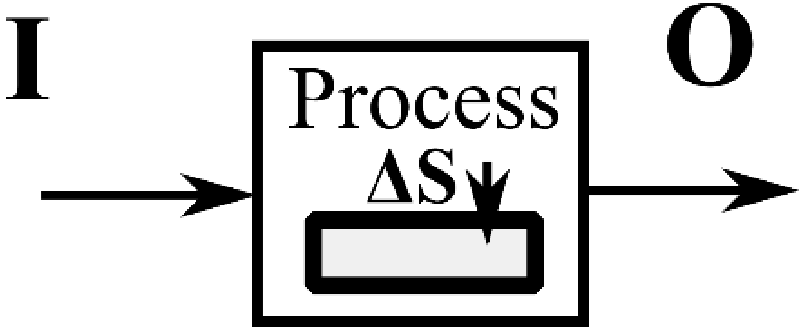
Solving dynamic MFA systems: Differential equations

In many practical cases the system equations of a dynamic MFA model can be formulated as differential equations, which are equations that have the derivatives of the stocks and flows as variables.

Basic example: Exponential decay or growth of a system variable X:

$$\frac{dX}{dt} = \gamma \cdot X$$



Of which a solution is

$$X(t) = X_0 \cdot e^{\gamma \cdot t}$$

For γ<0: Exponential decline, e.g.,
slowly decaying stock (‘leaching model’)

$$S(t) = S_0 \cdot e^{-|\gamma| \cdot t}$$

For γ>0: Exponential growth, e.g.,
Exponentially growing consumption

$$I(t) = I_0 \cdot e^{\gamma \cdot t}$$

Solving dynamic MFA systems: Logistic growth

To curb the exponential growth the growth term can be limited as follows:

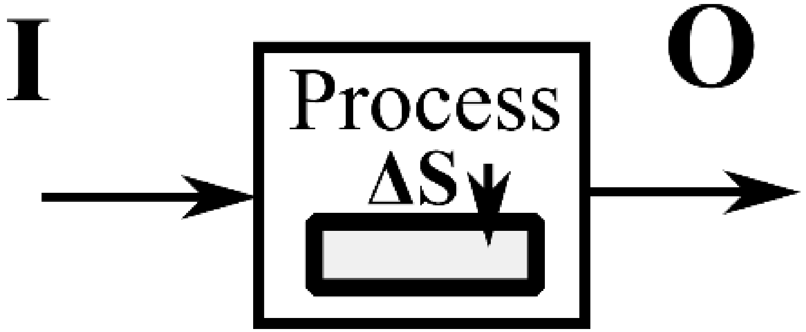
$$\frac{dS}{dt} = \gamma \cdot S \cdot (1 - S)$$

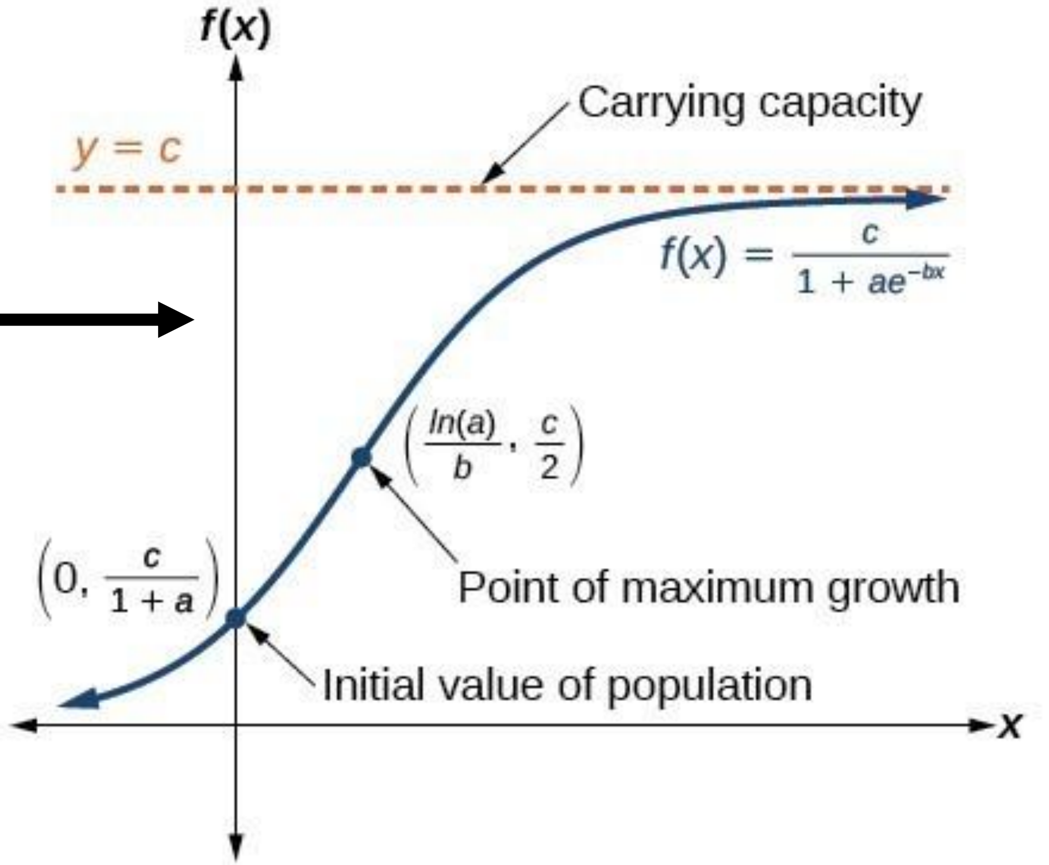
Of which a solution is

$$S = \frac{1}{1 + e^{-t}}$$

More general:

$$\frac{dS}{dt} = b \cdot S \cdot \left(1 - \frac{S}{c}\right)$$





https://en.wikipedia.org/wiki/Logistic_function

https://s3-us-west-2.amazonaws.com/courses-images-archive-read-only/wp-content/uploads/sites/924/2015/11/25202016/CNX_Precalc_Figure_04_07_0062.jpg

Dynamic MFA
Inflow-driven modelling

The inflow-driven model: Research questions

In-use stocks of buildings, vehicles, and infrastructure provide services to people and are a central determinant of sustainable development.

For many stocks, in particular, material stocks estimates are not available.

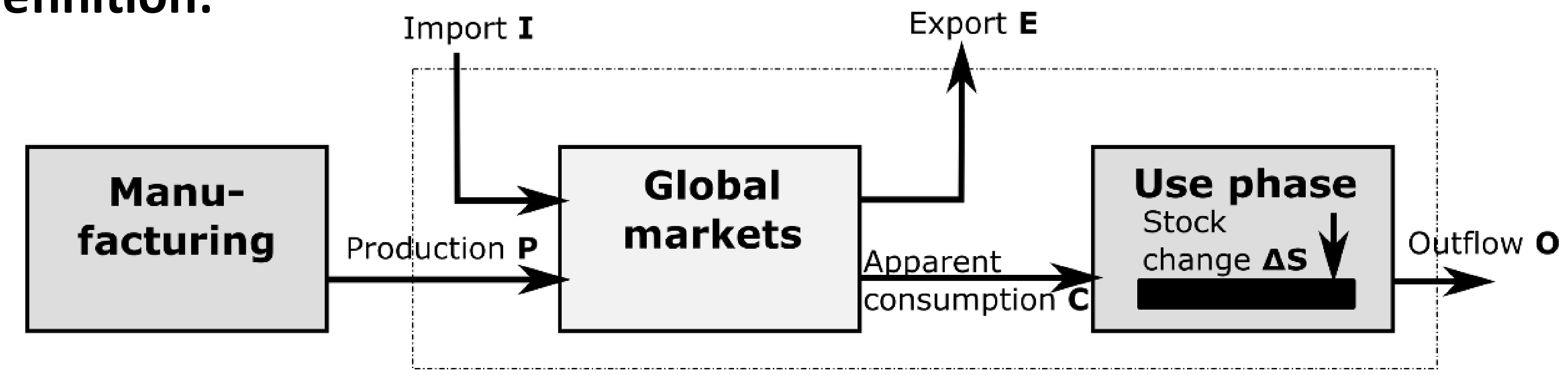
Material stocks can be determined

a) 'bottom-up': from building and vehicle statistics and product-specific material content data
b) 'top-down': from aggregated consumption data and a lifetime model

DOI 10.1016/j.gloenvcha.2013.11.006

Applying the inflow-driven model to estimate in-use stocks

System definition:



1) Determine apparent consumption: **C = P + I – E**

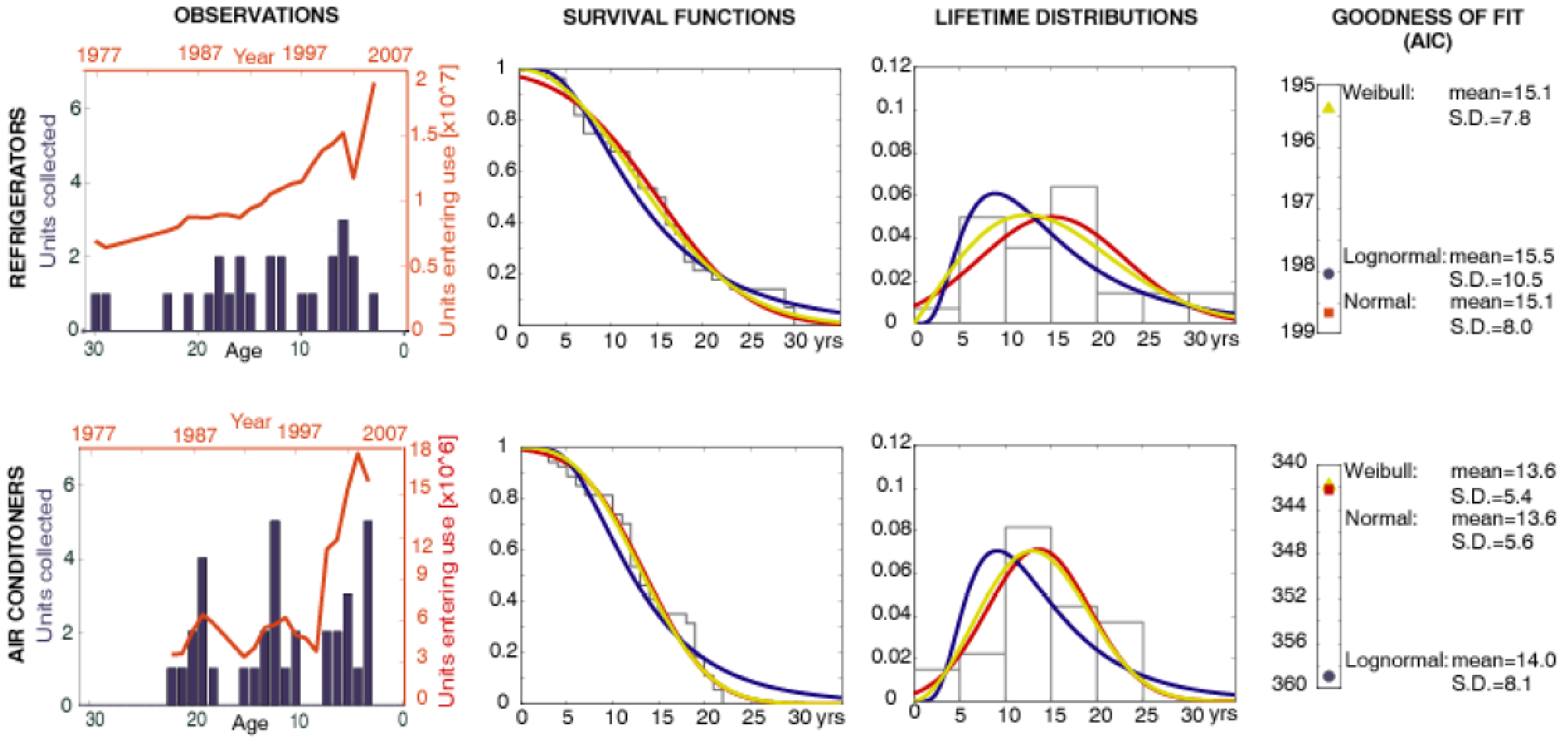
2) Apply the convolution: $O(t) = \int_{t_0}^{t} C(\tau) \cdot pdf(t-\tau)\,\mathrm{d}\tau$

3) Determine stock change $\Delta S(t) = C(t) - O(t)$

4) Determine stock $S(t) = S(t_0) + \int_{t_0}^{t} \Delta S(\tau) d\tau$

Product lifetimes in the inflow-driven model

Lifetime data are obtained or have to be inferred from surveys, statistical records, and Anecdotal evidence (newspaper report, blog entries, Wikipedia).



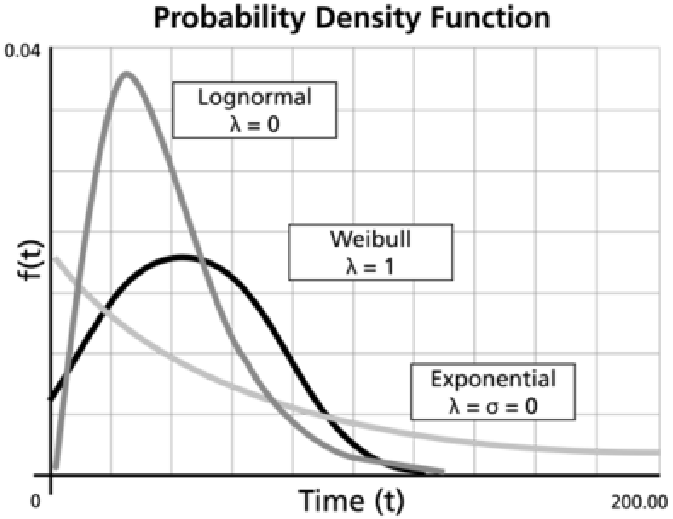
Müller et al. (2007): Service Lifetimes of Mineral End Uses. Report supported by U.S. Geological Survey (USGS), award number 06HQGR0174

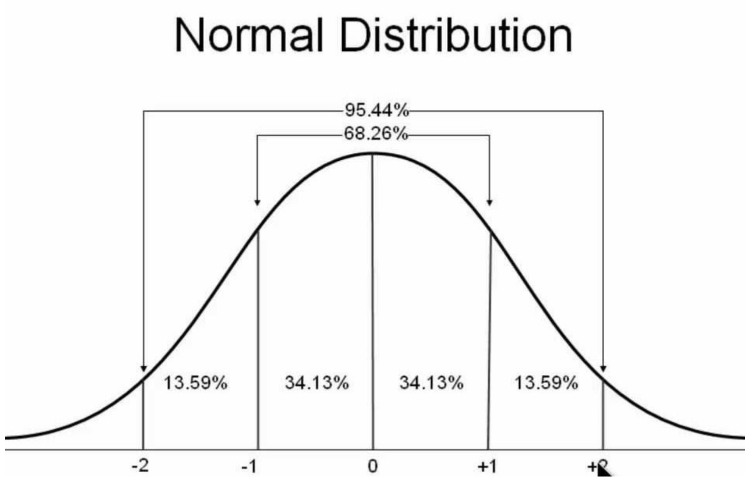
Product lifetimes in the inflow-driven model

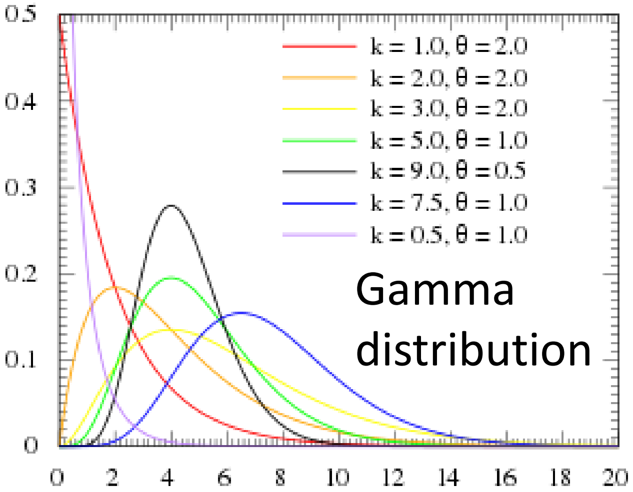
Lifetime data are scattered across the literature and often show large variations:

- NIES (Japan) lifetime database: http://www.nies.go.jp/lifespan/
- Consumer goods and vehicles: Müller et al. (2007): Service Lifetimes of Mineral End Uses. Report supported by U.S. Geological Survey (USGS), award number 06HQGR0174
- Product lifetime data in the industrial ecology data commons (iedc): https://www.database.industrialecology.uni-freiburg.de/ search for “3_LT” datasets

Normal, Gamma, Exponential, and Weibull distributions are commonly applied to model product lifetimes.







http://reliawiki.org/images/thumb/a/a5/WB_chp12_pdf.png/400px-WB_chp12_pdf.png
https://i.ytimg.com/vi/xgQhefFOXrM/maxresdefault.jpg
https://upload.wikimedia.org/wikipedia/commons/thumb/e/e6/Gamma_distribution_pdf.svg/325px-Gamma_distribution_pdf.svg.png

Implementing the inflow-driven model

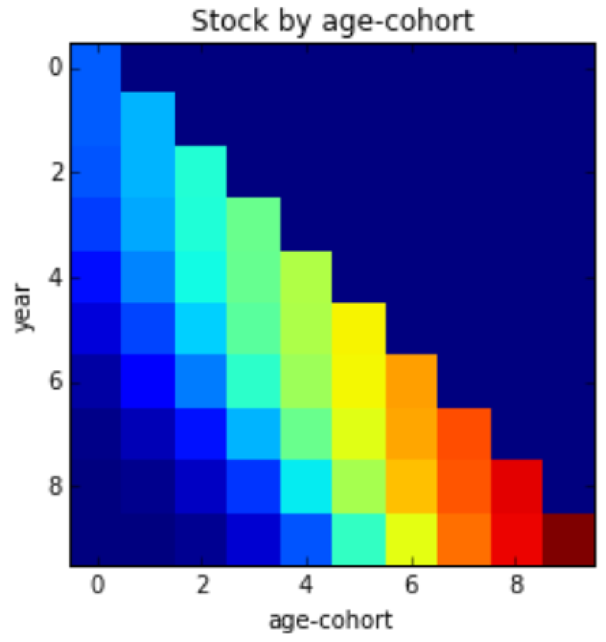
In Excel: The *pdf* can be generated using NORM.DIST, the rest is a standard Excel computation.

In Python: via the dynamic_stock_model functions:

```
TestDSM = DynamicStockModel(t = np.arange(1,11,1), i = np.arange(2.5,12.5,1),
lt = {'Type': 'Normal', 'Mean': np.array([5]), 'StdDev': np.array([1.5]) })

Stock_by_cohort, ExitFlag =
TestDSM.compute_s_c_inflow_driven()

O_C, ExitFlag =
TestDSM.compute_o_c_from_s_c()
```



→ **Applied in IEooc_Methods3_Exercise1 (Excel) and IEooc_Method3_Software1 (Python)**

Dynamic MFA
Stock-driven modelling

The stock-driven model for determining inflows

To build scenarios for the future development of material cycles, one can

- Extrapolate or assume future consumption levels and then calculate the stocks and the services provided.
- Extrapolate or assume future service levels, infer the stocks required to deliver them, and calculate the inflows required to expand and maintain those stocks.

The latter approach is often more realistic, as it allows us to link the actual outcome of economic activity, service provision, directly to the socioeconomic variables providing those services, stocks.

The research question is then:

How large is the inflow needed to maintain and expand the in-use stock so that it fits a given scenario?

The method that answers this question is called stock-driven modelling.

Müller (2006): Stock dynamics for forecasting material flows. DOI 10.1016/j.ecolecon.2005.09.025

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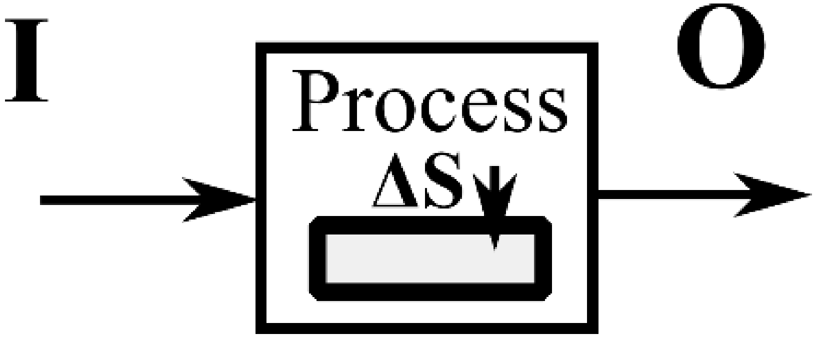
Applying the stock-driven model to estimate in-use stocks

System definition:



Mathematically, the determination of an inflow from an outflow is the inverse of the convolution operation used for the inflow-driven model.

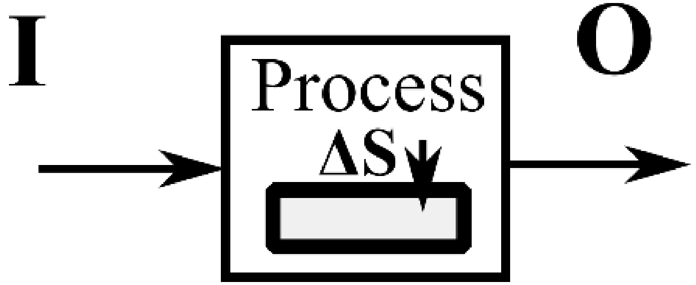
As the convolution involves the calculation of average values, its application to functions in general leads to a loss of information.

That means that the original signal (or inflow) can be reconstructed from the filtered signal (the outflow or stock) only in special cases.

In dynamic MFA such a special case is given if the age-cohort composition of the initial stock is known or that stock is zero.

Procedure of the stock-driven model to estimate in-use stocks

System definition:



Recursive procedure: Starting in the first model year, repeat the following steps for each year:

1) Calculate the outflow from the existing stock using the convolution of historic inflows:

$$O(t) = \int_{t_0}^{t} I(\tau) \cdot pdf(t-\tau)\,\mathrm{d}\tau$$

2) Calculate the gap *ΔS(t)* between the actual stock and the remaining stock (S_0 = 0):

$$\Delta S(t) = S_{ext}(t) - S(t) = S_{ext}(t) - \int_{t_0}^{t} (I(\tau) - O(\tau))\,\mathrm{d}\tau = S_{ext}(t) - \int_{t_0}^{t} \mathrm{I}(\tau)\,\mathrm{d}\tau - \int_{t_0}^{t}\int_{t_0}^{\tau} \mathrm{I}(\theta) \cdot pdf(\tau-\theta)\,\mathrm{d}\theta$$

3) Set the inflow to fill the gap *ΔS(t)*, where *T* is the time step of the model (e.g., 1 year):

$$I(t) = \Delta S(t) / \mathrm{T}$$

Then repeat from step 1.

Practical exercise: a simple dynamic stock model for the vehicle fleet

stock-driven model, fixed product lifetime: 3 years

Year	Stock (cars)	Age-cohort -2	-1	0	1	2	3	Use (km/yr)	Emissions (CO_2/yr)
-2	4	4	0	0	0	0	0	10	240
-1	5	4	1	0	0	0	0	9	261
0	6							10	
1	7							10	
2	8							9	
3	9							9	

Efficiency (CO_2/km)					
6	5	5	4	4	3

240 CO_2/yr = 4 cars * 10 km/yr * 6 CO_2/km

261 CO_2/yr = 4 cars * 9 km/yr * 6 CO_2/km
+ 1 car * 9 km/yr * 5 CO_2/km

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Practical exercise: a simple dynamic stock model for the vehicle fleet

stock-driven model, fixed product lifetime: 3 years

Year	Stock (cars)	Age-cohort -2	-1	0	1	2	3	Use (km/yr)	Emissions (CO_2/yr)
-2	4	4	0	0	0	0	0	10	240
-1	5	4	1	0	0	0	0	9	261
0	6	4	1	1	0	0	0	10	
1	7							10	
2	8							9	
3	9							9	

Efficiency (CO_2/km)					
6	5	5	4	4	3

240 CO_2/yr = 4 cars * 10 km/yr * 6 CO_2/km

261 CO_2/yr = 4 cars * 9 km/yr * 6 CO_2/km
+ 1 car * 9 km/yr * 5 CO_2/km

Practical exercise: a simple dynamic stock model for the vehicle fleet

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-1	5	4	1	0	0	0	0	9	261
0	6	4	1	1	0	0	0	10	
1	7	0	1	1	5	0	0	10	
2	8	0	0	1	5	2	0	9	
3	9	0	0	0	5	2	2	9	

Efficiency (CO_2/km)

-2	-1	0	1	2	3
6	5	5	4	4	3

240 CO_2/yr = 4 cars * 10 km/yr * 6 CO_2/km

261 CO_2/yr = 4 cars * 9 km/yr * 6 CO_2/km
+ 1 car * 9 km/yr * 5 CO_2/km

Practical exercise: a simple dynamic stock model for the vehicle fleet

stock-driven model, fixed product lifetime: 3 years

Year	Stock (cars)	Age-cohort -2	-1	0	1	2	3	Use (km/yr)	Emissions (CO_2/yr)
-2	4	4	0	0	0	0	0	10	240
-1	5	4	1	0	0	0	0	9	261
0	6	4	1	1	0	0	0	10	340
1	7	0	1	1	5	0	0	10	
2	8	0	0	1	5	2	0	9	
3	9	0	0	0	5	2	2	9	

Efficiency (CO_2/km)

-2	-1	0	1	2	3
6	5	5	4	4	3

240 CO_2/yr = 4 cars * 10 km/yr * 6 CO_2/km

261 CO_2/yr = 4 cars * 9 km/yr * 6 CO_2/km
+ 1 car * 9 km/yr * 5 CO_2/km

Practical exercise: a simple dynamic stock model for the vehicle fleet

stock-driven model, fixed product lifetime: 3 years

Year	Stock (cars)	Age-cohort -2	-1	0	1	2	3	Use (km/yr)	Emissions (CO_2/yr)
-2	4	4	0	0	0	0	0	10	240
-1	5	4	1	0	0	0	0	9	261
0	6	4	1	1	0	0	0	10	340
1	7	0	1	1	5	0	0	10	300
2	8	0	0	1	5	2	0	9	297
3	9	0	0	0	5	2	2	9	306
	Efficiency (CO_2/km)	6	5	5	4	4	3		

240 CO_2/yr = 4 cars * 10 km/yr * 6 CO_2/km

261 CO_2/yr = 4 cars * 9 km/yr * 6 CO_2/km
+ 1 car * 9 km/yr * 5 CO_2/km

The stock-driven model for determining inflows

The stock-driven model is the inverse of the inflow driven model:

- The inflow computed by the stock-driven model is identical to the original inflow.
- The stock computed with the inflow-driven model is identical to the original stock.

Be creative with the initial stock!

- Use stock obtained from inflow-driven model to apply stock-driven model from a time when there were virtually no stocks.
- If the original stock age-cohort composition is unknown, the leaching model can be applied to S_0.

Implementing the stock-driven model

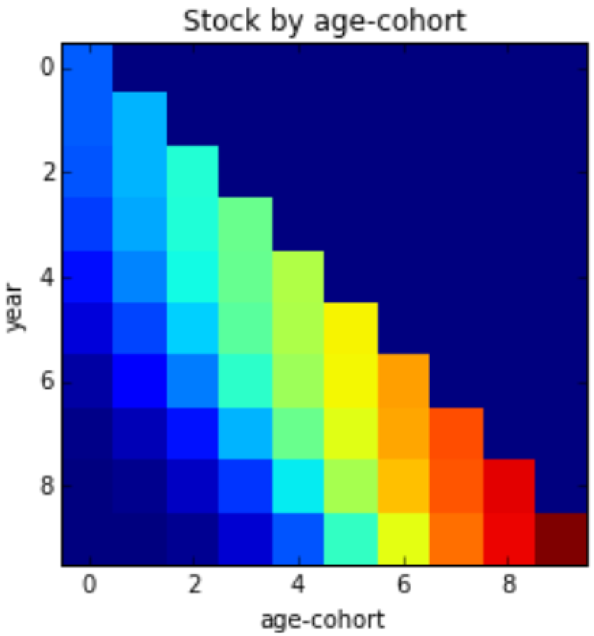
In Excel: Possible but a bit cumbersome. See *IEooc_Methods3_Software9* for an implementation.

In Python: via Jupyther notebooks, e.g., *IEooc_Methods3_Software1*

See section Methodology 3: Dynamic Material Flow Analysis of the IEooc

```
TestDSMX = DynamicStockModel(t = np.arange(1,11,1),
s = np.array([  2.5,   6. ,  10.5,  16. ,  22.5,  27.5,  32.5,  37.5,  42.5,  47.5]),
lt = {'Type': 'Normal', 'Mean': np.array([4]), 'StdDev': np.array([1.0]) })

S_C, O_C, I, ExitFlag = TestDSMX.compute_stock_driven_model
O, ExitFlag   = TestDSMX.compute_outflow_total()
DS, ExitFlag  = TestDSMX.compute_stock_change()
Bal, ExitFlag = TestDSMX.check_stock_balance()
```



→ **Applied in IEooc_Method3_Software1 (Python)**

Research & dissemination infrastructure @IEF

Blog ‚State of Affairs' and Twitter

Industrial ecology open online course

5 years IEOOC

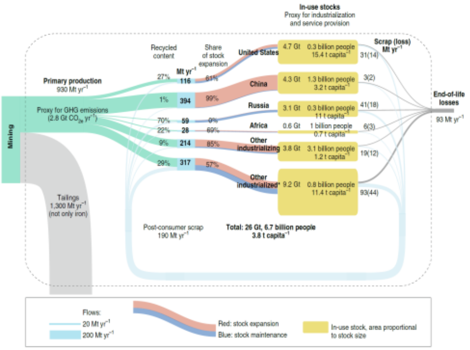
Open source software:
ODYM MFA framework
RECC scenario model

General data model and database:
Industrial ecology data commons (iedc)

Guidelines and standards:
Methodology & indicators
Reproducibility of results
Traceability & provenance


Industrial Ecology Freiburg
WORKING PAPER 1 2023
Good Practice Examples for Complete Traceability of Workflows and Reproducibility of Results in Industrial Ecology Research

Interactive visualisation:
Sankey diagrams
Scenario results
Circular economy profiles



https://www.industrialecology.uni-freiburg.de/

Thanks a lot for your interest!

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Application: Implications of low demand scenarios in the global bulding stock - materials and energy

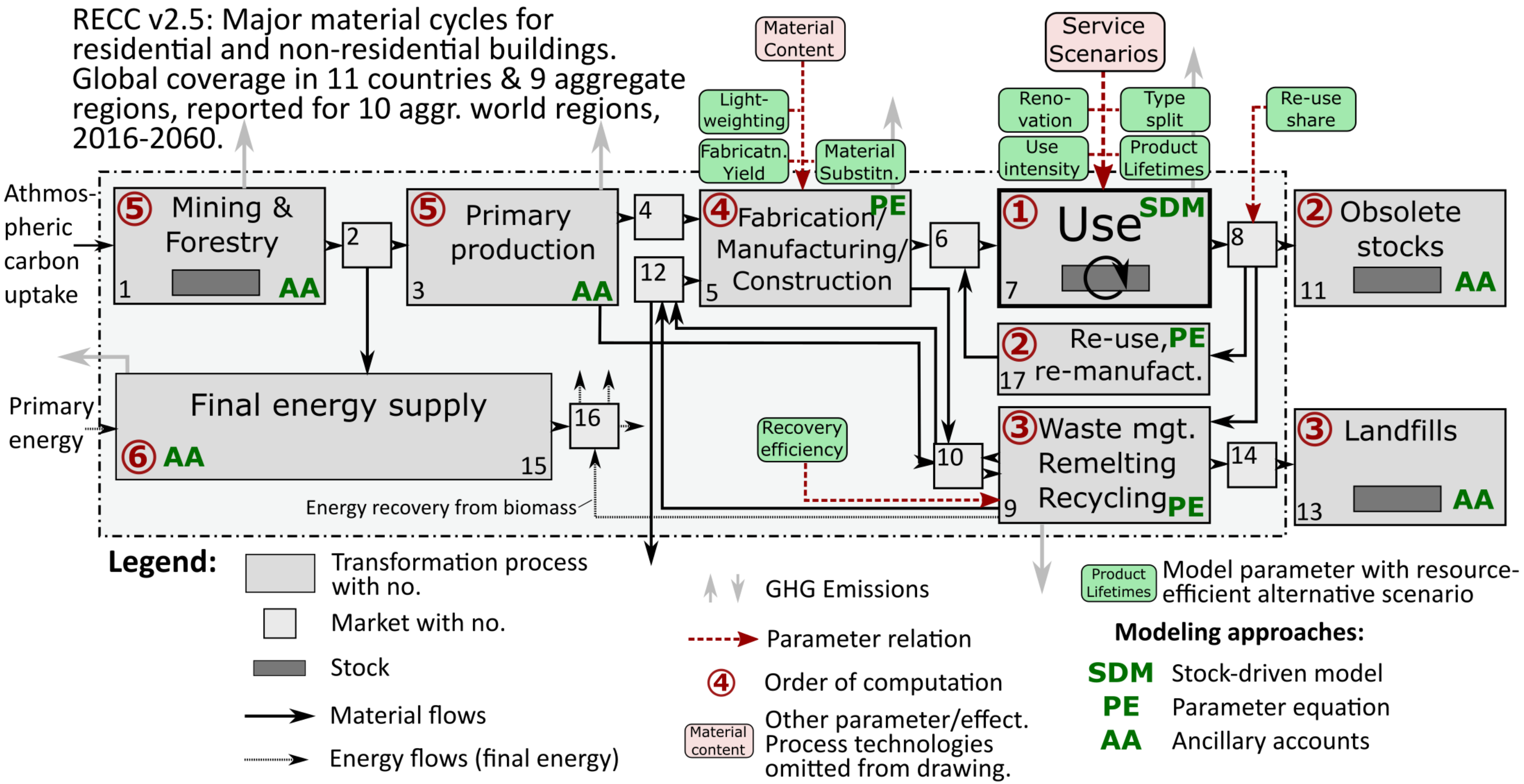
Stefan PAULIUK[1], Fabio CARRER[2], Niko HEEREN[2], and Edgar G. HERTWICH[2]
1) University of Freiburg, 2) NTNU Trondheim, Norway
October 2024

Motivation

- Residential and non-residential buildings are a major contributor to human wellbeing.
- Buildings cause 30% of final energy use, 18% of greenhouse gas emissions, and about 65% of material accumulation globally.
- With electrification and higher energy efficiency, material-related emissions gain relevance.
- The circular economy (CE) strategies, *narrow, slow, and close*, together with wooden buildings, can reduce material-related emissions.

→ Comprehensive set of building stock transformation scenarios for ten world regions until 2060, using the RECC model of the stock-flow-service nexus, including low energy and material demand futures (LEMD: Values from Grubler et al. (2018) study)

System definition of the RECC model (resource efficiency and climate change mitigation)

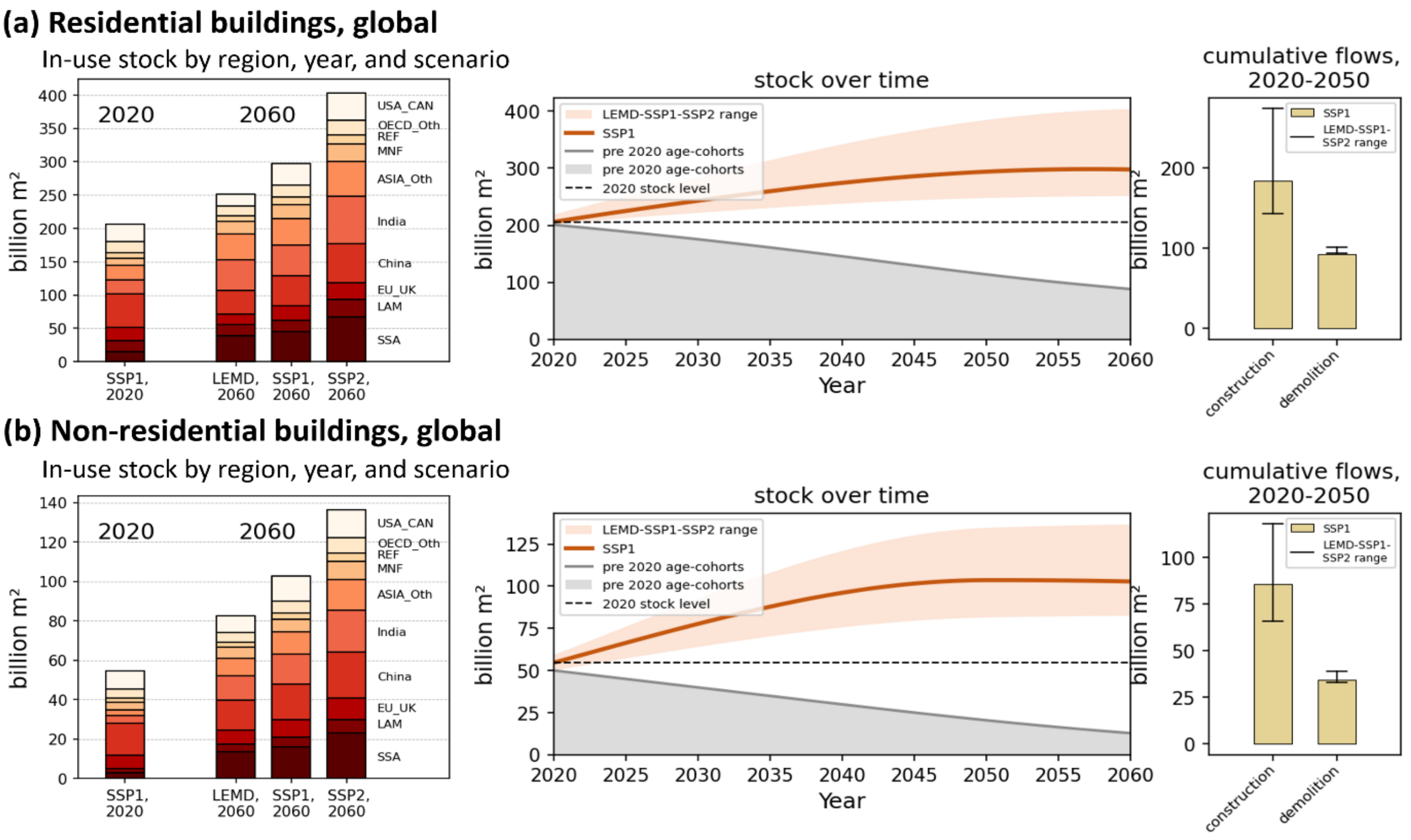


Main driver: per capita floorspace for residential and non-res. buildings

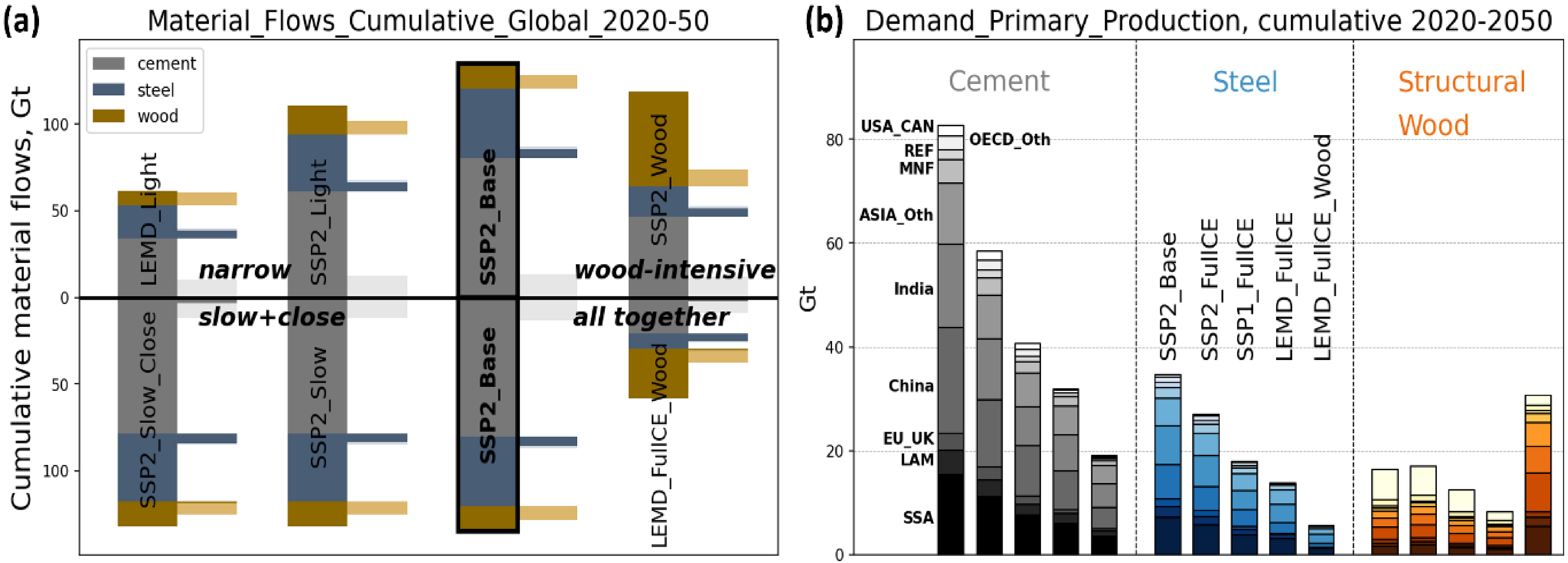
Table 1: Central parameters for the stock-flow-service nexus of the use phase: Initial and future service level (per capita floorspace) for the different socio-economic scenarios, and the typical building lifetime. Building lifetime can vary across age-cohorts and here, typical values are indicated. Region and scenario acronyms are defined in the text.

	2015 per capita stock (m^2)		2050 per capita stock, m^2, LEMD / SSP1 / SSP2		Typical Building lifetime (yr)	
Regions	**residential**	**non-res.**	**residential**	**non-res.**	**residential**	**non-residential**
SSA	11.4	0.8	19.4/26.9/33.4	7/10/12	50	45
LAM	34.4	3.0	30.3/34.4/44.3	7/10/12	50	45
EU_UK	37.7	12.5	31.2/40.1/46.2	12.8/16.1/20	100-180	60-80
China	36.1	10.8	31/40/50	13/16/20	27-40	30
India	11.7	0.8	25/28.7/38.1	7/10/12	50	45
Other_Asia	20.8	2.6	29.4/34.3/39	7.5/10.5/12.6	50	45
MNF	24.6	8.3	29.6/38.9/43.6	9/12/15	100	45
REF	23.5	5.9	29.5/38.9/43.5	9/12/15	120	60
Other_OEDC	38.0	6.5	30.5/39.9/44.5	9/12/15	100	50
USA_CAN	66.8	24.1	42.5/66.8/83.7	18/26/30	110	45

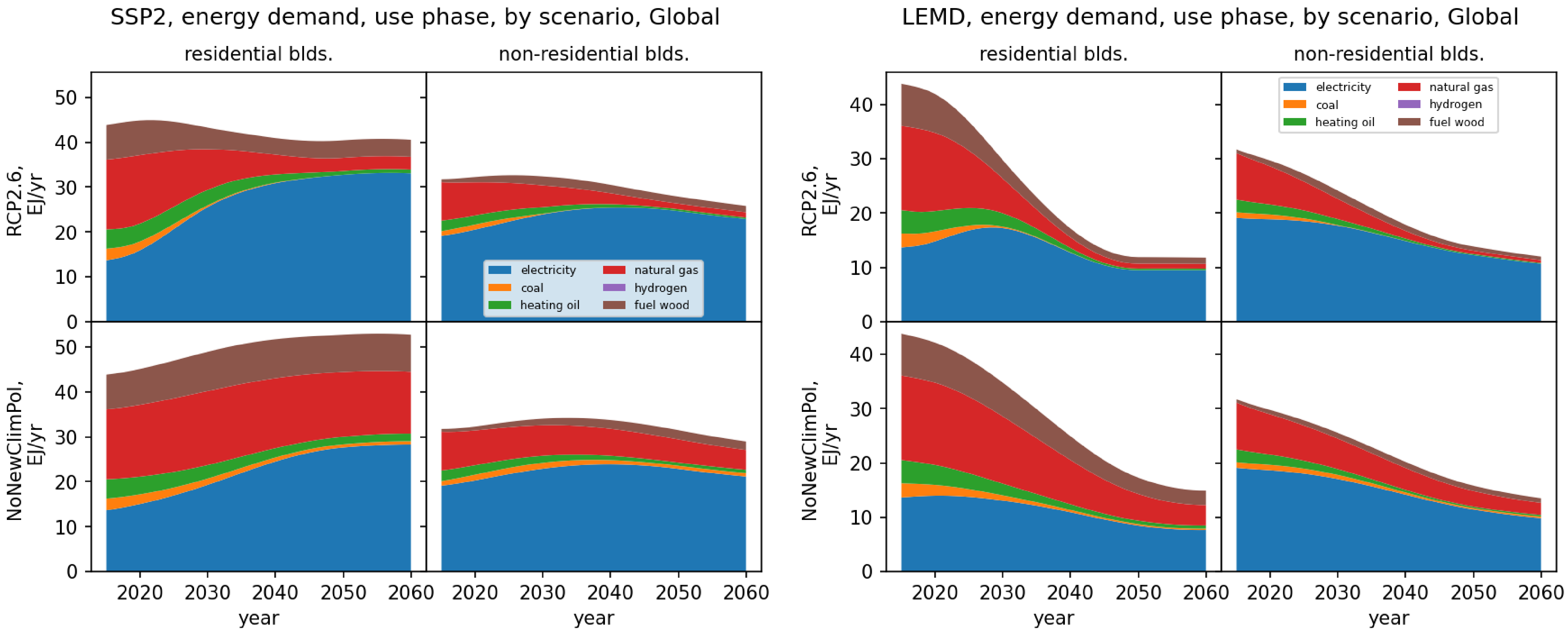
Stock and cumulative flows, global, 2020-2060



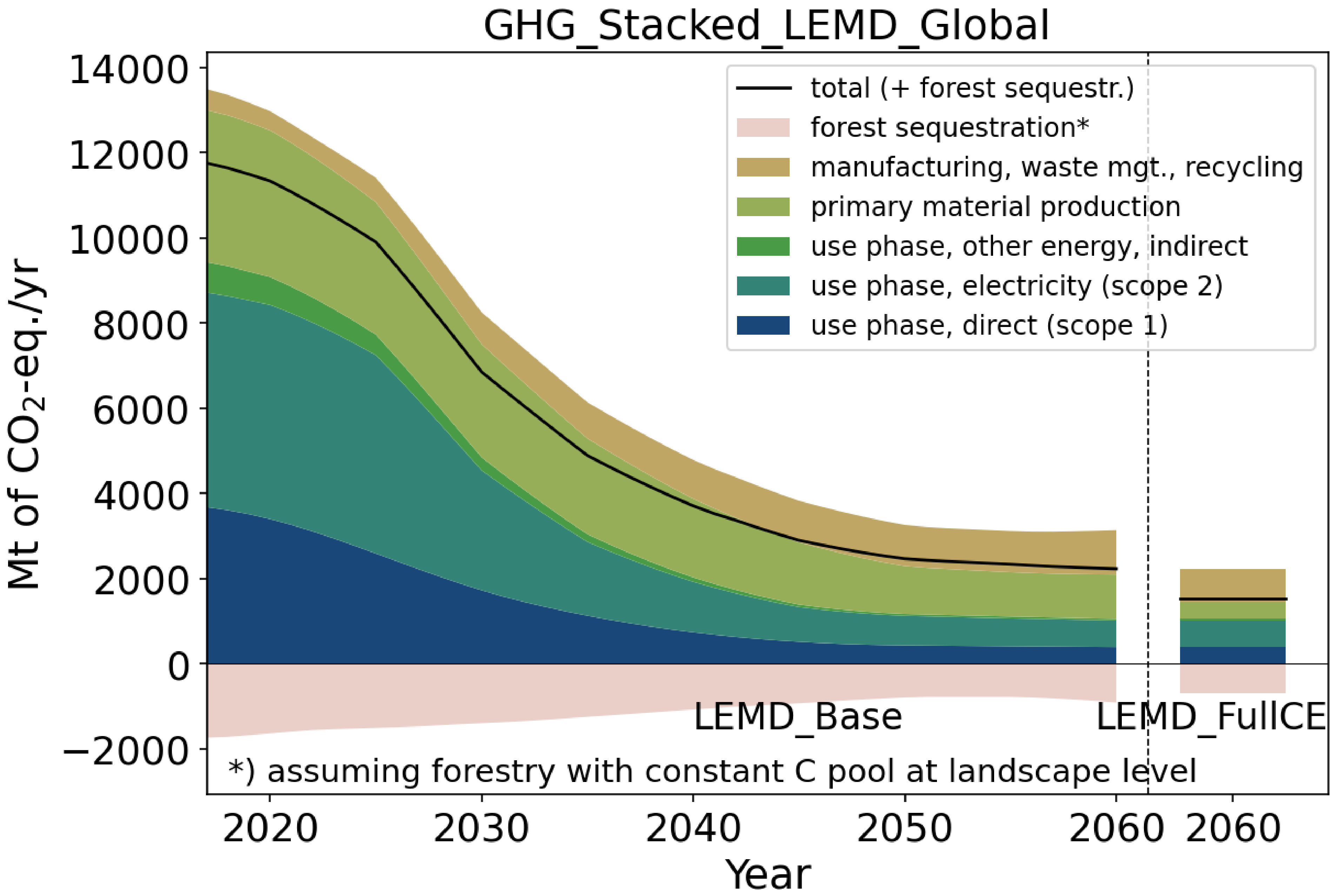
Cumulative material flows, global, 2020-2060



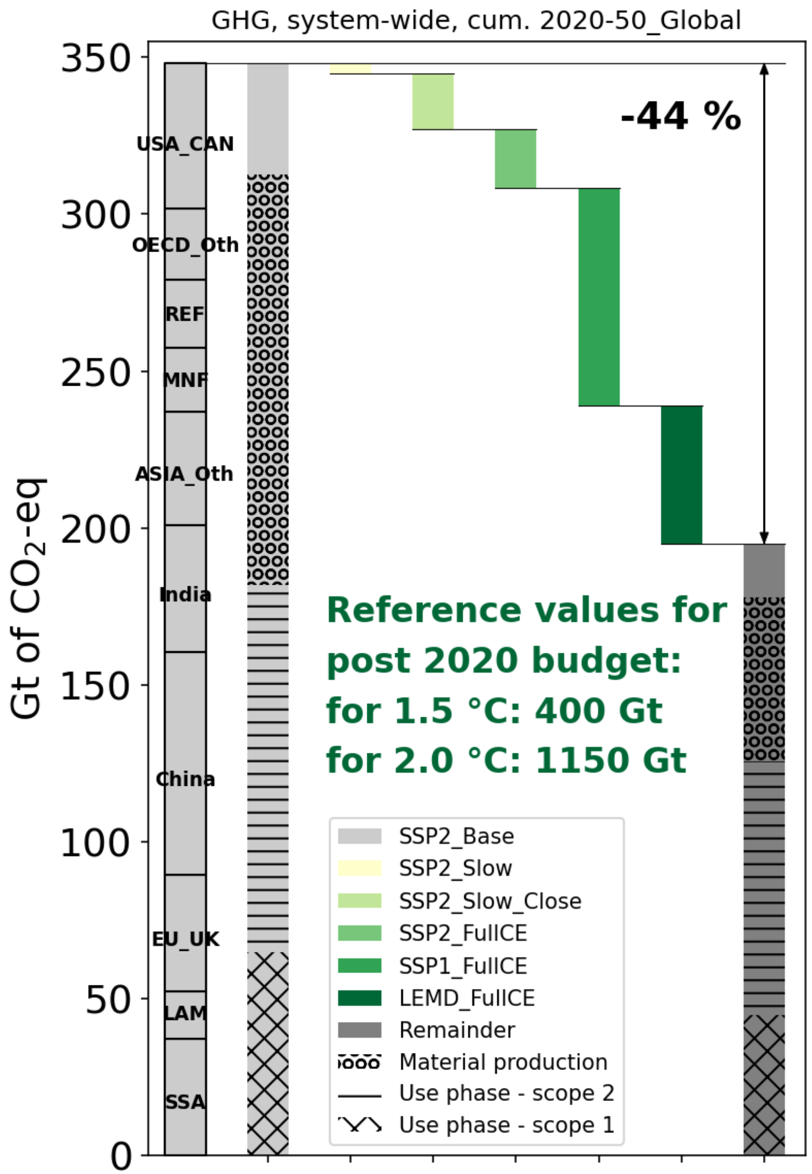
Use phase energy demand, global, 2020-2060

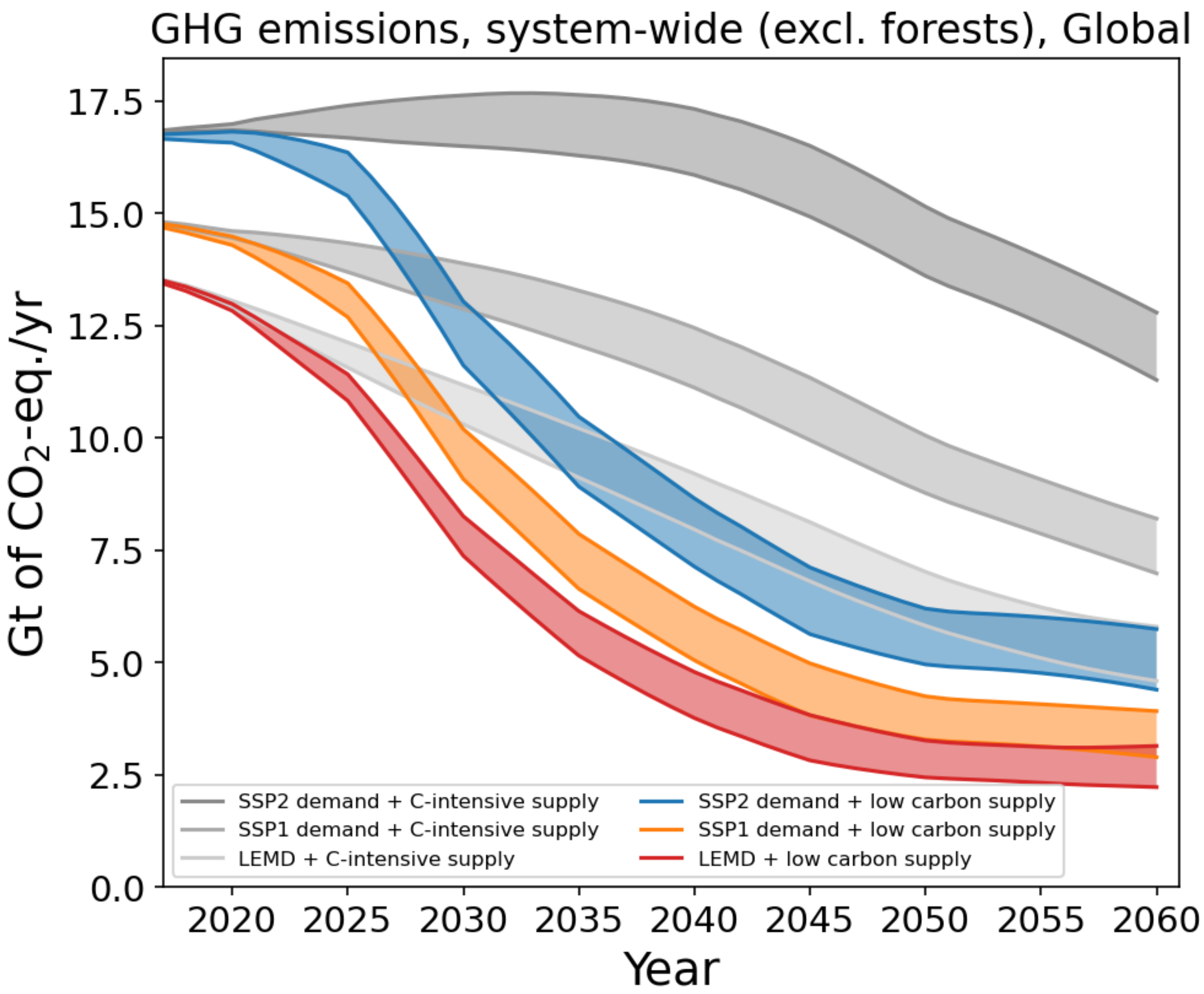


GHG time series by sector and region

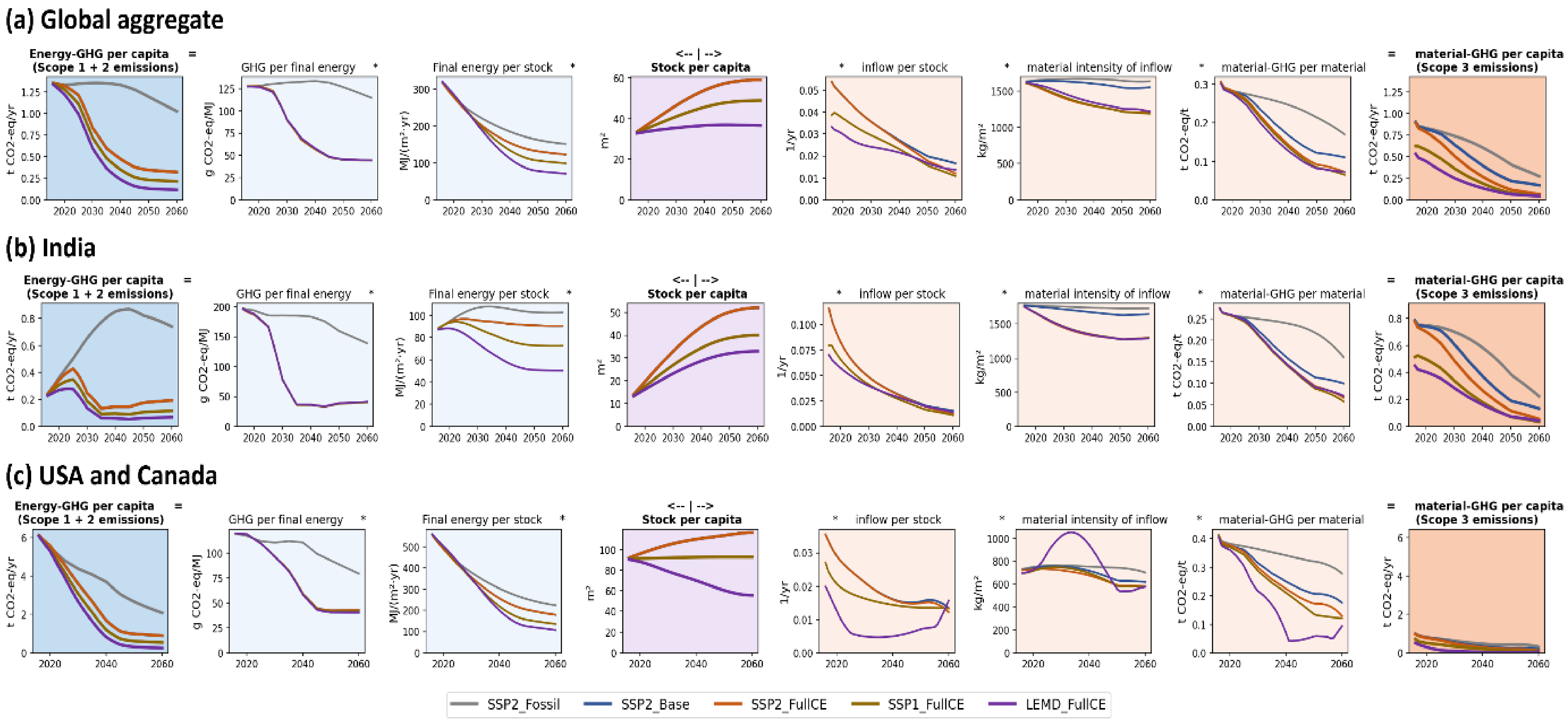


GHG reduction and scenario dependency





Decomposition analysis of Scope 1+2 and Scope 3 GHG



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Summary and outlook

- 2020-2050 global cumul. new construction ranges from 150 to 280 billion m^2 for residential and 70 120 billion m^2 for non-residential buildings. LEMD reduces cumul. 2020-2050 primary material demand from 80 to 30 gigatons (Gt) for cement and from 35 to 15 Gt for steel.
- Lowering floor space demand by 1 m^2 per capita leads to global savings of 800-2500 megatons (Mt) of cement, 300-1000 Mt of steel, and 3-10 Gt CO_2-eq, depending on industry decarbonization and CE roll-out.
- CE reduces 2020-2050 cumul. GHG by up to 44%, where the highest contribution comes from the narrow CE strategies, i.e., lower floorspace and lightweight buildings.
- Very low carbon emissions trajectories are possible only when combining supply and demand-side strategies.

→ Assess economic implications of LEMD! // Connect sector-level scenarios at the city scale!

Thank you for your attention!

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