Towards sustainable manufacturing

MICRO-301
Manufacturing Technologies

Yves Leterrier, May 28, 2025

Learning outcomes

- What are the main challenges towards sustainable manufacturing
- How to calculate the degree of circularity, and the material intensity of a product

slido

Please download and install the Slido app on all computers you use

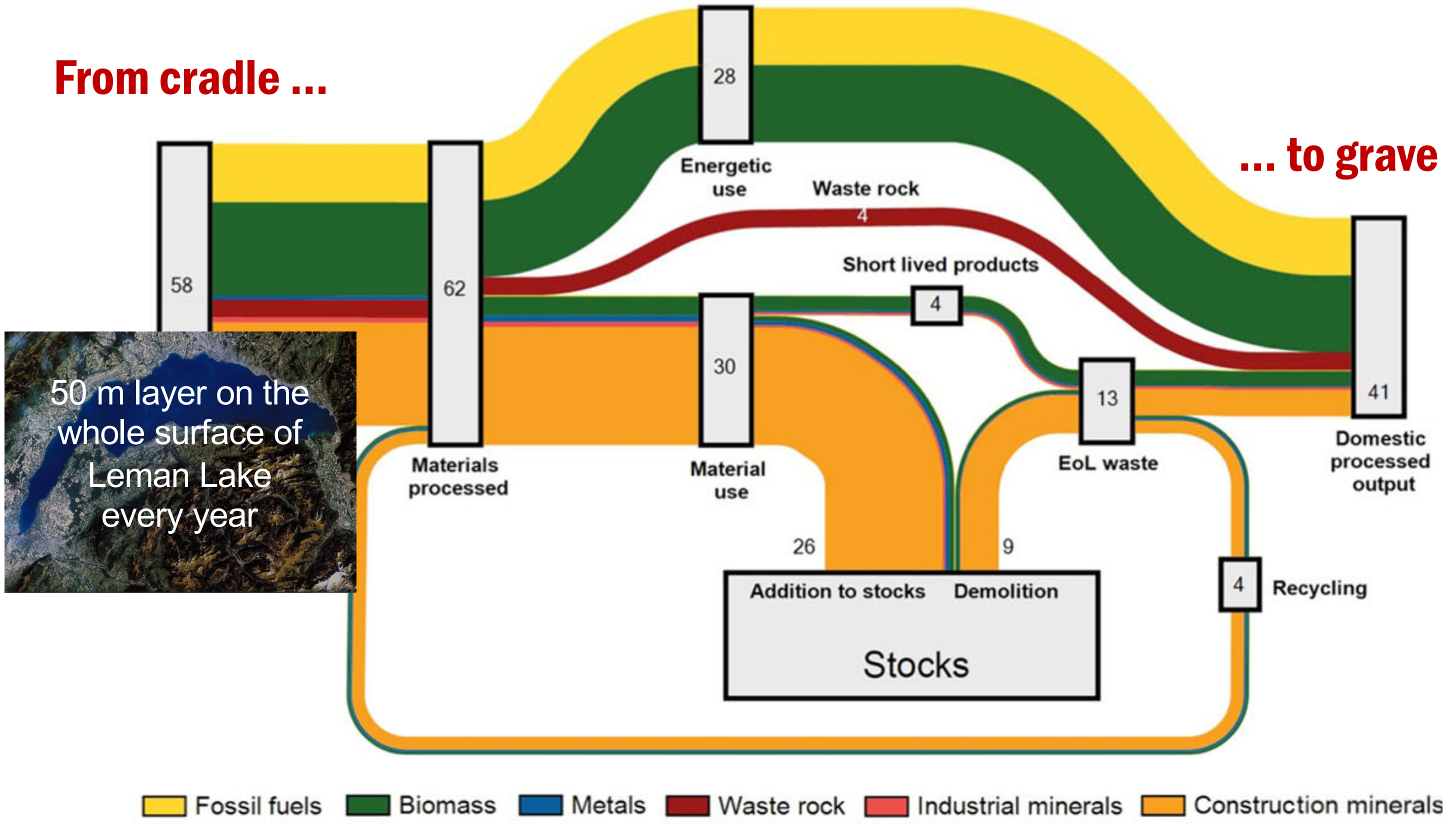
What is the degree of circularity of the present global economy?

ⓘ Start presenting to display the poll results on this slide.

Global materials flows [Gt/yr]

From cradle ...

... to grave



Haas, Krausmann, Wiedenhofer, Heinz, Journal of Industrial Ecology, 2015 (2005 data)

Outline

- Sustainability challenges
- Material circularity indicator (MCI)
- Material intensity per service unit (MIPS)
- Summary
- Appendix

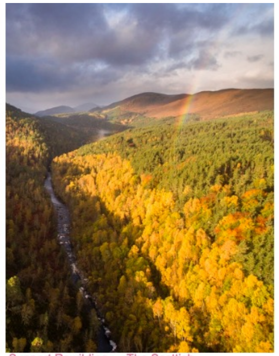
Case study of skis

2050: what is your vision?

AP to set up solar-wind hybrid project with battery back-up – The Leading Solar Magazine In India (eqmagpro.com)

Daily Mail Online

EV World Record: Mercedes Benz Vision EQXX Travels 1,000 Km On A Single Charge (forbes.com)



Support Rewilding — The Scottish Rewilding Alliance

Child Fun Outdoors - Free photo on Pixabay

ZEROe on the Rise at Airbus - CAFE Foundation Blog

[기업소개] 수소연료탱크 제조사 '일진다이아' : 네이버 블로그 (naver.com)

4 NetZero Energy Lessons | NetZero Buildings

People Group Many - Free photo on Pixabay

Sustainable development

Gro Harlem Brundtland, former prime minister of Norway

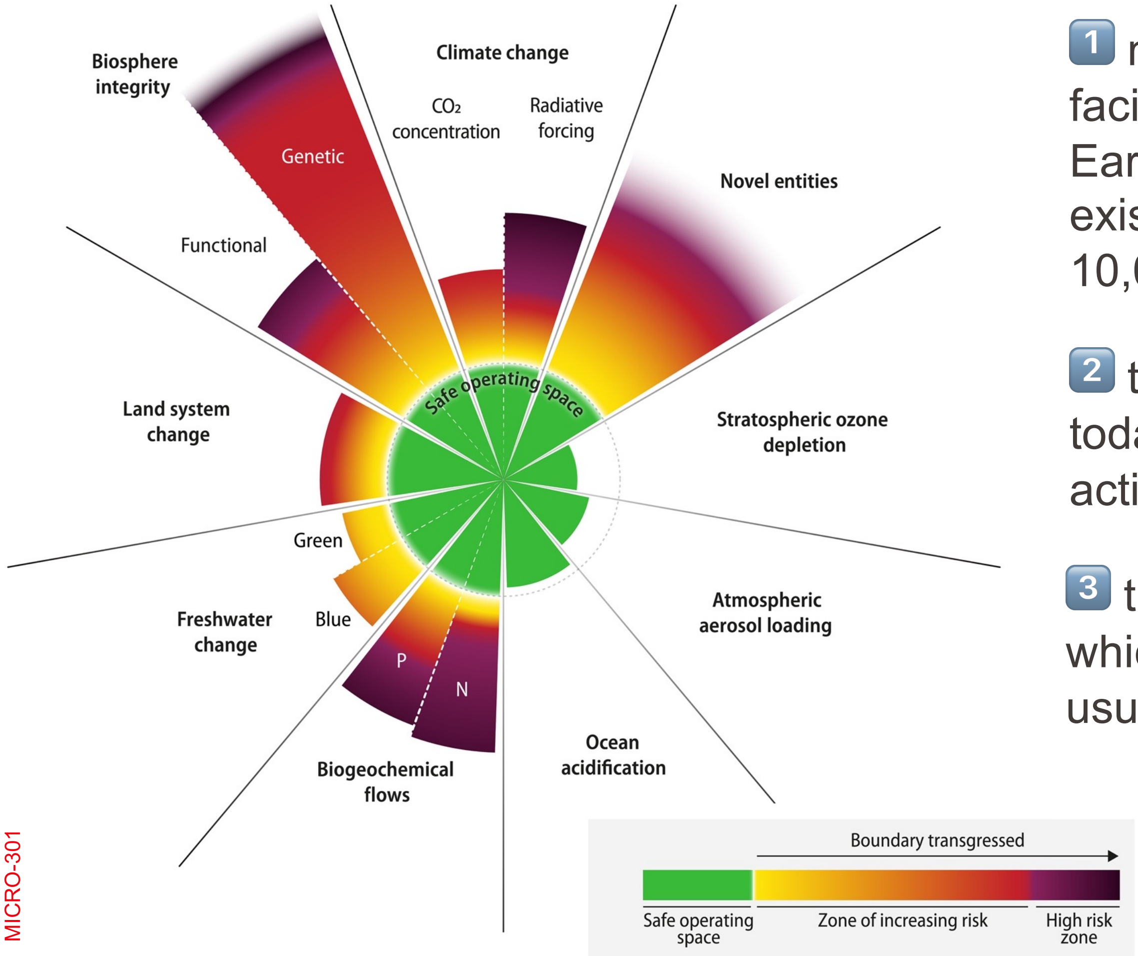
"Avoiding the depletion of our natural resources in order to maintain a balanced ecosystem and preserve natural capital while meeting the needs of the present without compromising the ability of future generations to meet their own needs"

World Commission on Environment and Development (Brundtland Commission, 1987)

Challenges!

- Earth beyond six of nine planetary boundaries
- Transition from a linear economy to a circular economy
- Hard-to-abate and critical raw materials
- Recycling
- Water
- Global South
- … and more!

Earth beyond six of nine planetary boundaries!



Richardson *et al.*, *Sci. Adv.* **9**, eadh2458 (2023)

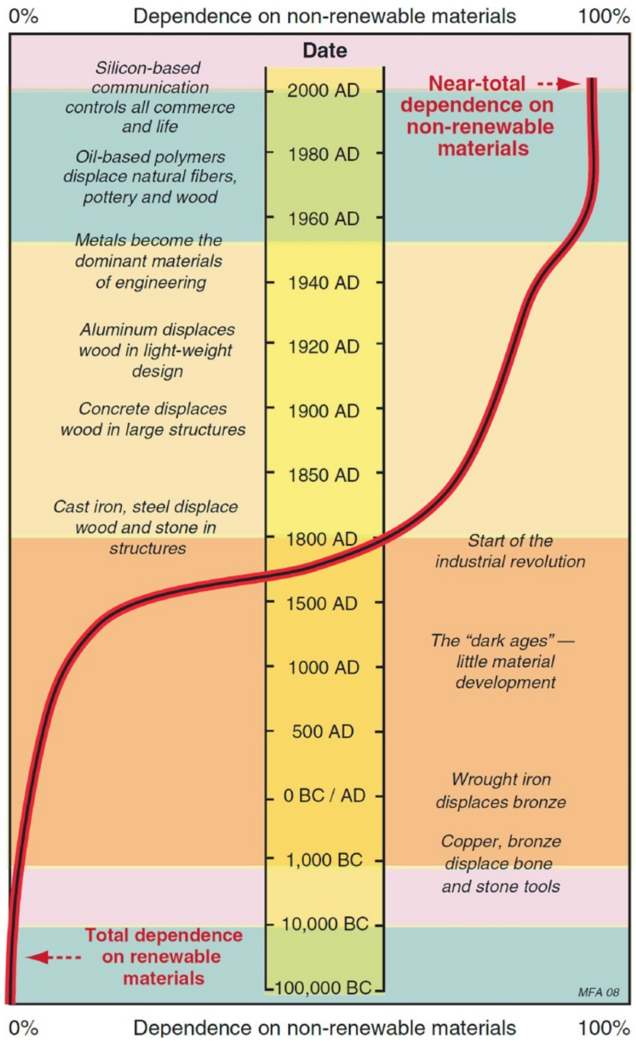
1 nine major processes facilitate and regulate the Earth's system as it has existed for approximately 10,000 years (*Holocene*);

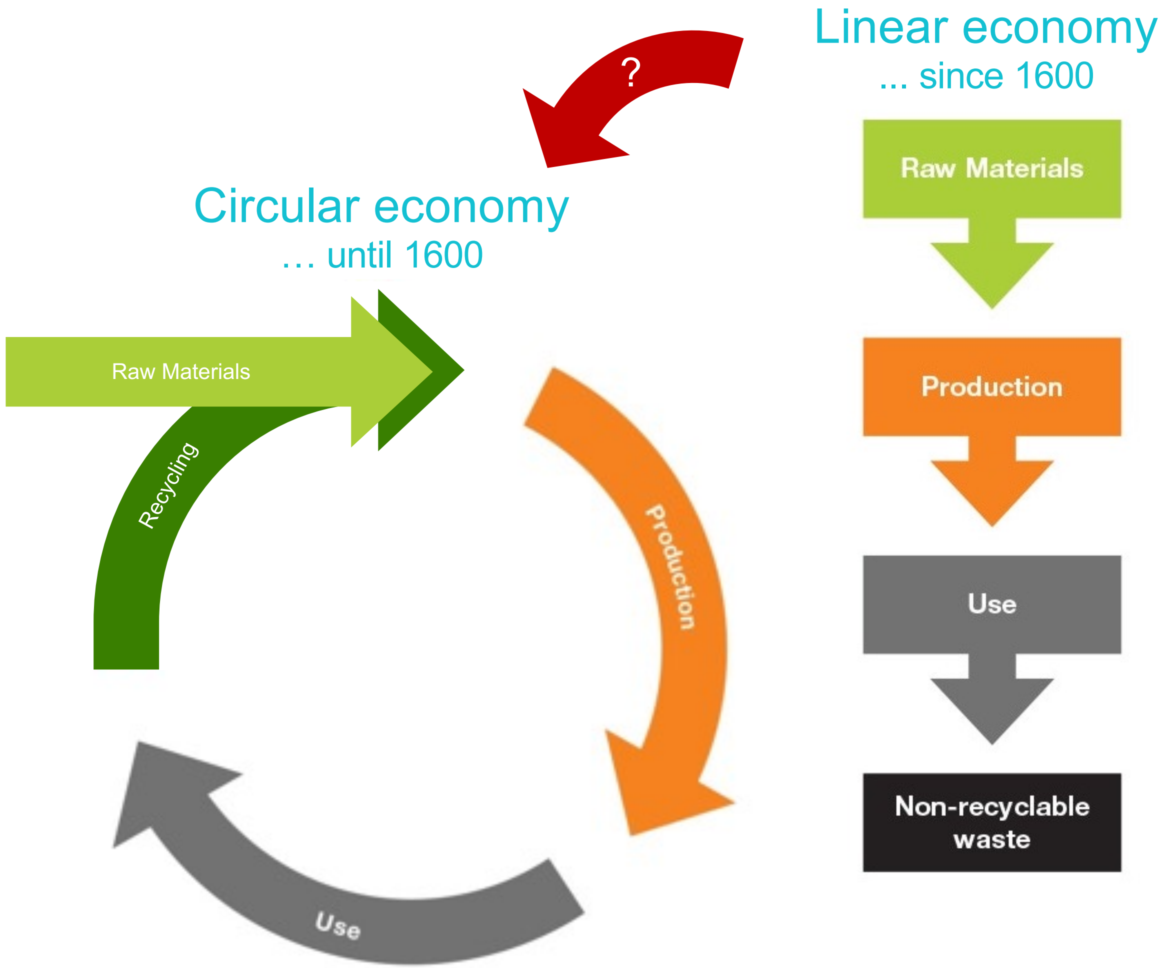
2 these processes are today impacted by human activities;

Prof. Johan Rockström, Director of the Potsdam Institute for Climate Impact Research

3 there exists for each of these a limit beyond which the process will no longer produce the usual effects and lead to radical imbalances.

Transition from a linear economy to a circular economy!





Gutowski et al., Phil Trans Roy Soc A, 2013, 371, 20120003
Ashby, *Materials and the environment: eco-informed material choice, 2nd Ed.* 2012: Butterworth-Heinemann, Oxford

Hard-to-abate and critical raw materials!

Hard-to-abate = hard to reduce in amount, degree, intensity or force

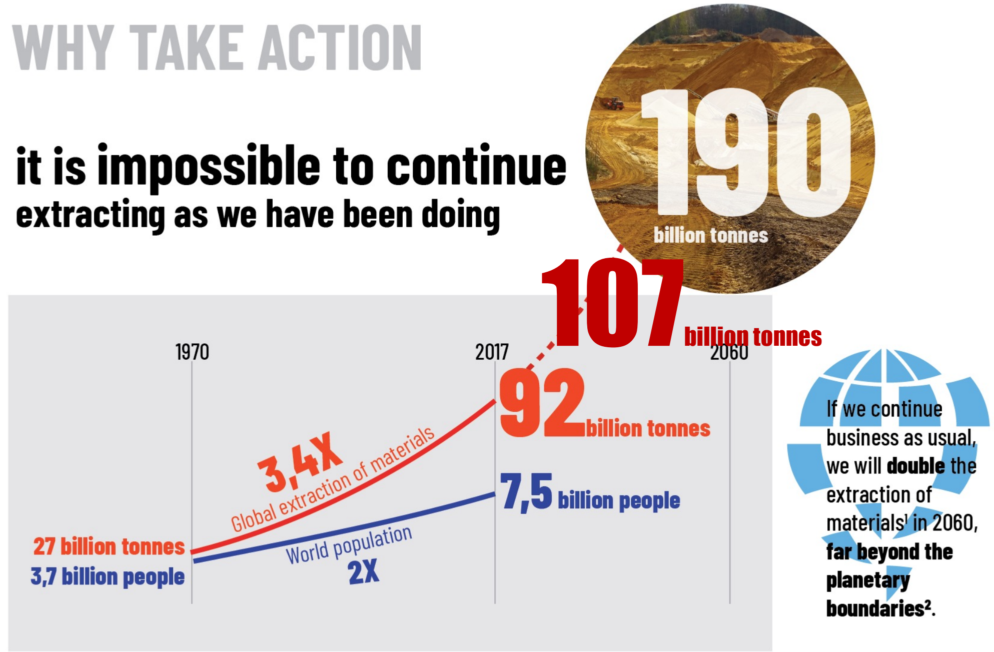
- Concrete
- Steel
- Aluminium
- Copper
- Petrochemicals and plastics

> 2/3 of total industrial carbon footprint

Critical = key for renewable energy and with supply risk

- Lithium
- Rare earth elements
- Copper
- Cobalt
- Silicon
- … and 28 others

We extracted 107 billion tonnes of raw materials from our planet in 2024, still increasing at 2.3%/yr



Source: IRP (2019): Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel. United Nations Environment Programme. Nairobi, Kenya
1: "Materials" include biomass, fossil fuels, metals and non-metallic minerals, being are a subset of natural resources which encompasses all material plus water and land.
2: For more information: https://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html

Recycling!

x 40

Primary gold ore ~ 5 g/ton

Secondary gold ore ~ 200 g/ton

Kalgoorlie, Australia

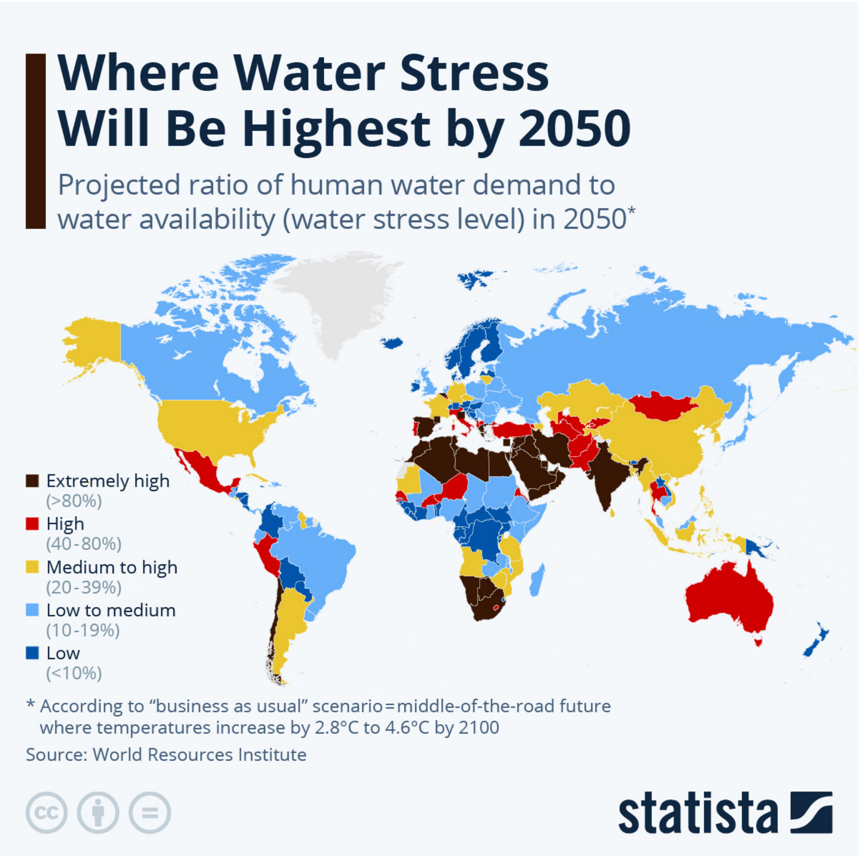
x 3.6

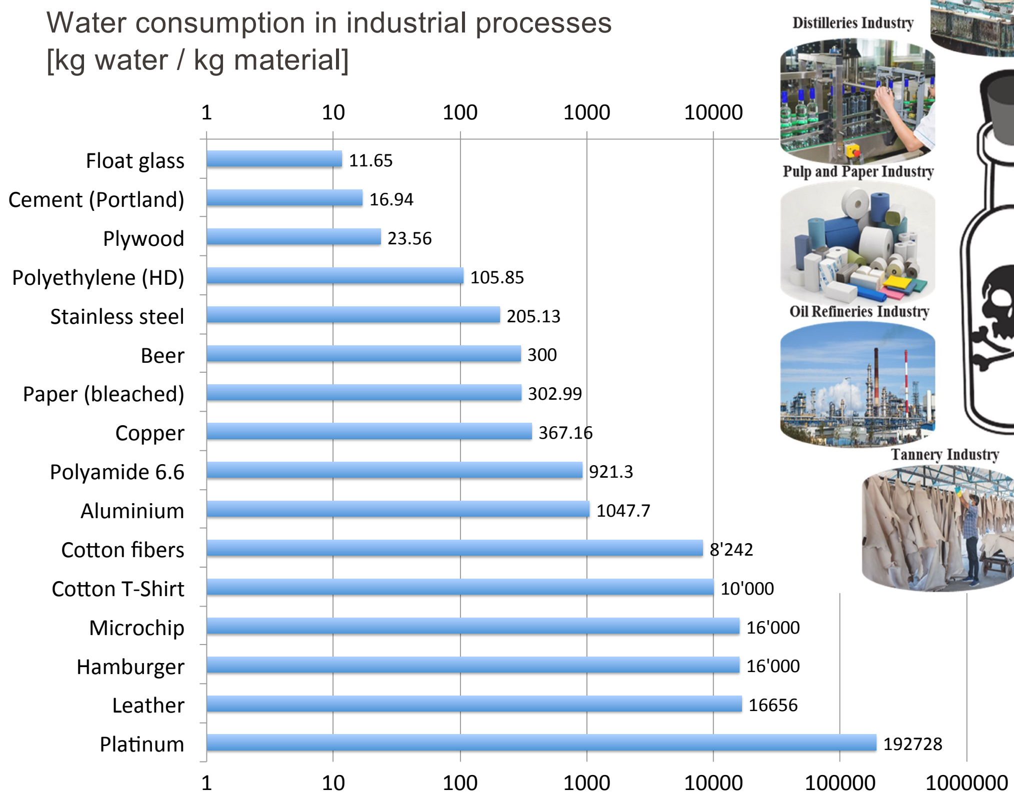
Production ~ 3’600 t/yr

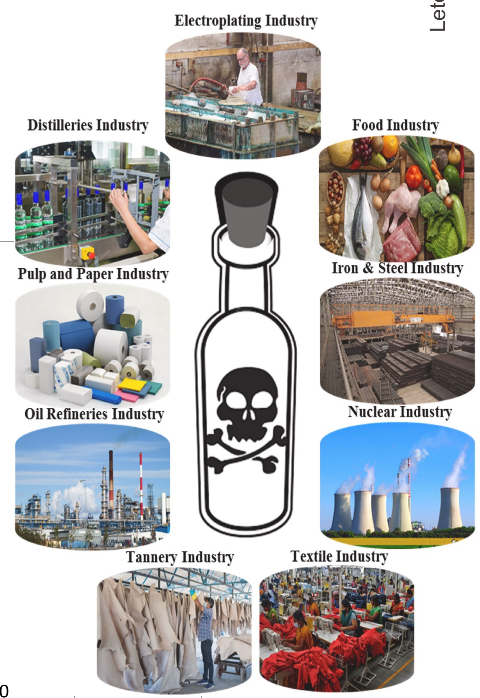
Production ~ 13’000 t/yr

Water!

Contamination of water in industrial processes

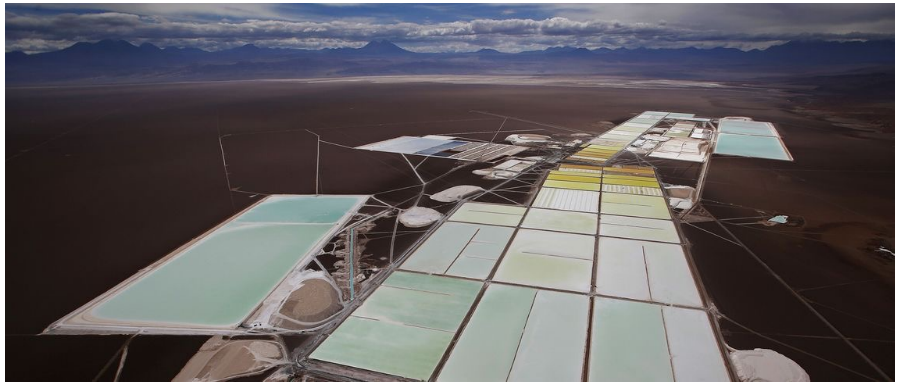






https://www.statista.com/chart/26140/water-stress-projections-global/
Wuppertal Institute for Climate, Environment and Energy
Alagan et al., Chemosphere 335 (2023): 139178

Global South!



Rockwood lithium plant on the Atacama salt flat in northern Chile (Reuters)

The Global South's double burden

The energy transition will require huge quantities of metals and minerals, such as lithium, copper, and other rare earths.

Electromobility in 2040 as an example:

- 40X increase for lithium
- 2X increase for copper

Currently known resources do not cover the needs!
(50% for Li, 80% for Cu)

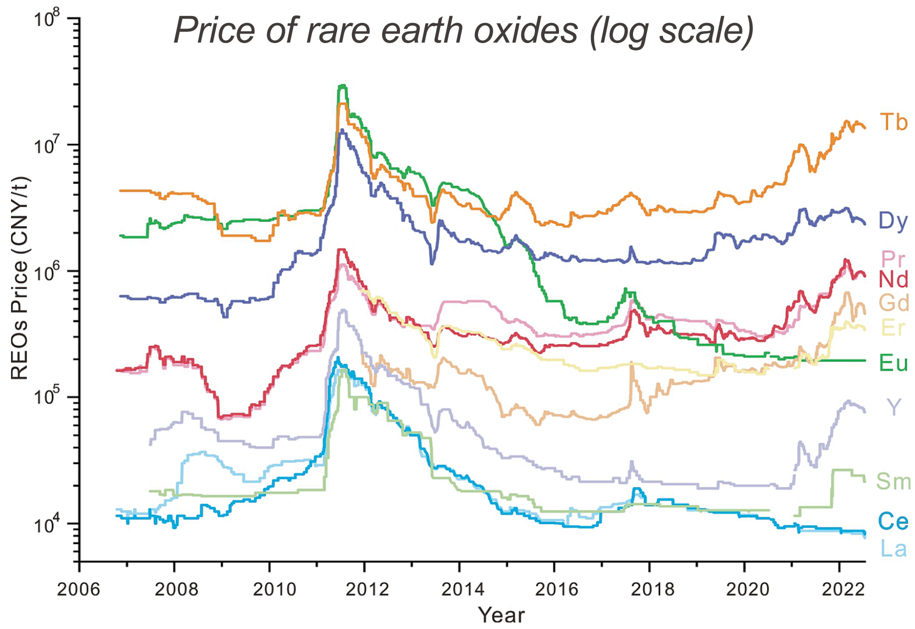
Local populations do not benefit from the material gains of the increasing resource exploitation, but are exposed to considerably negative social, economic, and environmental effects, largely without protection.

Over the coming decades, the importance of recycling and closed raw material cycles must increase because of resource scarcity and climate impacts. This is the only way of ensuring that climate protection in Western industrialized countries does not take place on the backs of disadvantaged groups and ecosystems in Latin America and other parts of the world.

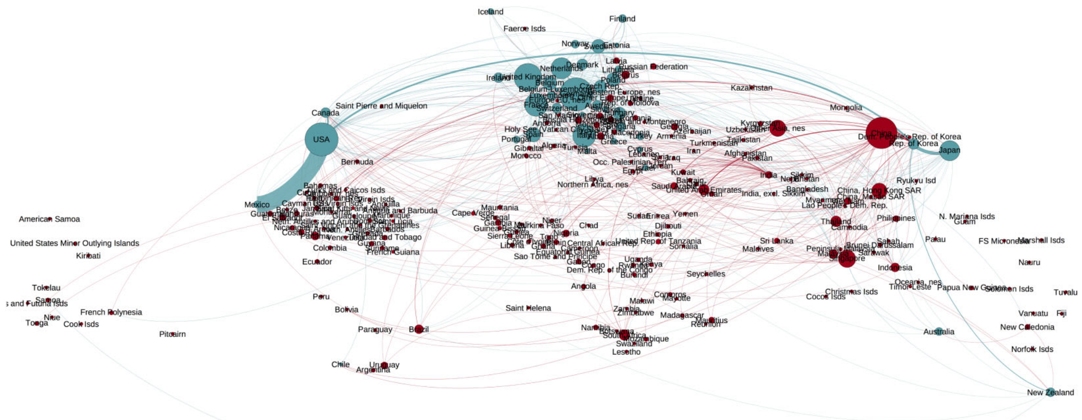
Adapted from Becker, *IPS Journal, 12.11.2021*
https://www.ips-journal.eu/topics/economy-and-ecology/the-global-souths-double-burden-5539/

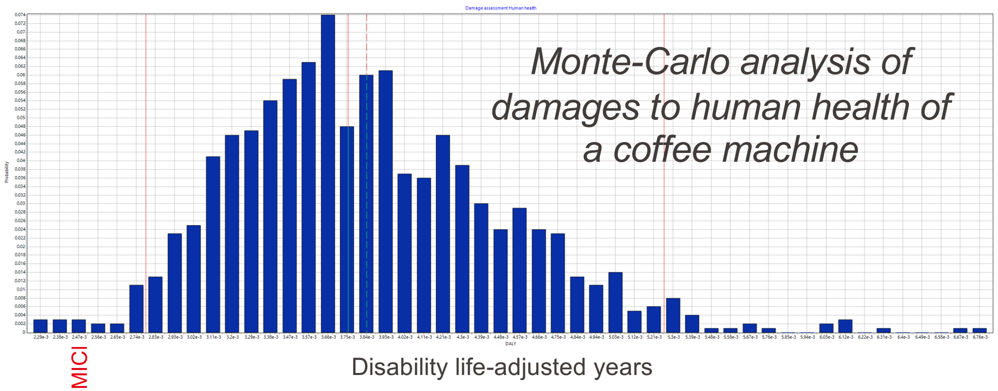
More challenges!

- Price volatility
- Logistics
- Modeling uncertainty
- …



Global e-waste trade logistics network, 2012





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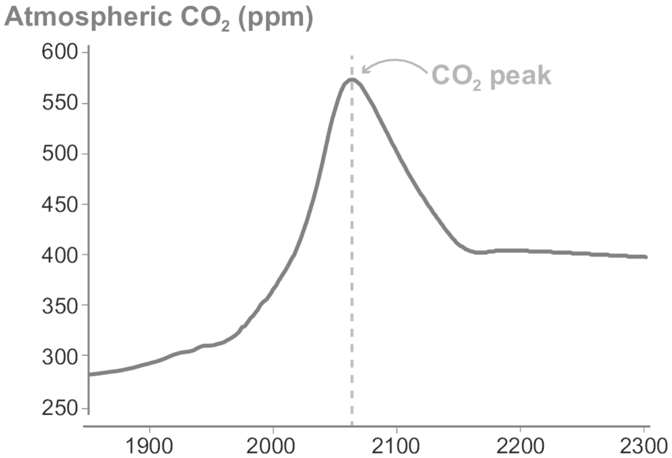
MICI

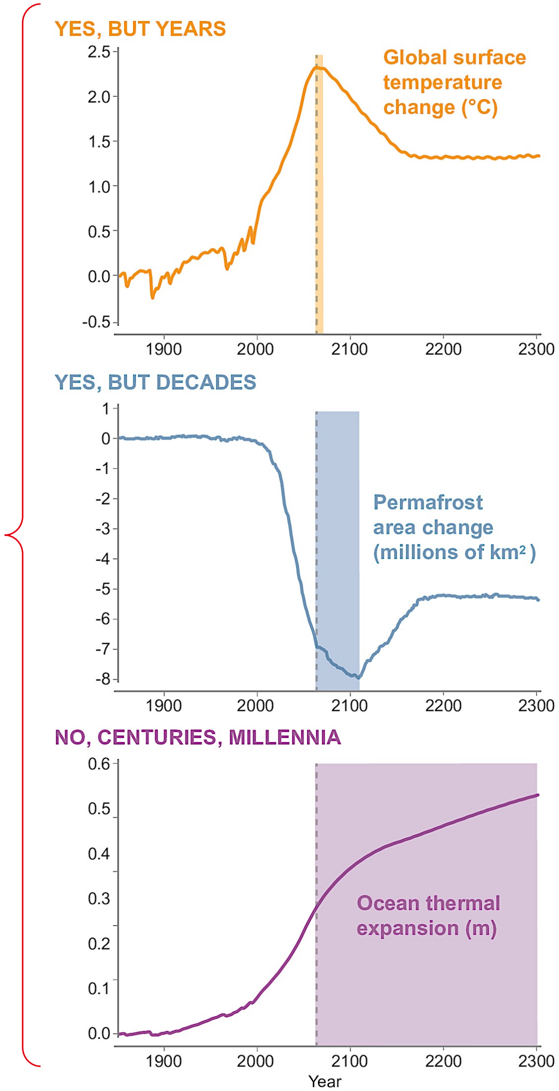
The tragedy of the horizon

Mark Carney, governor of the bank of England (2013-2020)



Climate change is the «Tragedy of the Horizon»

The catastrophic effects of climate change will be felt (well) beyond the traditional horizons of most (financial) actors



https://www.ipcc.ch/report/ar6/wg1/

Flight, fight, or freeze

- Aim is to help you fight
- Not freeze in data overload
- Not run away and ignore the issue

https://giphy.com/gifs/peter-rabbit-peter-rabbit-9SIOcABjpsyvNIQZbR

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UN’s 17 sustainable development goals

SUSTAINABLE DEVELOPMENT GOALS
17 GOALS TO TRANSFORM OUR WORLD

Materials & manufacturing are central, especially 6,7,9,11,12,13

Sustainable manufacturing

- Aims to produce goods and services using processes that conserve material and energy resources, regenerate natural systems, minimize environmental impacts, and ensure economic viability
- Encompasses the entire lifecycle of a product, from raw material sourcing to end-of-life disposal, and emphasizes efficient resource utilization, waste reduction, and circular economy principles
- Safe and healthful for workers, communities, and consumers; and socially and creatively rewarding for all working people

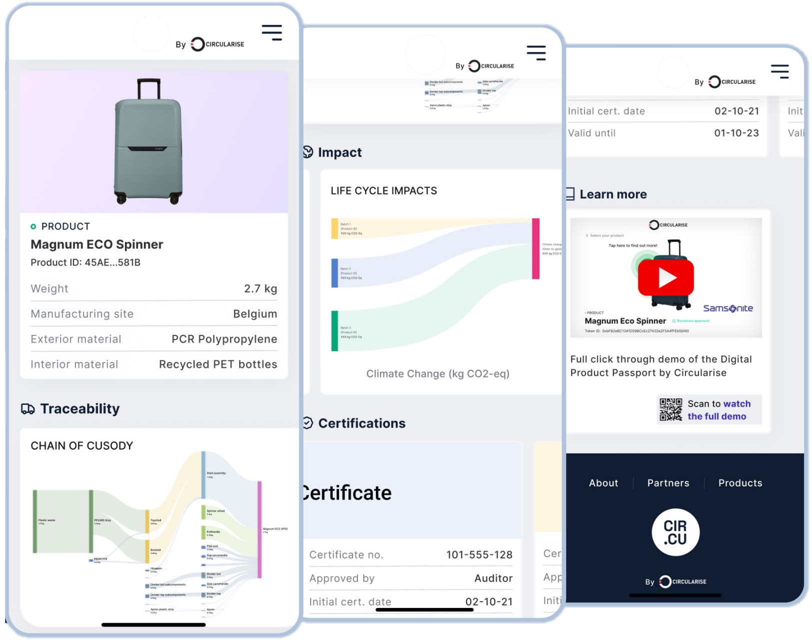
"Sustainable manufacturing" does not exist!

You have to think in terms of "sustainable product life cycles"

Sustainable Production: a Working Definition. Informal meeting of the committee members. Lowell Center for Sustainable Production (1998)
After Jawahir & Dillon (2007). "Sustainable Manufacturing Processes: New Challenges for Developing Predictive Models and Optimization Techniques," (Keynote Paper), Proceedings of First International Conference on Sustainable Manufacturing, Montreal, Canada, 1-19 (2007)

Sustainable manufacturing digital product passports

- Digital Product Passports (DPPs) are crucial for sustainable manufacturing!
- Enhance traceability, transparency, and circularity throughout the product lifecycle, promoting responsible resource management and reducing waste.
- Help businesses comply with regulations, optimize supply chains, and foster consumer trust.

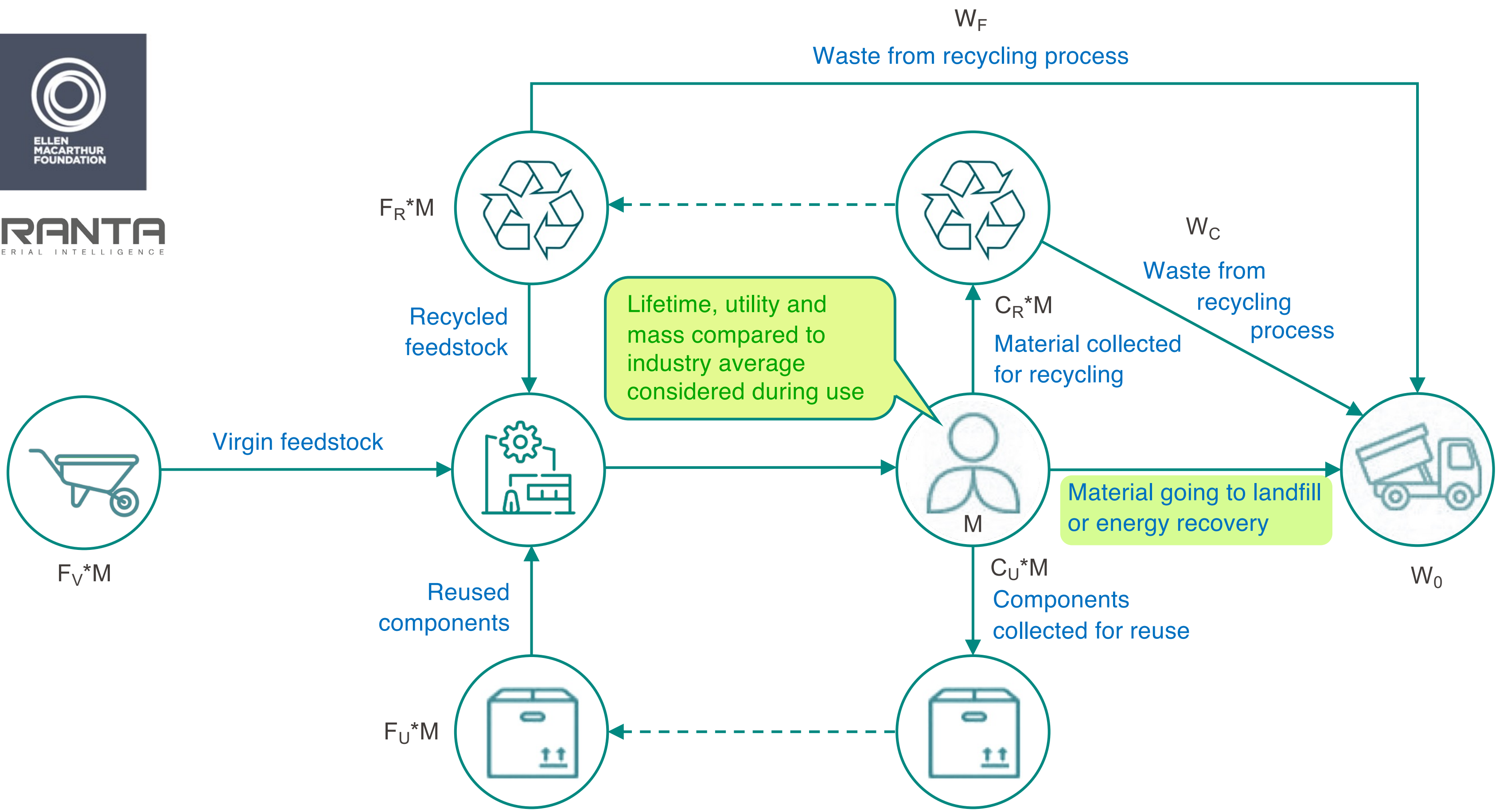


Google AI 'what is the role of digital product passports for sustainable manufacturing'
https://www.circularise.com/blogs/digital-product-passports-dpp-what-how-and-why

Material circularity indicator (MCI*)

ELLEN MACARTHUR FOUNDATION

GRANTA MATERIAL INTELLIGENCE



(*) details in Appendix

Material circularity indicator (MCI)

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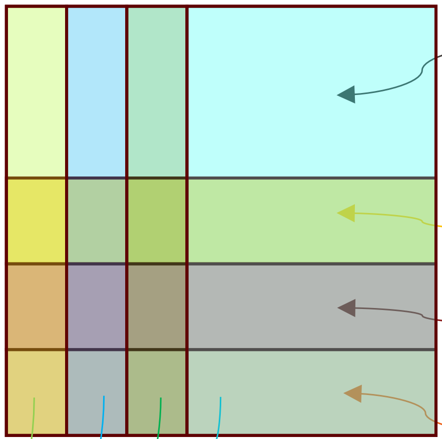
Product mass M



$V = F_V * M$ (virgin material)
$= (1 - F_S - F_R - F_U) * M$

$F_S * M$ (biological material; efficiency 100%)

$F_R * M$ (recycled material; efficiency E_F;
unrecoverable waste mass(1) $W_F = M*(1 - E_F)*F_R)/E_F)$

$F_U * M$ (reused material; efficiency 100%)

Feedstock materials 'upstream'

$C_E * M$ (biological material for energy recovery; efficiency E_E(2);
unrecoverable waste mass(3) $W_0 = M * (1 - C_R - C_U - C_C - C_E))$

$C_C * M$ (material to be composted; efficiency 100%)

$C_R * M$ (material for recycling; efficiency E_C(4); unrecoverable waste mass $W_C = M*(1 - E_C)*C_R)$

$C_U * M$ (material for reuse; efficiency 100%)

Total unrecoverable waste mass(5) $W = W_0 + (W_F + W_C)/2$

Waste materials '*downstream*'

(1) F_R*M enters the product, i.e., a mass F_R*M/E_F has to be recycled
(2) materials from sustained production; (3) includes landfill; (4) $E_C = E_F$ in closed loop recycling;
(5) a 50:50 approach is considered to give same emphasis to the 2 recycling processes F_R and C_R

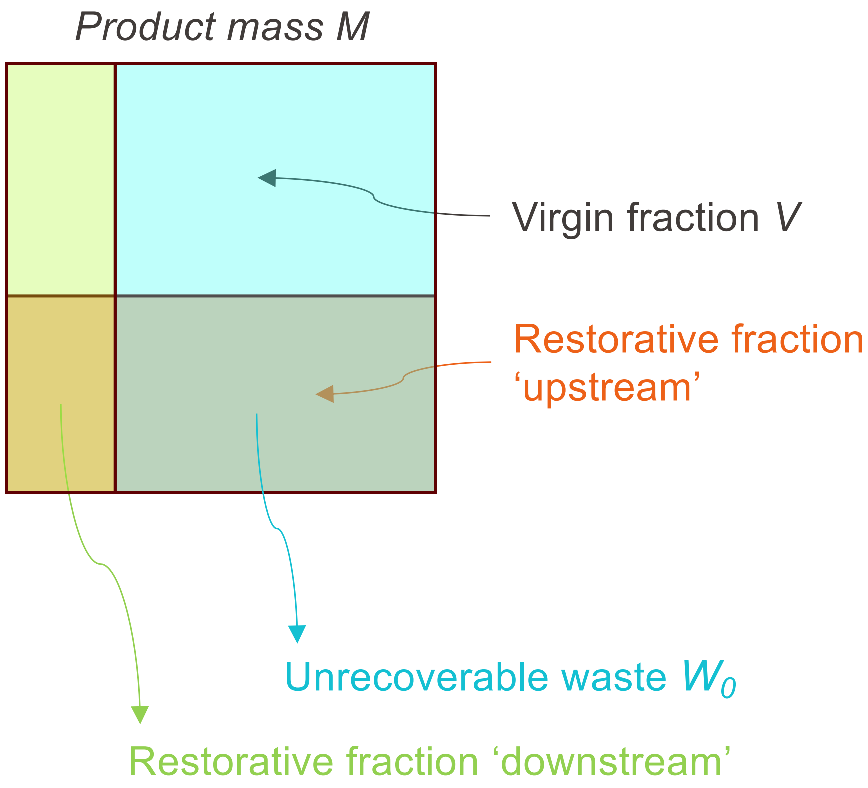
Linear Flow Index (LFI)

The Linear Flow Index (*LFI*) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste.

If there is no waste from the recycling processes ($W_F = W_C = 0$) then:

$$LFI = \frac{V + W_0}{2M}$$

- If only virgin materials ($M = V$) and no recycling ($M = W_0$) then $LFI = 1$
- If no virgin materials ($V = 0$) and no waste ($W_0 = 0$) then $LFI = 0$



Restorative fraction = proportion of the product that comes from reused or recycled sources and is restored through reuse or recycling.

Linear Flow Index (LFI)

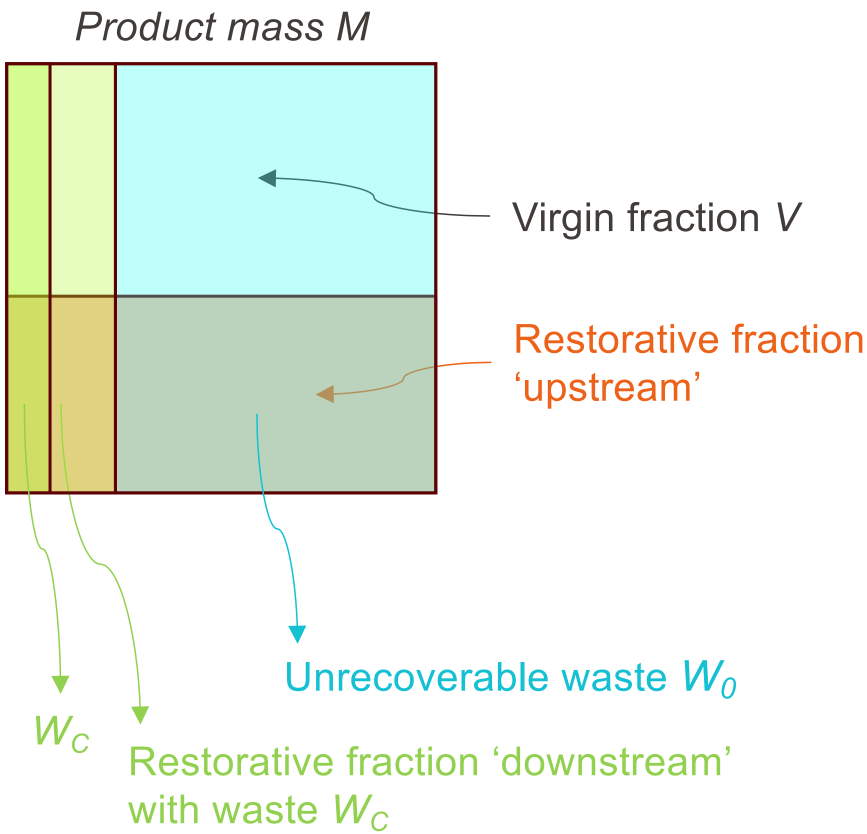
The Linear Flow Index (*LFI*) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste.

If there is waste from the end of life recycling process ($W_C > 0$) then:

$$LFI = \frac{V + W_0 + W_C/2}{2M - W_C/2}$$

Only 50% of the waste W_C is counted as part of the waste generated by the product being recycled. The other 50% is counted as part of the waste created by a product using the recycled material ('50:50 approach')

$W_C/2$ is excluded from the total mass flow *2M* since it will never be counted as waste generated by the product and neither can it form part of the restorative flow.



Restorative fraction = proportion of the product that comes from reused or recycled sources and is restored through reuse or recycling.

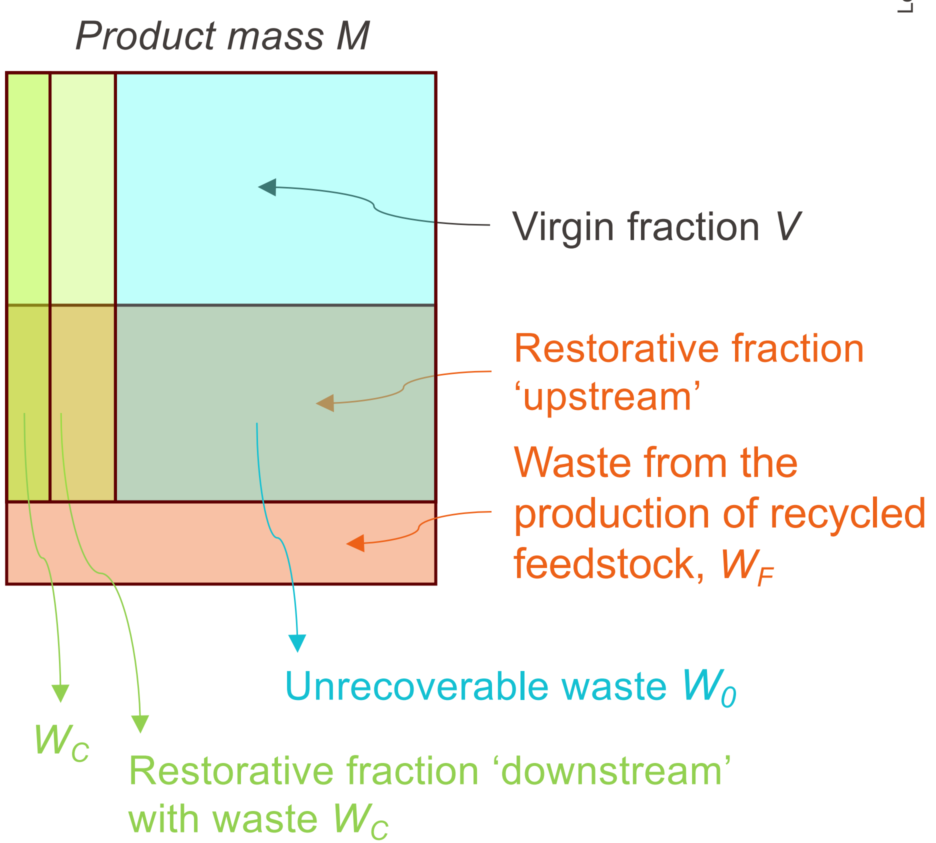
Linear Flow Index (LFI)

The Linear Flow Index (*LFI*) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste.

If there is also waste from the production of recycled feedstock ($W_F > 0$) then:

$$LFI = \frac{V + W_0 + W_C/2 + W_F/2}{2M - W_C/2 + W_F/2}$$

The waste W_F does not come from the material that is part of the product, and must be added to the total mass and waste flows. Following the same 50:50 approach as for the end-of-life recycling waste W_C, only 50% of W_F is considered, and added to both the waste W_0 and total mass $2M$.



Restorative fraction = proportion of the product that comes from reused or recycled sources and is restored through reuse or recycling.

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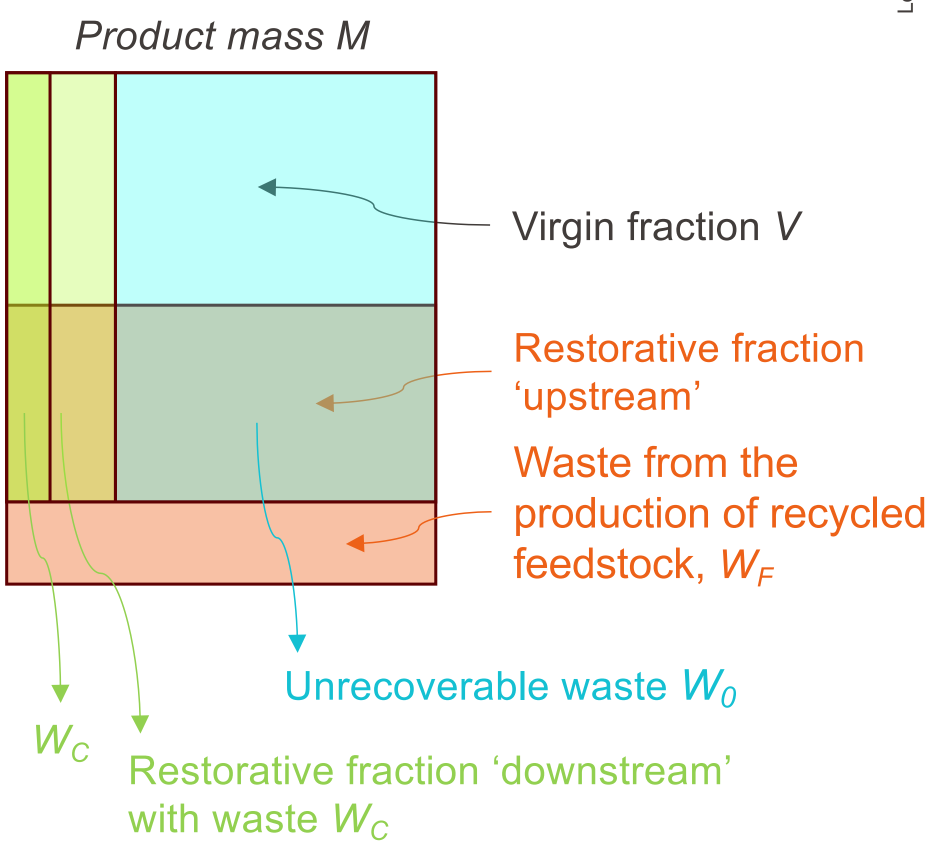
Linear Flow Index (LFI)

The Linear Flow Index (*LFI*) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste.

Finally, using the total unrecoverable waste mass W:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$$

- Linear product: if only virgin materials ($M = V$) and no recycling ($M = W$) then $LFI = 1$
- Circular product: if no virgin materials ($V = 0$) and no waste ($W = 0$) then $LFI = 0$



Restorative fraction = proportion of the product that comes from reused or recycled sources and is restored through reuse or recycling.

Utility factor X and utility function F(X)

The utility factor *X* has three components: one accounting for the product lifetime, another for the intensity of the product use and the third one for the product mass:

Lifetime, utility and mass compared to industry average considered during use

$$X = \frac{L}{L_{av}} \frac{U}{U_{av}} \frac{M_{av}}{M}$$

L = product lifetime
L_{av} = industry-average lifetime
U = product use intensity (number of '*functional units*'(1))
U_{av} = industry-average use intensity
M = product mass
M_{av} = industry average mass

- The intensity of use U/U_{av} reflects the extent to which a product is used to its full capacity(2)
- *X* increases when *L* and *U* increase, and *M* decreases

The utility function $F(X) = 0.9/X$

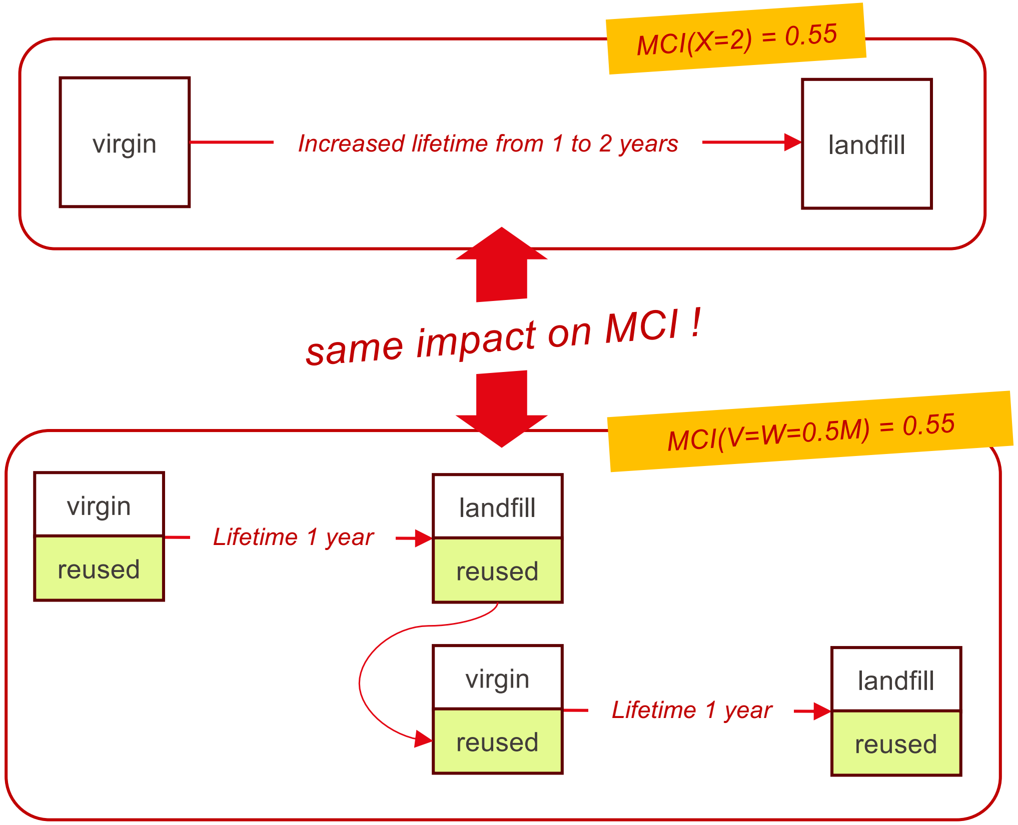
(1) functional units here could be one kilometer driven for a car, or one wash cycle for a washing machine.

(2) Increasing a product's use intensity results in a more efficient use of any resources that take a linear path in the material flow, and hence an improvement in the final MCI.

Utility factor X and utility function F(X)

The utility function $F(X) = 0.9/X$

- F ~ 1/X so that an increase of utility (via e.g., an increased lifetime) leads to a decrease of the LFI, hence an increase of the MCI.
- 0.9 is a constant to calibrate the model so that the MCI for products with perfect linear mass flows and utility equal to the industry average is equal to 0.1, whereas those with utility below industry average the MCI is below 0.1.
- F is designed to penalize products with short lifetimes, poor utility, and high mass.



Material circularity indicator (MCI)

$$MCI = max\left[0, \left(1 - LFI * F(X)\right)\right]$$

$$\Rightarrow \quad MCI = 1 - \left(\frac{V + W}{2M + \frac{W_F - W_C}{2}}\right)\left(\frac{0.9}{X}\right)$$

- Linear product: if only virgin materials (*M* = *V*) and no recycling (*M* = *W*) then *LFI* = 1 and 0 < *MCI* < 0.1
- Circular product: if no virgin materials (*V* = 0) and no waste (*W* = 0) then *LFI* = 0 and *MCI* = 1

MCI case studies

Case study #1: Is is better to extend the lifetime of a product or to recycle it to increase its circularity?

Case study #2: Manufacture of skis

Case study #1: Is is better to extend the lifetime of a product or to recycle it to increase its circularity?

$$MCI = 1 - \left(\frac{V+W}{2M + \frac{W_F - W_C}{2}}\right)\left(\frac{0.9}{X}\right)$$

Influence of lifetime (L/L_{av}) on circularity

$$MCI\left(\frac{L}{L_{av}}\right) = 1 - 0.9\,\frac{L_{av}}{L} \;\rightarrow 1 \text{ when } L \rightarrow \infty$$

Hypotheses for the lifetime calculation
1) no recycling, only lifetime increases ($V = W = M$; $W_F = W_C = 0$)
2) utility $U = U_{av}$ and mass $M = M_{av}$

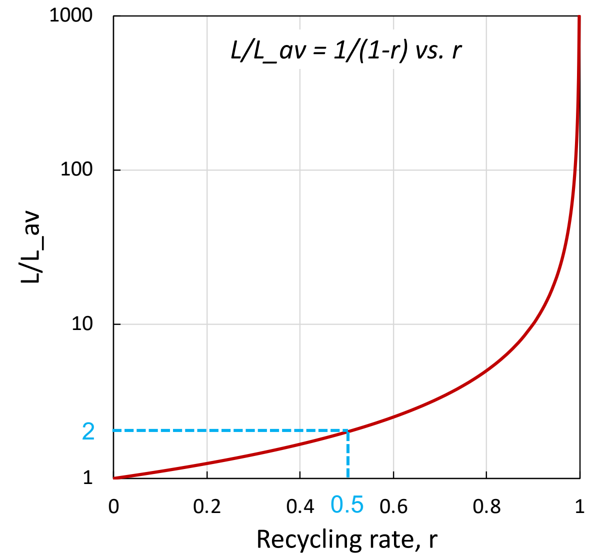
Influence of recycling rate ($0 < r < 1$) on circularity

$$MCI(r) = 0.1 + 0.9\,r \;\rightarrow 1 \text{ when } r \rightarrow 1$$

Hypotheses for the recycling calculation
1) closed-loop recycling ($r = F_R = C_R$)
2) Efficiencies $E_F = E_C = 100\%$

Equivalence between lifetime and recycling rate

$$MCI\left(\frac{L}{L_{av}}\right) = MCI(r) \Leftrightarrow \frac{L}{L_{av}} = \frac{1}{1-r}$$



Doubling the lifetime is equivalent to increase recycling from 0 to 50%

Case study #2: Manufacture of skis

https://www.loetschental.ch/en/winter/ski-arena

The thinkstep MCI tool

The calculator follows the Ellen MacArthur Foundation methodology, and includes the 2024 addendum that enables MCI to be calculated as a percentage. The MCI methodology is a reliable tool that conforms to the requirements of a circularity metric as defined by ISO 59020. It includes all of the mandatory core indicators and one of the optional core indicators specified in this standard.

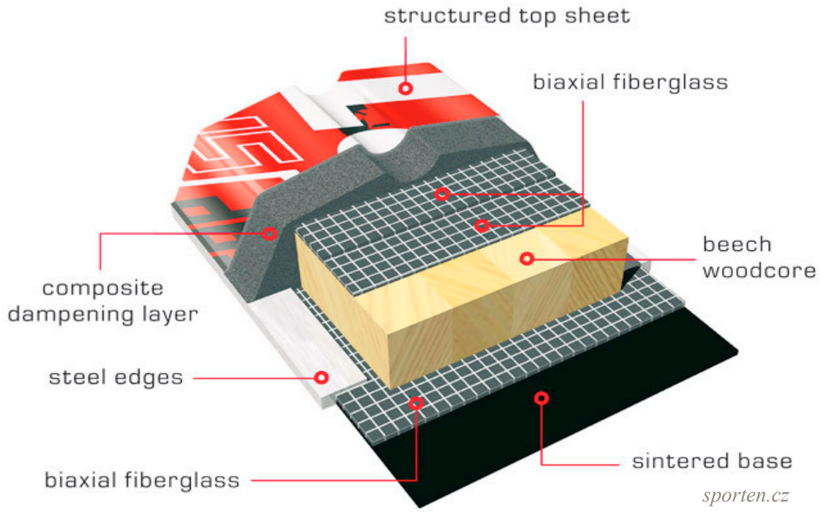
https://www.thinkstep-anz.com/services/product/material-circularity-indicator-mci-calculator/

thinkstep anz

Product:	Widgets
Description:	Widgets case study – Standard – Premium – New design (cf. Circularity-Indicators_Project-Overview.pdf)
Version:	V1
Tool Version:	MCI Calculator thinkstep-anz 2024 (V1.0-Public)

Component Name	Mass Each kilograms	Quantity	Resource Inflows Material Type	Source	% Regenerative	Utlity Based on
Standard widget Aluminium 2 kg	2	0	Aluminium	Recycle	50%	Lifetime
Standard widget ABS 8 kg	8	0	ABS	Virgin	0%	Lifetime
Premium widget Aluminium 8 kg	8	1	Aluminium	Recycle	50%	Lifetime
Premium widget ABS 2 kg	2	1	ABS	Virgin	0%	Lifetime
New design widget Aluminium reused = 83% of 6 kg = 5 kg	5	0	Aluminium	Recycle	100%	Lifetime
New design widget Aluminium recycled = 17% of 6 kg = 1 kg	1	0	Aluminium	Recycle	100%	Lifetime
New design widget ABS 1 kg	1	0	ABS	Recycle	100%	Lifetime

MCI input data

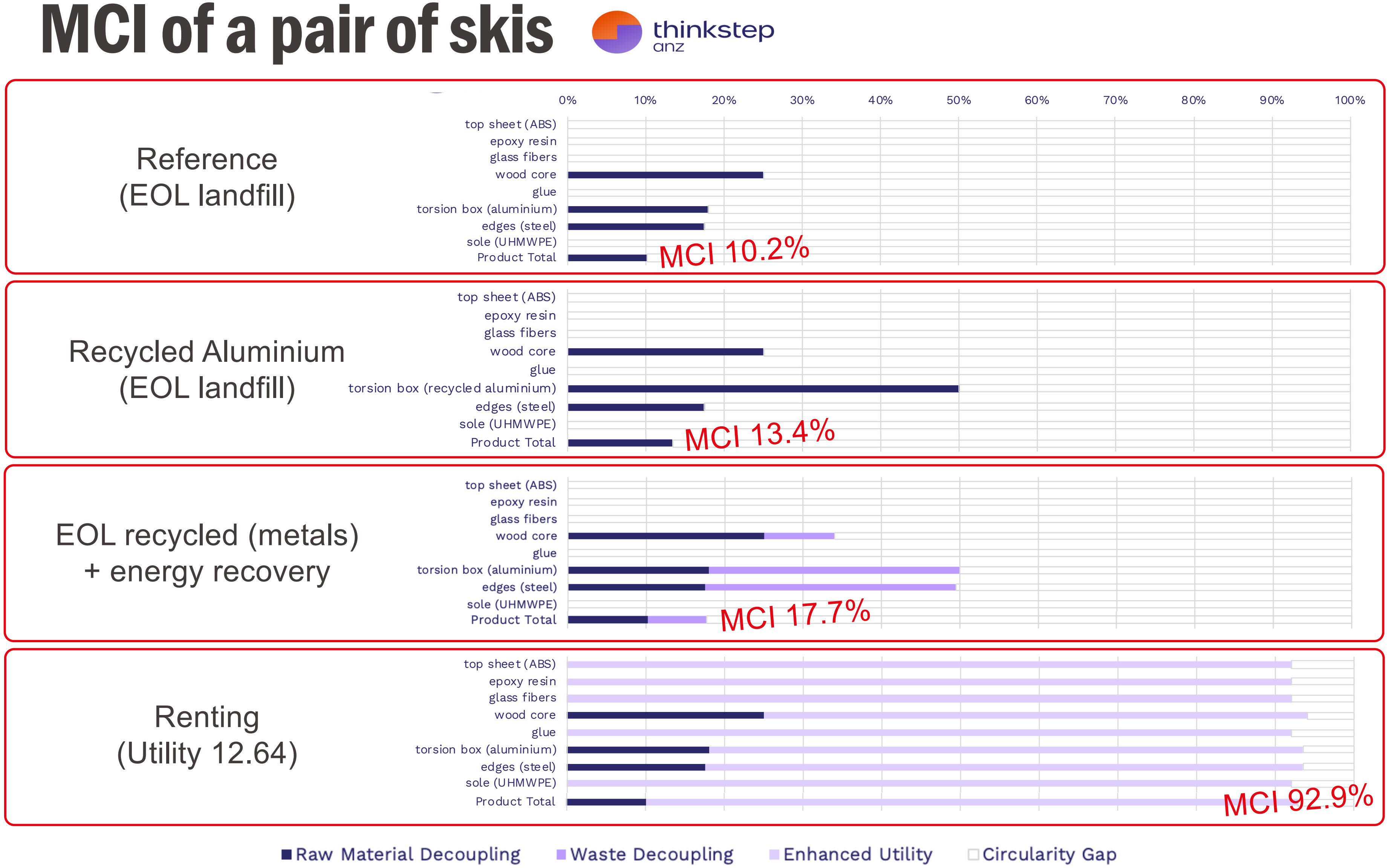


1 ski: 1.8 kg

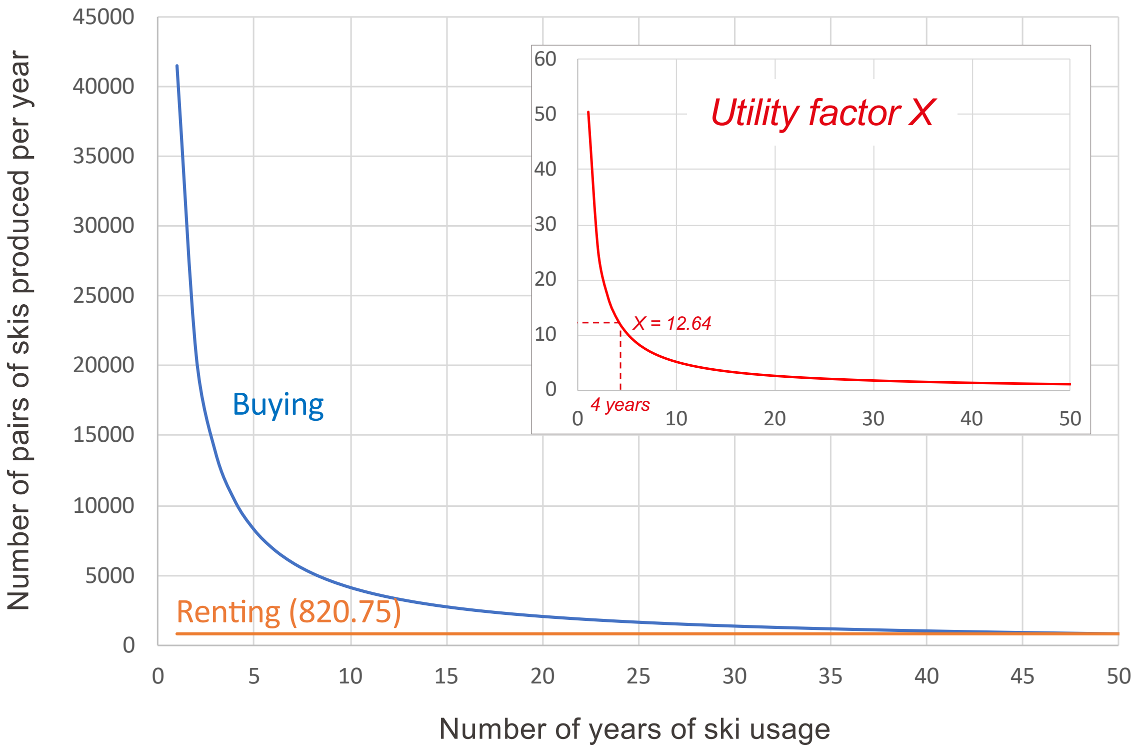
Component	Material	Weight fraction (%)	Mass for 1 ski (kg)	Source (recycled fraction FR %)	Recycling efficiency EF (%)	Regenera-tive fraction (%)	Utility factor X (reference)	Utility factor X for rental 4 years	Collection rate CR (%)	EOL (reference)	EOL recycling efficiency EC (%)
top sheet	ABS	5	0.090	0	–	0	1	12.64	0	Landfill	–
Composite resin	Epoxy resin	12	0.216	0	–	0	1	12.64	0	Landfill	–
Composite reinforcement	Glass fibers	18	0.324	0	–	0	1	12.64	0	Landfill	–
wood core	Wood	30	0.540	0	–	50	1	12.64	0	Landfill	–
glue	Resin	15	0.270	0	–	0	1	12.64	0	Landfill	–
torsion box	Aluminum	10	0.180	35	80	0	1	12.64	0	Landfill	80
edges	Steel	5	0.090	36	80	0	1	12.64	0	Landfill	80
sole	UHMWPE	5	0.090	0	–	0	1	12.64	0	Landfill	–
Total		100	1.8								

Data courtesy Stöckli skis

MCI of a pair of skis



Renting skis?



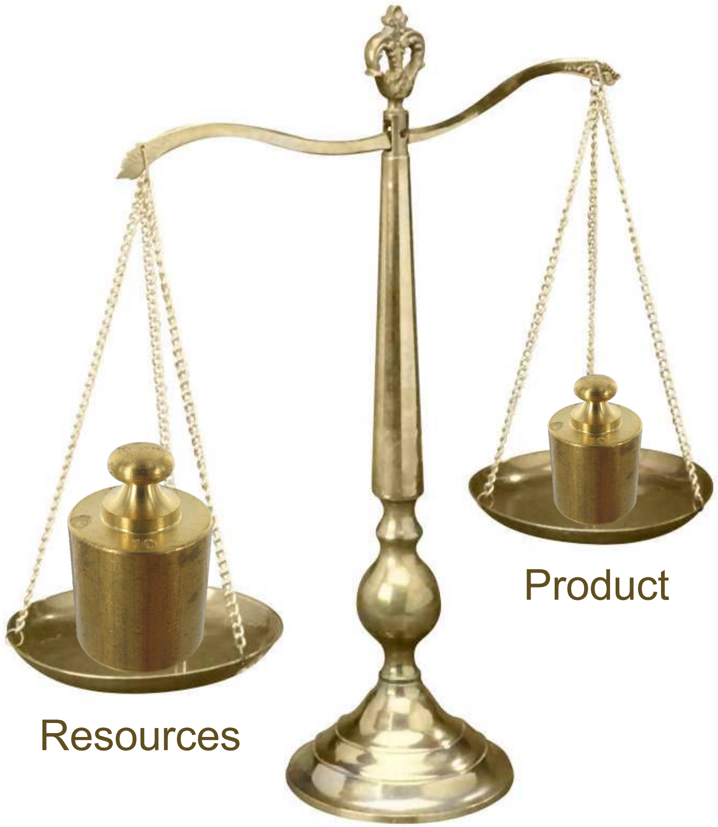
- *139 opening days/year*
- *41476 different skiers/year*
- *5.5 average number of ski days/skier*
- *228118 skiers*days in total/year*
- *3283 average number of pairs of rental skis per day (with safety factor of 2)*
- *4 years of renewal rate for rental skis*

Yearly production number of skis 820.75

Abdi Jalebi et al., Assessing the ecological impact of ski boots and bindings and of the life in service of skis, EPFL Master Course MSE-430 'Life Cycle Engineering of Polymers' (2011)

Which life-cycle step dominates the environmental impact of skis?

Material intensity per service unit (MIPS)



MIT = Material Intensity = Material Input in relation to:

- a weight (kg / kg)
- an energy (kg / kWh)
- a transport (kg / kg.km)

1/MIT = productivity

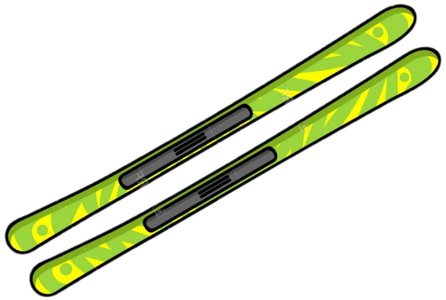
5 categories

- abiotic raw materials
- biotic raw materials
- water
- erosion
- air

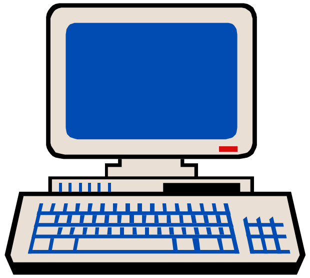
https://wupperinst.org/en/a/wi/a/s/ad/584/

MIPS to manufacture products

Pair of skis (4 kg)



Tabletop computer (10 kg)



Material intensity of selected raw materials

Material	Material intensity (t/t)
Crude oil	1.2
Sand & gravel	1.4
Aluminum (secondary)	0.85
Polypropylene	2.1
Wood (douglas fir)	0.63 (plywood 2.0)
Steel (oxygenation)	8.5
Aluminum (primary)	37
Gold	540’000
Diamond	5’260’000

Computer	~ 20
Car	~ 25

Extract of Wuppertal database 2014 (abiotic resources)

Material intensity of skis

Step 1: define the **Production unit** and the **Functional unit**

Production unit: 1 pair of skis
Functional (or service) unit: 1 person skiing for 3 winter seasons in a resort

https://www.loetschental.ch/en/winter/ski-arena

EPFL

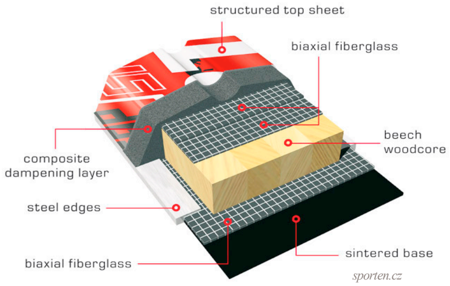
Production unit and functional unit: some examples

Product	Function	Production unit	Functional unit	Key parameter: ratio prod. unit/func. unit
Packaging foam	protect; insulate	m^3	packed good	Product/pack, number of reuses
Paint	protect; decorate	1 kg	m^2•years	kg/m^2, lifetime
Shoes	protect; good appearance	1 pair	man•years	Lifetime of a shoe

what you buy … … for what service

MIPS input data

Step 2: bill of materials and manufacturing processes



1 ski: 1.8 kg

Component	Material	Weight fraction (%)	Mass for 1 ski (kg)
top sheet	ABS	5	0.090
Composite resin	Epoxy resin	12	0.216
Composite reinforcement	Glass fibers	18	0.324
wood core	Wood	30	0.540
glue	Resin	15	0.270
torsion box	Aluminum	10	0.180
edges	Steel	5	0.090
sole	UHMWPE	5	0.090
Total		100	1.8

Step 1: Planer/grinder

Step 2: Printer

Step 3: Press

Process	Process energy (kWh)
Planer/grinder	0.6
Printer	1.0
Press (20’ 80°C)	22.9
Total	24.5

Data courtesy Stöckli skis

MIPS for raw materials

Wuppertal database ↓

Component	Material	Weight fraction (%)	Mass for 2 skis (kg)	MIT resource (kg/kg)	MIPS part (kg/pair of skis)
top sheet	ABS	5	0.180	10.0	1.80
Composite resin	Epoxy resin	12	0.432	13.7	5.92
Composite reinforcement	Glass fibers	18	0.648	6.2	4.02
wood core	Wood	30	1.080	2.0	2.16
glue	Resin	15	0.540	13.7	7.40
torsion box	Aluminum	10	0.360	37.0	13.32
edges	Steel	5	0.180	8.5	1.53
sole	Polyethylene	5	0.180	5.4	0.97
Total		100	3.6		37.1

*ABS calculation: 1.8 kg/ski * 2 skis * 5 wt% * 10 kg resources/kg ABS = 1.80 kg/pair of skis*

Data from Stökli and Wuppertal Institute

EPFL

MIPS for raw materials

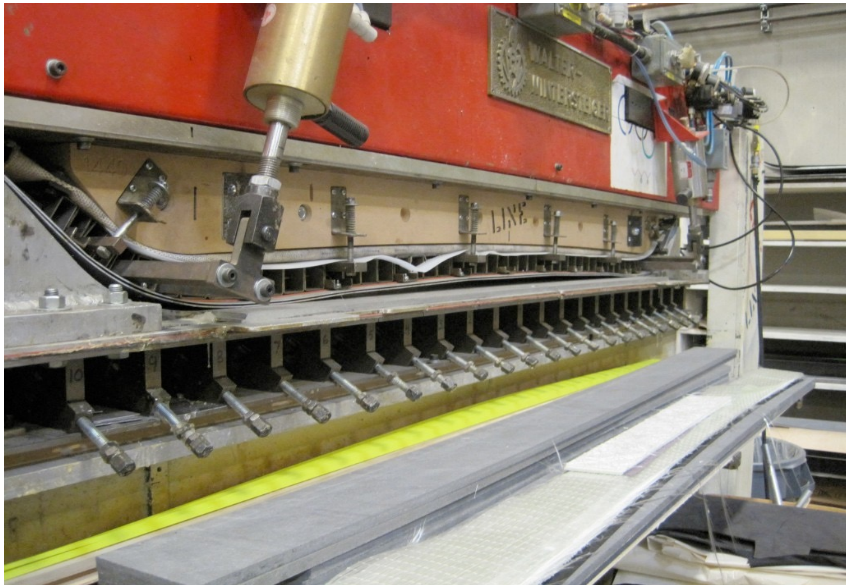
Wuppertal database ↓ (MIT resource)

Component	Material	Weight fraction (%)	Mass for 2 skis (kg)	MIT resource (kg/kg)	MIPS part (kg/pair of skis)
top sheet	ABS	5	0.180	10.0	1.80
Composite resin	Epoxy resin	12	0.432	13.7	5.92
Composite reinforcement	Glass fibers	18	0.648	6.2	4.02
wood core	Wood	30	1.080	2.0	2.16
glue	Resin	15	0.540	13.7	7.40
torsion box	Aluminum	10	0.360	0.85	0.31
edges	Steel	5	0.180	8.5	1.53
sole	Polyethylene	5	0.180	5.4	0.97
Total		100	3.6		24.1

Using recycled aluminium reduces MIPS by 35% (and improves MCI by 31%)

Data from Stökli and Wuppertal Institute

Material intensity of manufacturing



Energy carrier	Source	Material intensity [kg/kWh]
Electricity mix	Public network (DE)	3.15
	Industrial (DE)	2.67
	Europe	1.58
	OECD	1.55
Coal (H ~ 25 MJ/kg)	World	1.47 – 17.15
Natural gas (H ~ 41 MJ/kg)	Germany	1.22
Crude oil	World	1.22
Biogas	Germany	0.60
Steam (H ~ 3 MJ/kg)	Germany	0.39
Nuclear power	Germany	0.31
Concentrated solar power	Germany	0.20
Wind power (20 yrs operation)	CH	0.09

Courtesy K2
Source: Wuppertal database 3.1

MIPS for manufacturing

Step 1: Planer/grinder *Step 2: Printer* *Step 3: Press*

tjskl.org.cn

courtesy Bohême

courtesy K2

Process	Process energy (kWh)	MIT resource (kg/kWh)	MIPS part (kg/pair of skis)
Planer/grinder	0.6	1.58	0.95
Printer	1.0	1.58	1.58
Press (20’ 80°C)	22.9	1.58	36.2
Total	24.5		38.7

MIPS for manufacturing skis is comparable to MIPS for the raw materials

Data from Stökli and Wuppertal Institute

Material intensity for transport

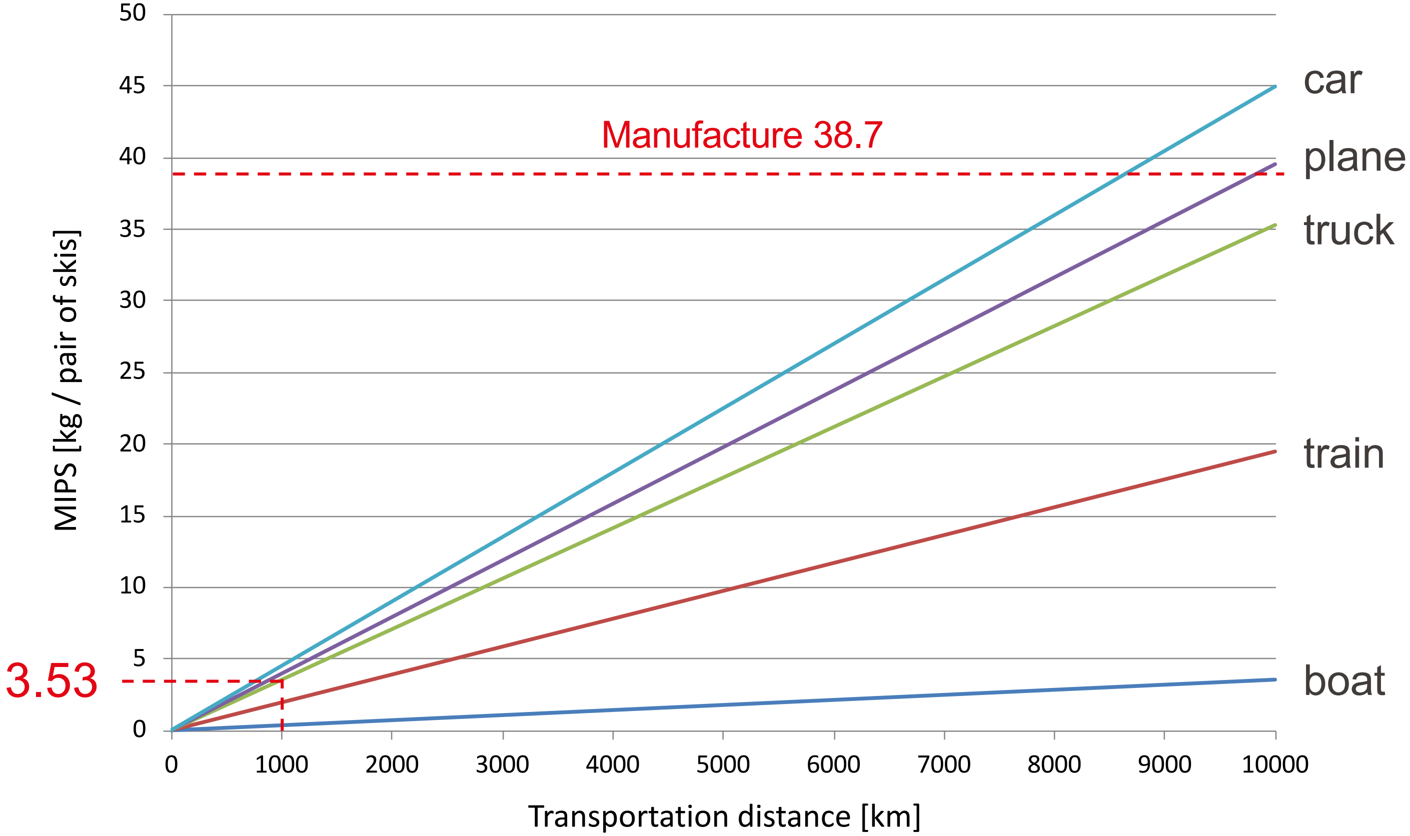
Transportation carrier (incl. infrastructure)	Source	Material intensity [g / ton / km]
Sea cargo	Average	100
Cargo trains	Average	540
Truck	Average	980
Air cargo	Medium distance	1100
Car (estimated)	Average	1250

Source: Wuppertal database 3.1

EPFL

MIPS for transportation of a pair of skis

Leterrier



EPFL

Material intensity of a ski resort

Electricity, fuel and water consumption for Grimentz during 2010-2011 season (139 opening days)

Electrical power (kWh) *	1’695’861
Diesel (liters) **	105’000
Whole resort, 1 season [kg]	2’800’840

- Total number of skiers (2010-2011): **41476**
- Average number of ski days per skier: **5.5**

Material intensity [kg/skier]	
Per skier , 1 season	**67.5**
Per skier , 3 seasons	**202.6**
Per skier , 5 seasons	**337.7**
Per skier , 7 seasons	**472.7**

(the same analysis was done in 2018 for la Fouly resort, resulting in 153 kg/skier for 1 season)

* Data recieved from M. Yves Salamin, director of the resort
** Data collected from the annual report
Abdi Jalebi et al., Assessing the ecological impact of ski boots and bindings and of the life in service of skis, EPFL Master Course MSE-430 ‘Life Cycle Engineering of Polymers’ (2011)

Recycling of skis

Ski Waste

↓

Shredding

↓

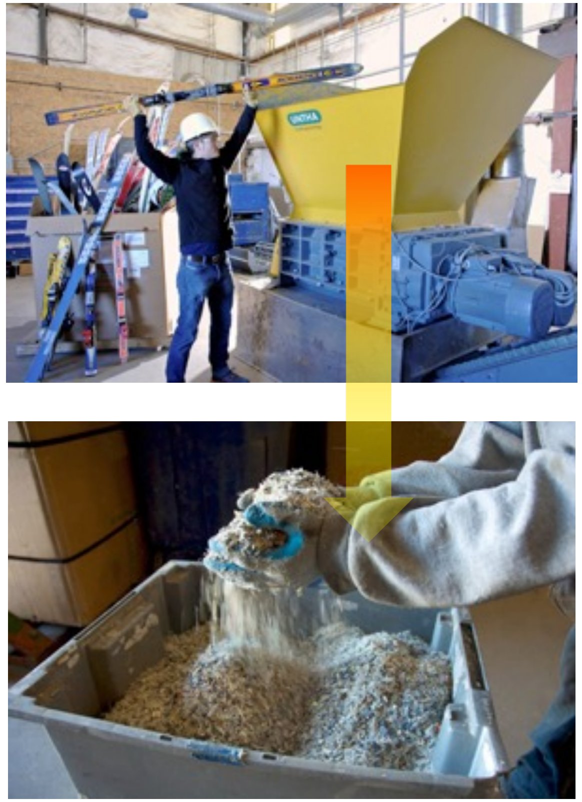
Magnet → Steel fraction (5 %wt)

↓

Eddy current → Aluminium fraction (10 %wt)

↓

'Shredder' fraction (85% wt)
⇔ oil equivalent



https://www.pinterest.com/pin/83739492803811148/
Courtesy of SIA Snow Sports Recycling Program

Recycling of skis

1 ton of SKIS

↓

Grinding: ~ 100 kWh / ton @ 1.58 kg / kWh = 158 kg / ton

Separation: ~ 100 kWh / ton @ 1.58 kg / kWh = 158 kg / ton

316 kg of resources / ton of skis (~ 1 kg / pair of skis)

50 kg of STEEL → Secondary steel production (substitution of primary steel)

100 kg of ALUMINIUM → Secondary Al production (substitution of primary Al)

850 kg of SHREDDER RESIDUE → Secondary fuel for cement plants (substitution of oil, with heat value ~ 50% oil)

EPFL

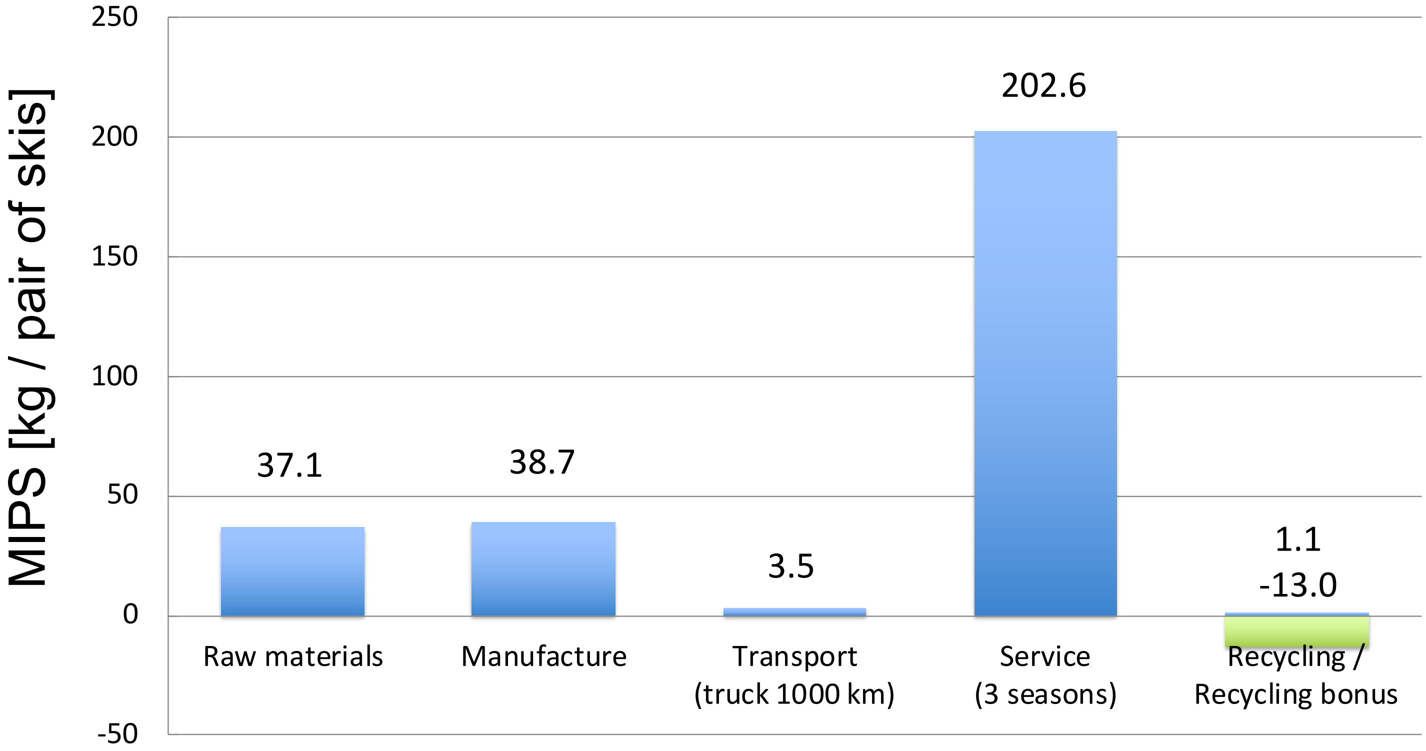
Recycling of skis

	STEEL	ALUMINIUM	SHREDDER RESIDUE
Substitution potential	Primary steel	Primary aluminium	Crude oil
Material Intensity of primary material	8.5 tons of resources / ton	37 tons of resources / ton	1.2 tons of resources / ton
Material Intensity of secondary material (recycled from skis)	316 kg of resources / 50 kg **6.32 tons of resources / ton**	316 kg of resources / 100 kg **3.16 tons of resources / ton**	316 kg of resources / 850 kg Heat value ~50% oil 0.74 tons of resources / ton
RESOURCES SAVINGS	2.18 tons / ton 0.39 kg/pair of skis	33.8 tons / ton 12.2 kg/pair of skis	456 kg / ton 0.70 kg/pair of skis
Total	36.5 tons / ton of skis ⇔ 13.1 kg / pair of skis		

Source: Wuppertal database 3.1

MIPS of ski life-cycle

Total (w/o recycling) 282 kg of resources / pair of skis
Total (with recycling) 270 kg of resources / pair of skis



How to decrease the environmental impact of skiing?

Go cross-country!

Power the resort with renewables

Power the manufacture with renewables

Use recycled materials

Rent your skis

Summary

- Aiming at a sustainable world is THE grand challenge, and everyone including engineers should engage:

> « First, we need peace,
> second, we need solidarity,
> third, we need a surge in implementation,
> and fourth we need gender equality. »

António Guterres, Secretary-General of the United Nations (2024)

- Manufacturing processes towards sustainable products lifecycles are possible based on circular economy principles:
  - Eliminating waste and pollution
  - Circulating products and materials
  - Regenerate natural systems
  - Use renewable energies

! Digital product passports
Circularity and environmental assessment metrics

See you in 2026!

Towards Sustainable Materials

MSE-433 Towards Sustainable Materials

Yves Leterrier, Martyn Wakeman

Spring 2026

Appendix: Material circularity indicator (MCI)

The **Material Circularity Indicator (MCI)** focuses on the restoration of material flows at product and company levels and is based on the following six principles:

1. Sourcing biological materials from sustained sources
2. Using feedstock from reused or recycled sources
3. Keeping products in use longer (e.g., by reuse/redistribution/increase durability)
4. Reusing components or recycling materials after the use of the product
5. Making more intensive use of products (e.g. via service, sharing or performance models)
6. Ensuring biological materials remain uncontaminated and biologically accessible

MCI is constructed by first computing *virgin feedstock* and *unrecoverable waste*, then calculating the *Linear Flow Index*, and finally building in the *utility factor*.

Appendix: Material circularity indicator (MCI)

Composting requirements for circularity

1. Biological materials that are compostable according to standards
2. Non-toxic to ecosystems
3. Biocompatible with ecosystems
4. By-products must also be made biologically available(1)

⬇

Efficiency 100%(2)

Energy recovery requirements for circularity

1. Other end of life options, besides landfill, must have been exhausted(3)
2. The material must be from a biological source from a source of Sustained Production(4)
3. The biological material must be completely uncontaminated(5) and non-toxic
4. Energy recovery must be optimized to displace non-renewable alternatives
5. By-products must be biologically beneficial(6) and must not be detrimental to the ecosystems to which they are introduced

(1) This restriction exists to prevent the landfilling or sequestering of otherwise valuable nutrients that are required by the biological cycle to produce new materials as part of a circular bioeconomy.

(2) Where these conditions are met, the composting of biological materials may be treated as being up to 100% efficient depending upon the application of the resulting solid and liquid nutrients to specific ecosystems and the degree to which these are retained by those ecosystems, taking into account losses through leaching and run-off post- application.

(3) e.g. the product is not practically or economically recyclable or compostable.

(4) Sustainable production is defined as “the creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers, communities, and consumers; and socially and creatively rewarding for all working people” (Journal of Cleaner Production 206 (2019) 211e226).

(5) by technical materials including coatings, preservatives and fillers except when these are demonstrably inert

(6) for example as a soil conditioner

Appendix: The thinkstep MCI tool

MCI calculation steps with input data:

1. Add your bill of materials including the quantity and mass of each component
2. Select the material type for each component from the list (which is very limited … so if your material is not listed, you can select another one and update the data, including CO_2 footprint and cost)
3. Select the source of your material for each component (Virgin; Recycled; Remanufactured; Reused) / If your material type is biological, you can also add what proportion is from a verified regenerative source (e.g. FSC).
4. Define the utility factor based on lifetime, product use and/or mass
5. Indicate the collection efficiency for each component
6. Define the end-of-life scenarios for each component (Reuse; Remanufacture; Recycle; Compost; Energy Recovery; Landfill)

You can modify all these input data for sensitivity analyses!

Appendix: The thinkstep MCI tool

MCI results:

- MCI and %MCI
- Breakdown into factors that contribute most to circularity:
  - Raw Material Decoupling - The contribution to circularity that comes from avoiding non-renewable material inputs to the component.
  - Waste Decoupling - The contribution to the circularity that comes from waste avoidance.
  - Enhanced Utility - The contribution to the circularity that comes from making the product lighter, last longer or using it more intensively.
  - Circularity Gap - The remaining deficit between your circularity result and a fully circular system.
- Circular and Linear Mass
- Hot-spot graphs
  - Circularity vs Embodied CO_2
  - Circularity vs Material Cost