TU Clausthal

Institute for Software and Systems Engineering

Emerging Technologies for the Circular Economy

Lecture 2: Circular Economy

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- Updated versions of these slides will be available in our Github repository.

NEWS/UPDATES

Lectures – IoT and Digitalization for the Circular Economy

- 17.04.2023 → Organization (L00) + Introduction (L01)
- 24.04.2023 → Circular Economy (L02)
- 08.05.2023 → Lifecycle Assessment – LCA (L03)
- 15.05.2023 → Introduction to the Internet of Things (L04)
- 22.05.2023 → Internet of Things – Communication + Security and Privacy (L05)
- 05.06.2023 → Internet of Things – Data Processing and BigData (L06)
  → Extra MOOC - Foodsharing
- 12.06.2023 → Industrial Internet of Things (L07)
- **19.06.2023 → No Lecture**
- **26.06.2023 → IoT in Mining I (L08)**
- **03.07.2023 → IoT in Mining II (L09)**
  → Technologies for Sustainability – MOOC Content (L10)
- ***10.07.2023 → Coding Workshop I (Goslar)***
- ***17.07.2023 → Coding Workshop II (Goslar)***
- **31.07.2023 → Exam Q&A**

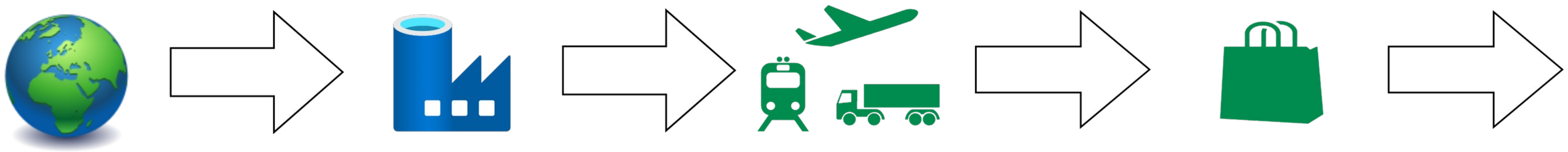
Exercises – IoT and Digitalization for the Circular Economy

- 17.04.2023 → Exercise 01 – Carbon Footprint
- 24.04.2023 → Exercise 02 – Performance Economy
- 01.05.2023 → Exercise 03 – Your Favourite Fruit or Vegetable
- 08.05.2023 → Exercise 04 – LCA of Your Favourite Fruit or Vegetable
- 12.06.2023 → Exercise 05 – Industrial IoT
- **03.07.2023** → Exercise 06 – IoT in Mining
- **10.07.2023** → Exercise 07 – Technology Assessment

The Linear (Industrial) Economy

LINEAR INDUSTRIAL ECONOMY

PRODUCERS *IN-CONTROL*



RESOURCES **MANUFACTURING** **DISTRIBUTION** **POINT OF SALE**

GLOBALIZED INDUSTRIALIZED PROCESSES

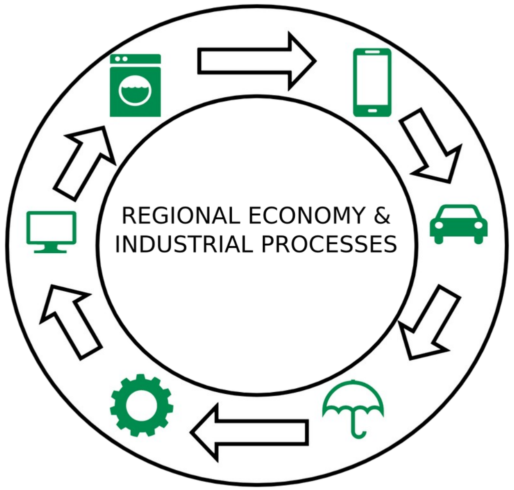
NATURAL RESOURCES (Water, Energy, Materials) and Human Resources (Labor and Skills) are used to produce manufactured **objects** (infrastructure, buildings, equipment, durable projects).

GLOBALIZED DISTRIBUTION LOGISTICS

COMMERCIALIZATION at the factory gate or at point of sale these objects are put to use (sold, leased, rented, sold as service)...

CIRCULAR ECONOMY

USERS *IN-CONTROL*

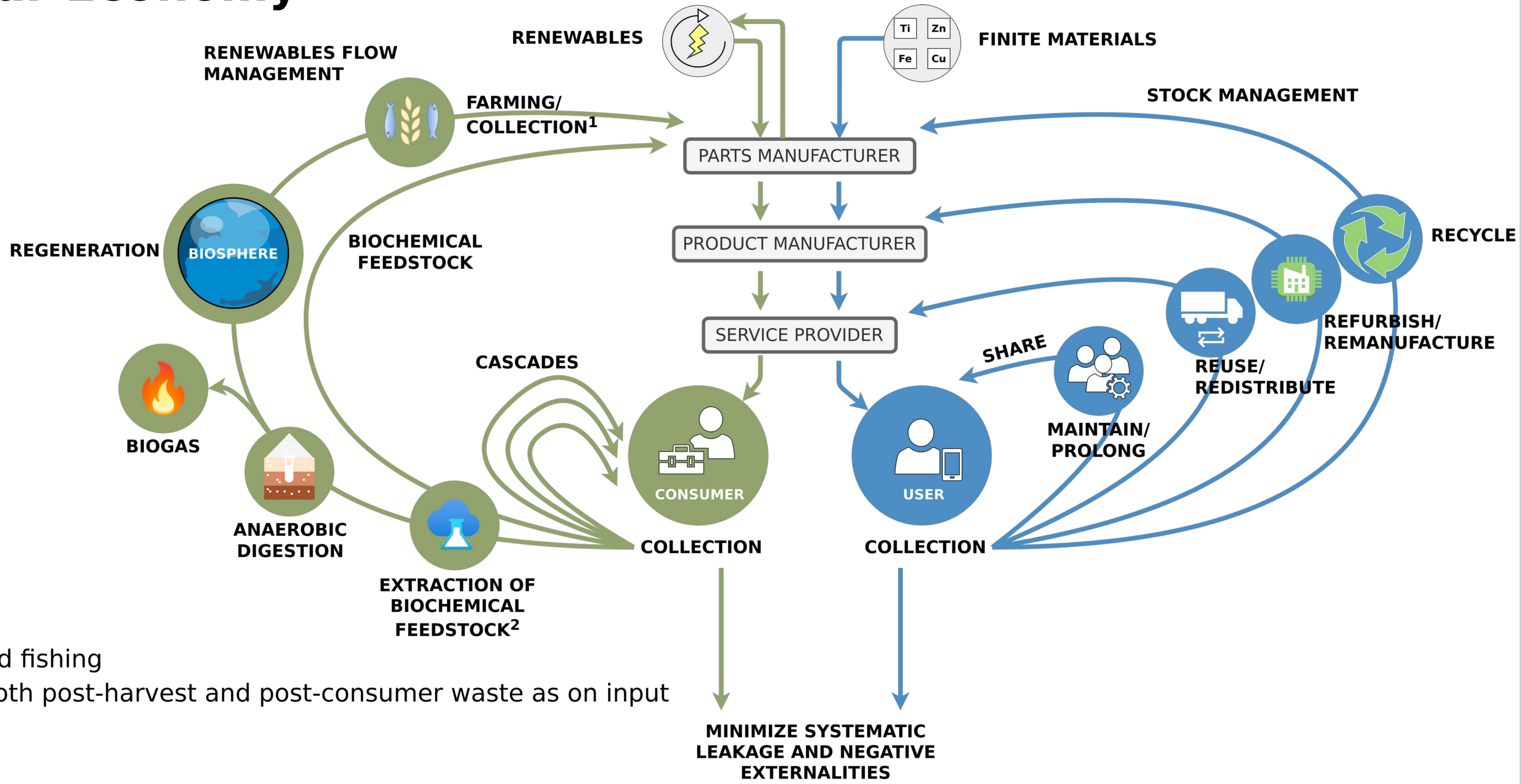


... and later **REUSED** as objects **AT THEIR HIGHEST VALUE** and function, or recovered as molecules at their highest value and purity

Image adapted from: Walter R. Stahel (2019) – The Circular Economy: A User’s Guide.

THE CIRCULAR ECONOMY

Circular Economy



[1] Hunting and fishing
[2] Can take both post-harvest and post-consumer waste as on input

Image adapted from https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic

Circular Economy

Center for Digital Technologies (DIGIT) (2022) – https://www.digit-research.de/fileadmin/DIGIT/Presse_und_News/Downloads/Grafikpaket_Reallabor_DCE_Kreislaufmodell_V2_ccby.zip –

Circular Economy – Definitions

“Conceptualizing the circular economy: An analysis of 114 definitions.”

Kirchherr, Julian, Denise Reike and Marko P. Hekkert. Resources Conservation and Recycling 127 (2017): 221-232.

https://doi.org/10.1016/J.RESCONREC.2017.09.005

Kirchherr, J., Reike, D., & Hekkert, M. (2017) – Conceptualizing the circular economy: An analysis of 114 definitions. Resources, conservation and recycling, 127, 221-232.

Circular Economy – Definitions

"A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."

– Ellen MacArthur Foundation

https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

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– Ellen MacArthur Foundation

"The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended."

– European Parliament

https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf
https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefts

Circular Industrial Economy – Definitions

"The circular industrial economy manages stocks of manufactured assets, such as infrastructure, buildings, vehicles, equipment and consumer goods, to maintain their value and utility as high as possible for as long as possible; and stocks of resources at their highest purity and value."

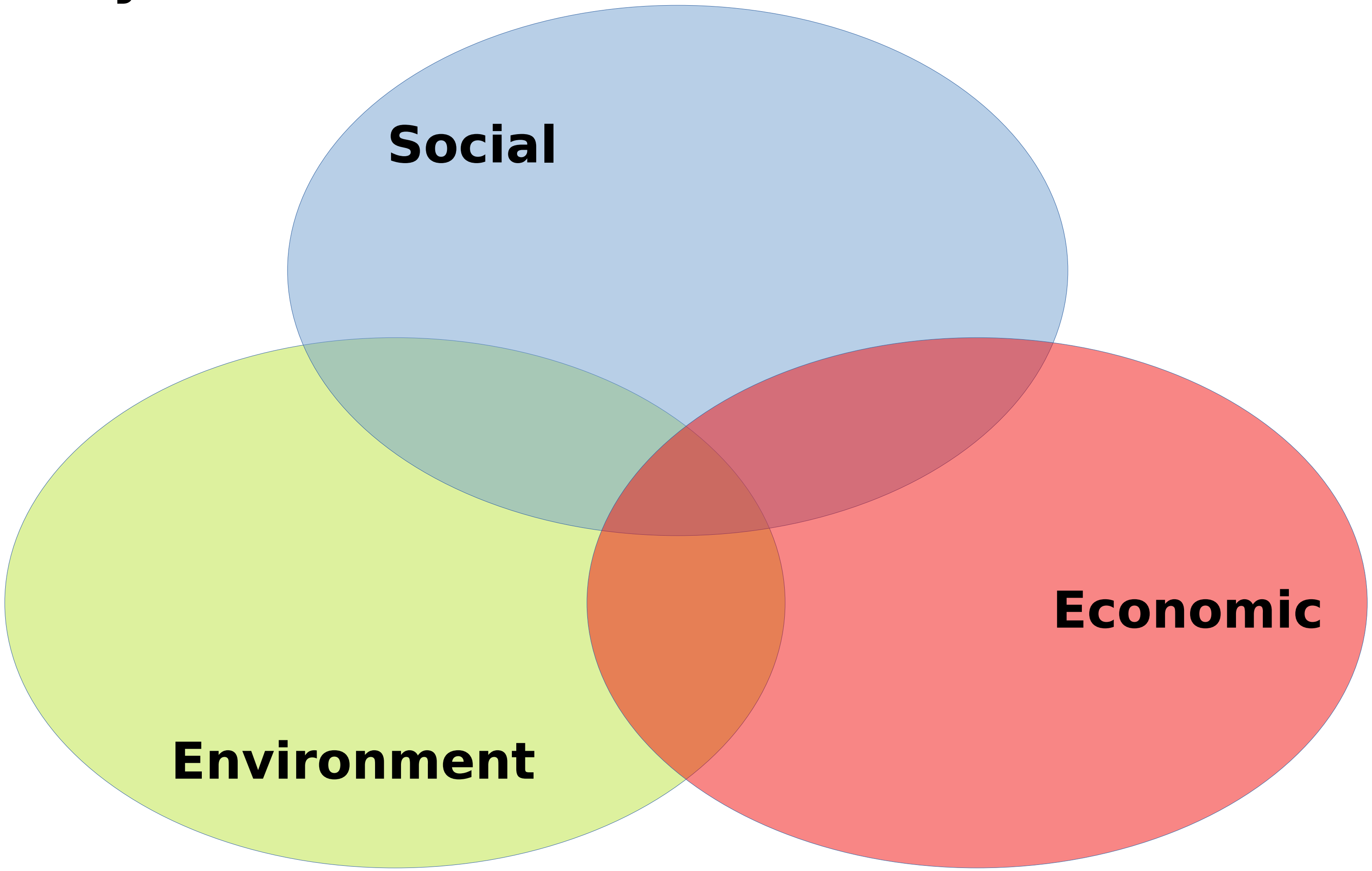
Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

Sustainability – Definition

„Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

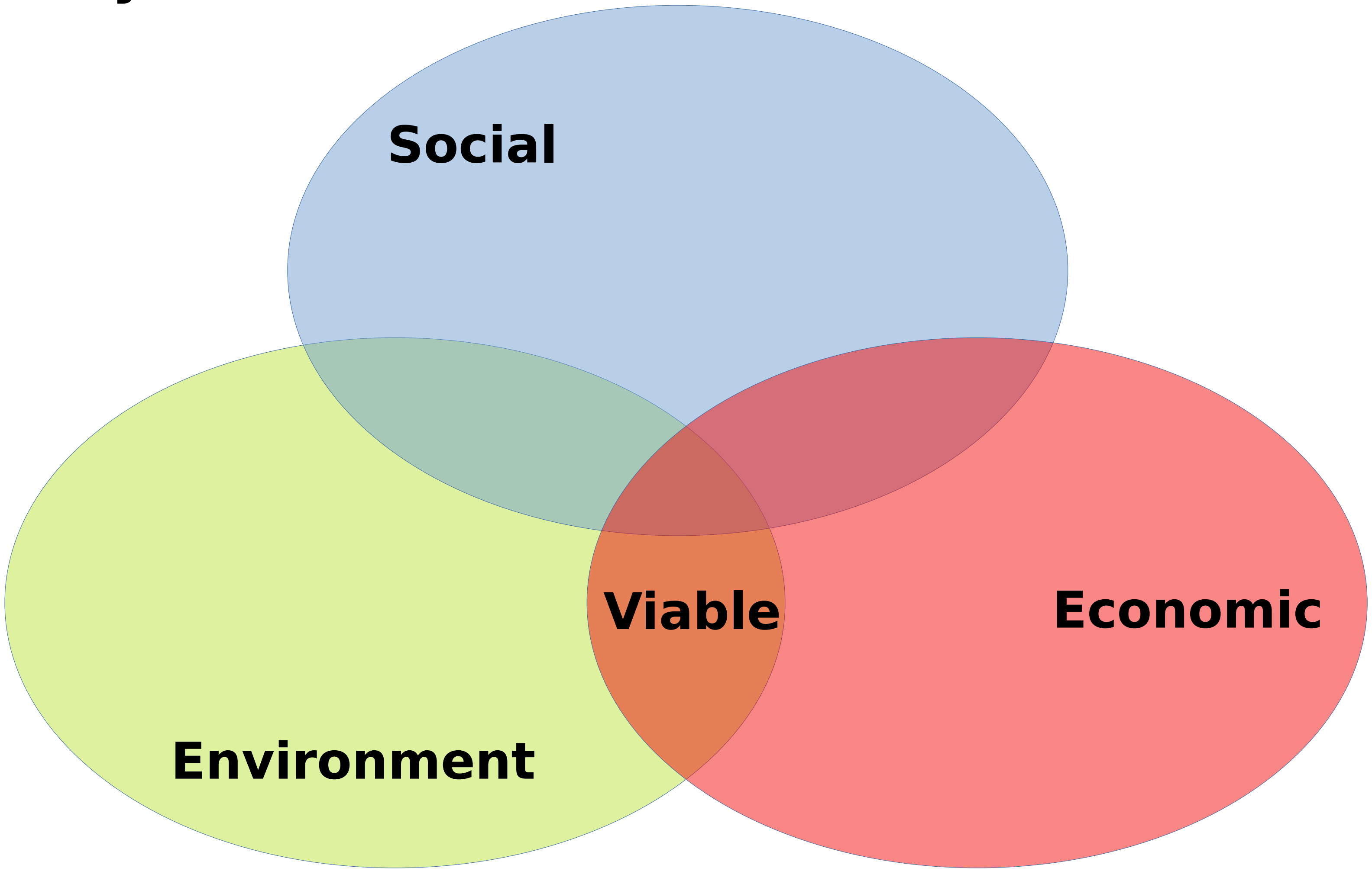
Report of the World Commission on Environment and Development: Our Common Future (1987) – http://www.un-documents.net/our-common-future.pdf

Sustainability – Definition



Based on: Thomsen C. (2013) Sustainability (World Commission on Environment and Development Definition). In: Idowu S.O., Capaldi N., Zu L., Gupta A.D. (eds) Encyclopedia of Corporate Social Responsibility. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-28036-8_531

Sustainability – Definition



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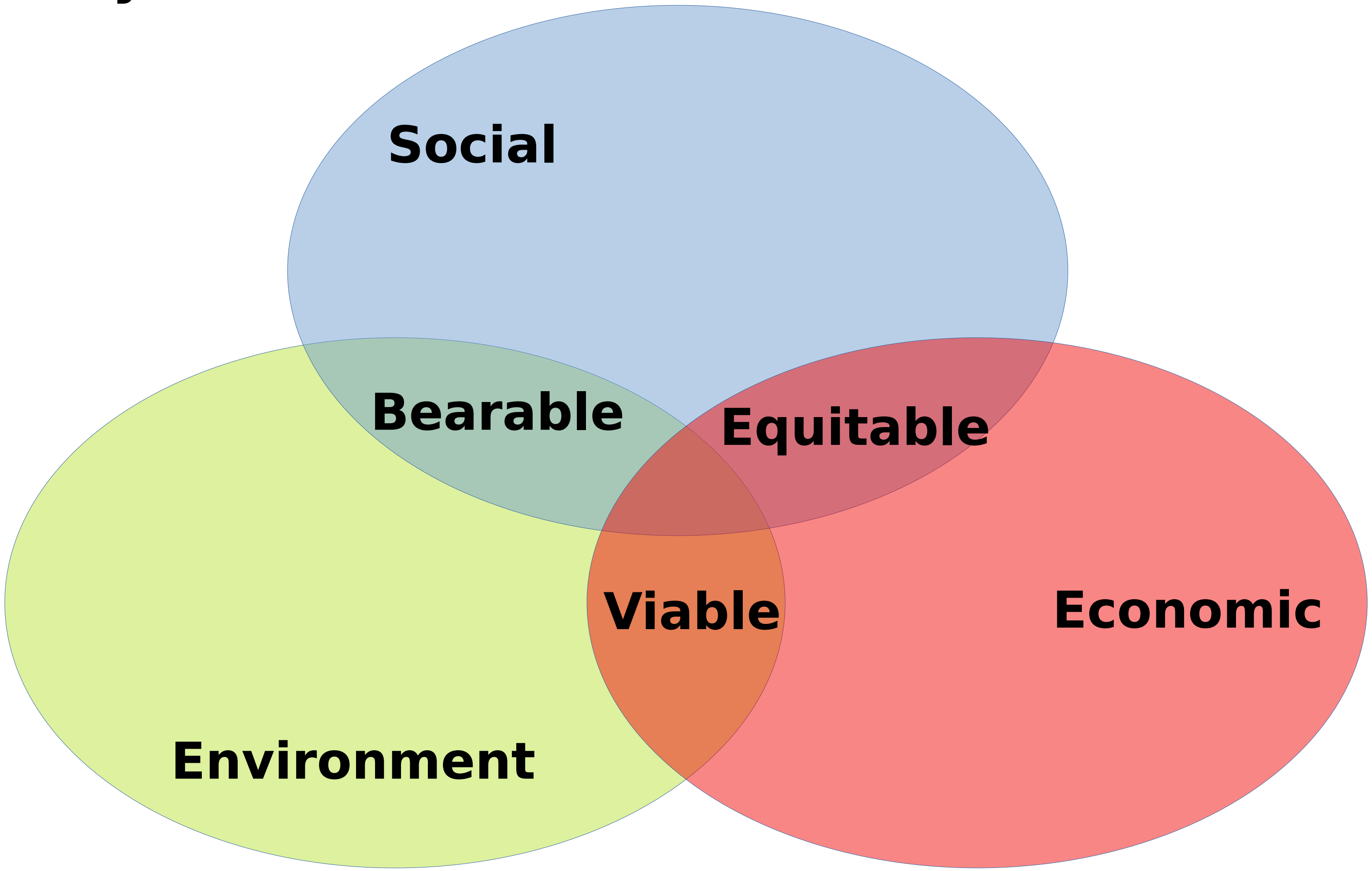

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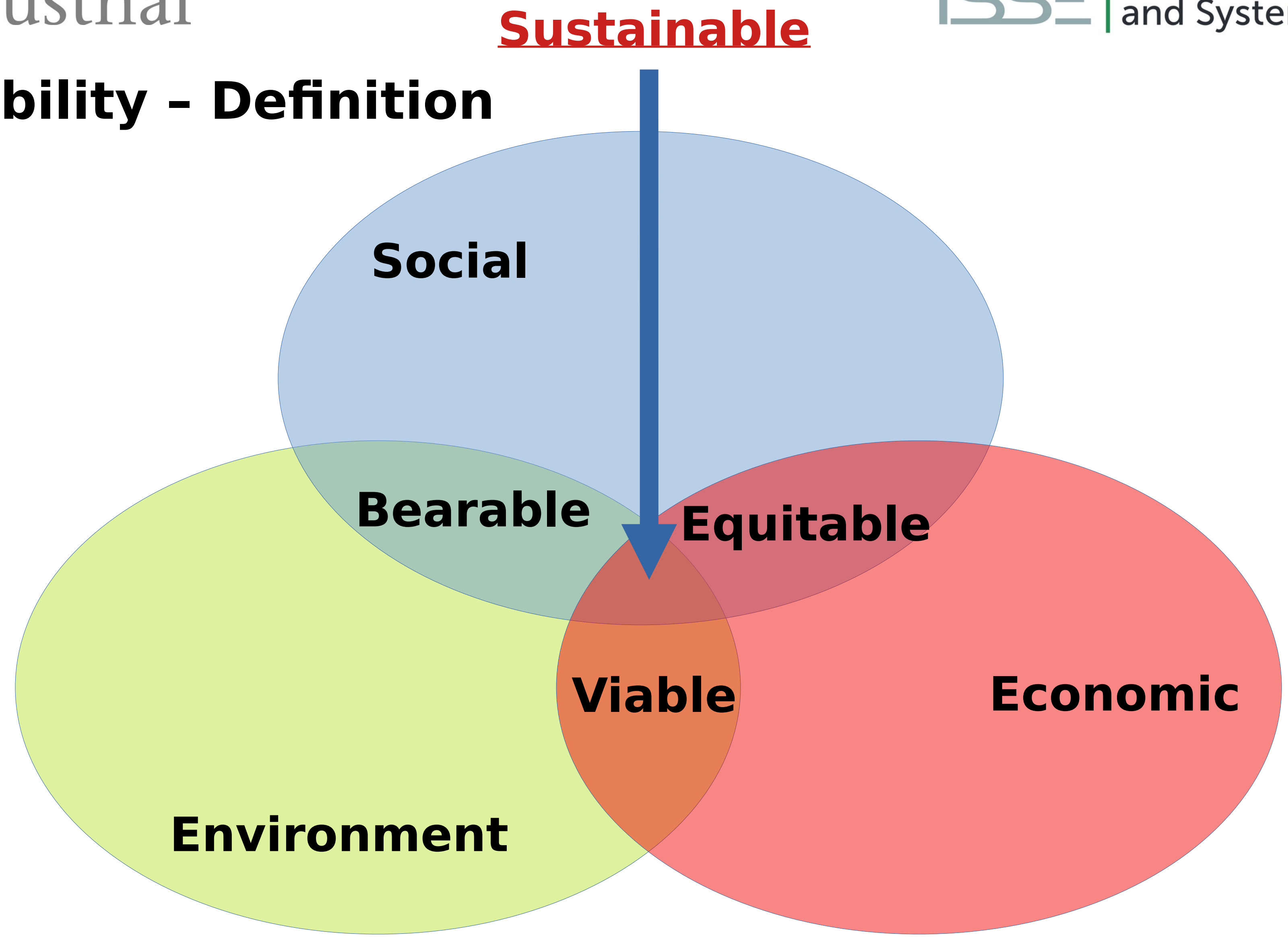

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Sustainability – Implications

Sustainability → Consume less

Report of the World Commission on Environment and Development: Our Common Future (1987) – http://www.un-documents.net/our-common-future.pdf

Circular Economy – Characteristics

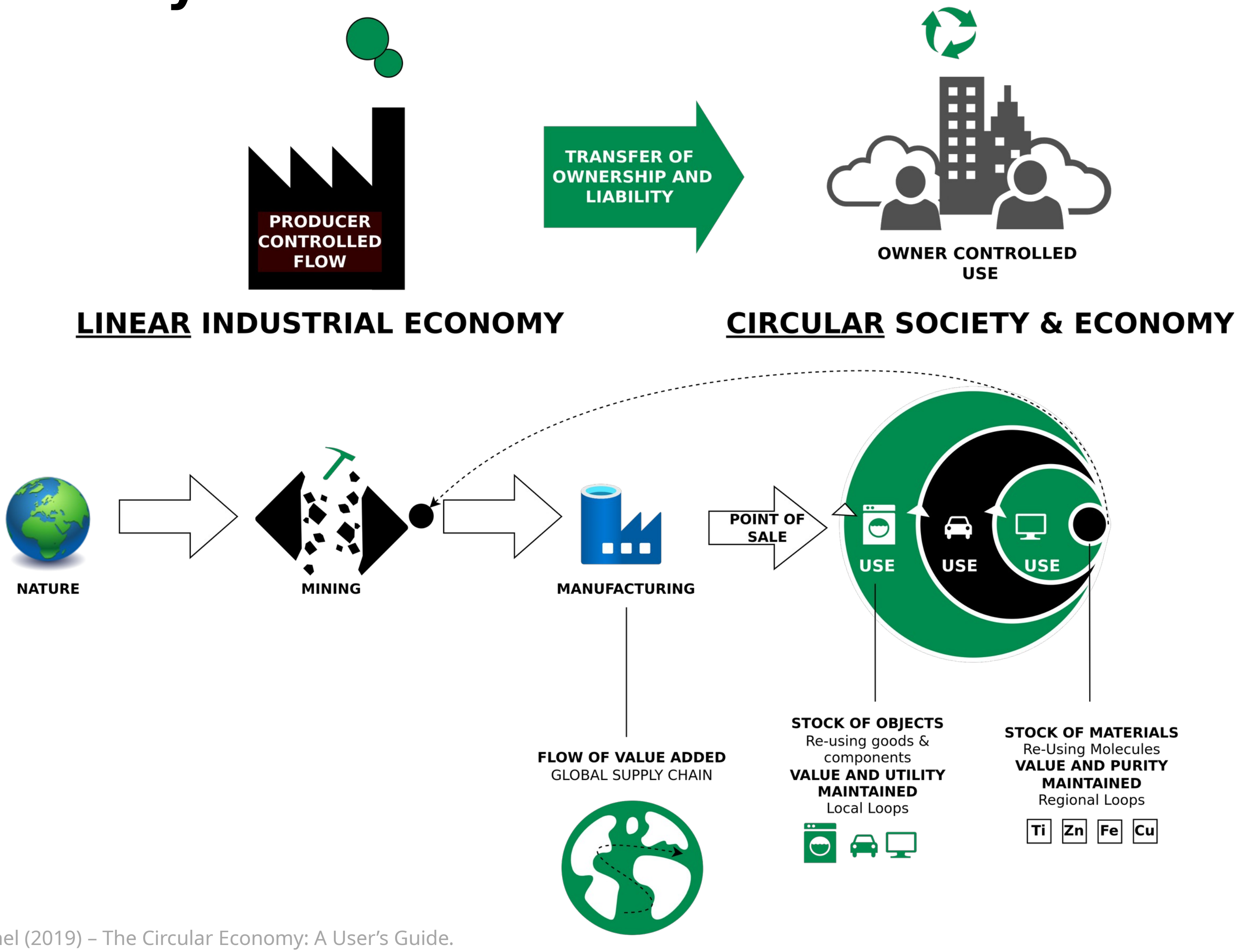


Image adapted from: Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

The Era of R

Techno-commercial strategies to keep goods and components at highest value level through:

- **R**euse
- **R**epair
- **R**emarket
- **R**emanufacture
- **R**e-refine
- **R**eprogramme goods

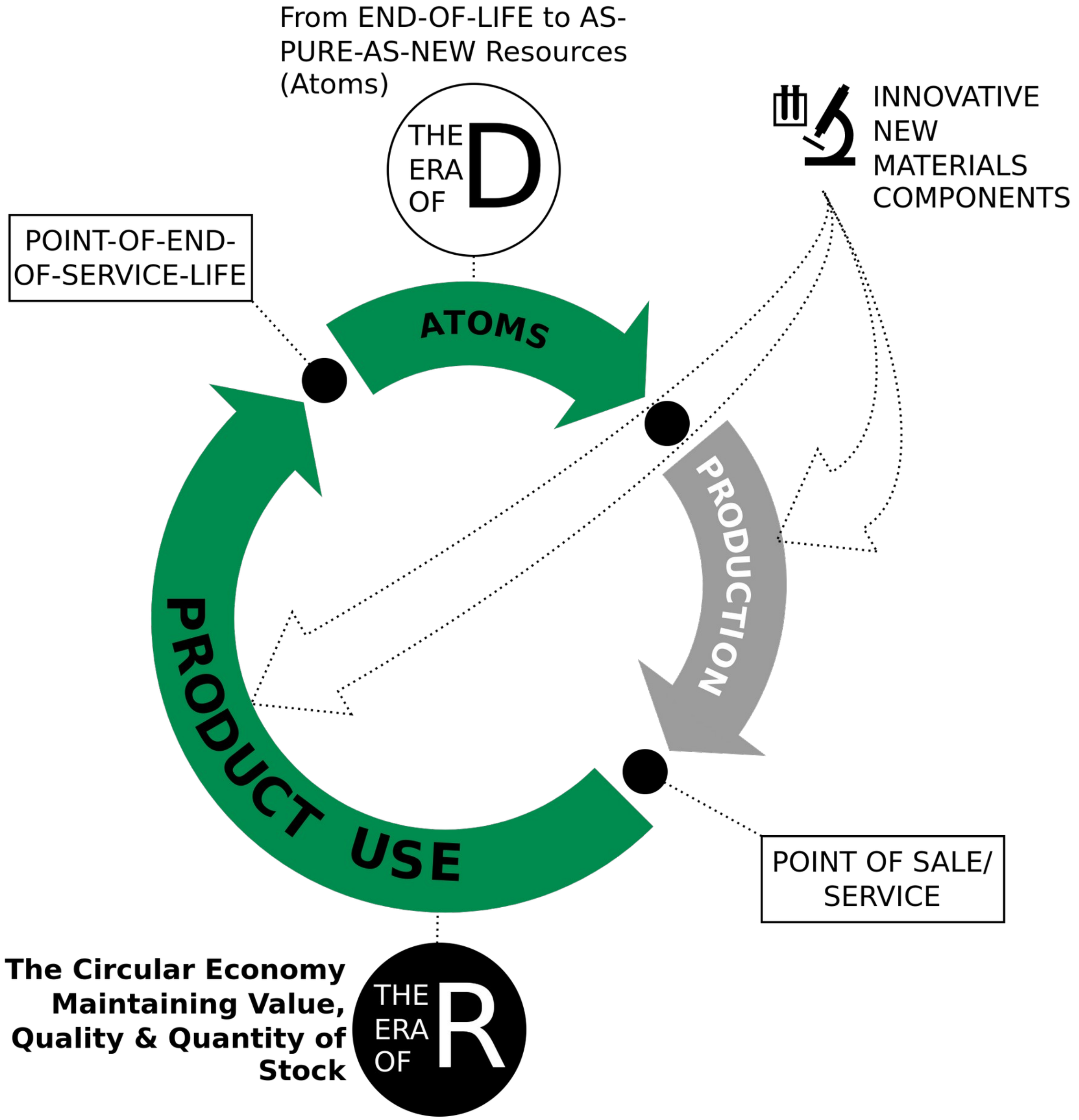


Image adapted from Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

The Era of D

Technologies and actions to recover atoms and molecules at highest quality (purity and value) level as pure as virgin:

- **D**e-polymerise
- **D**e-alloy
- **D**e-laminate
- **D**e-vulcanise
- **D**e-coat materials
- **D**e-construct high-rise buildings and major infrastructure

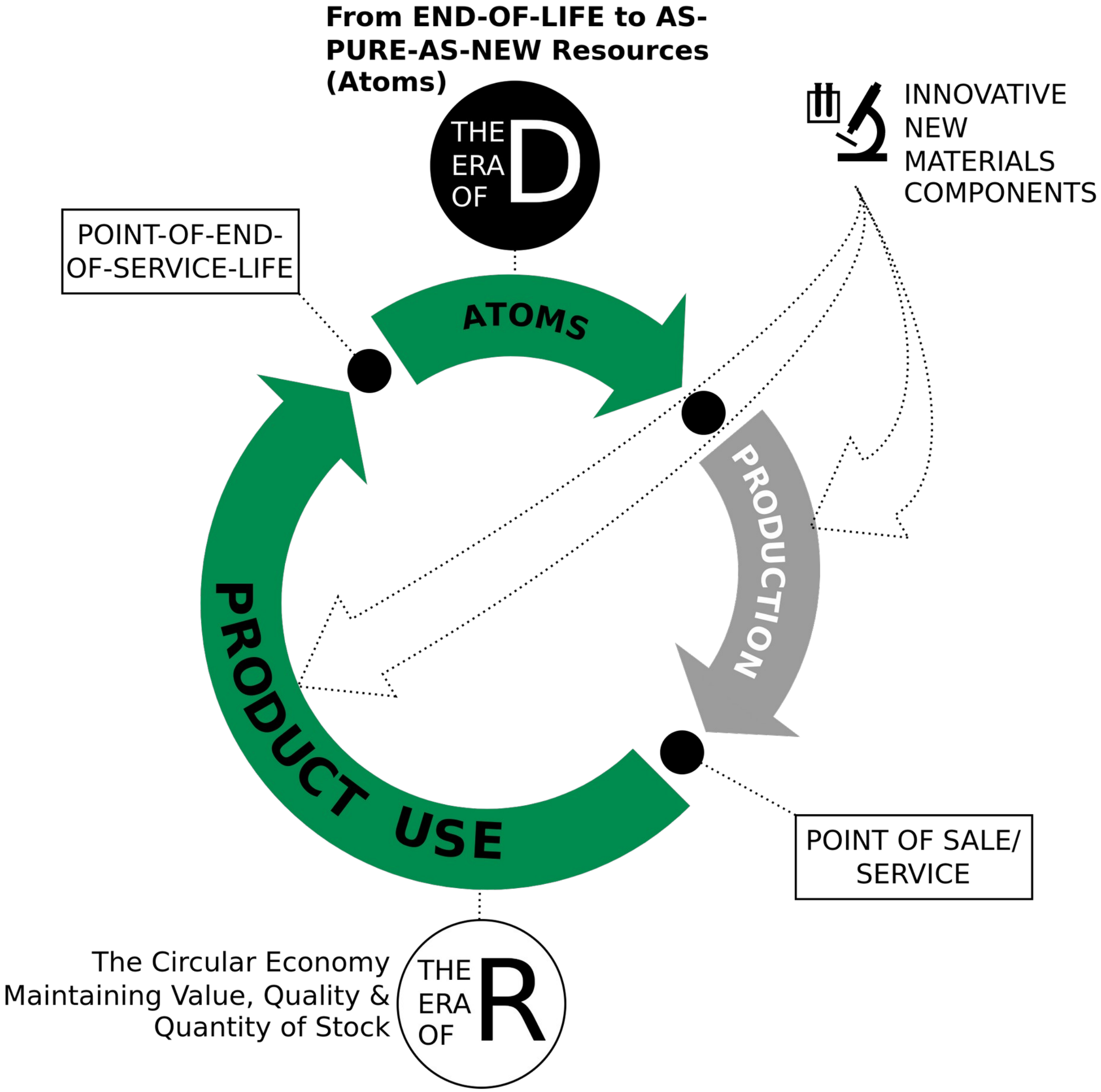


Image adapted from Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

End-of-service-life business opportunities for value preservation: Reuse or Recycle?

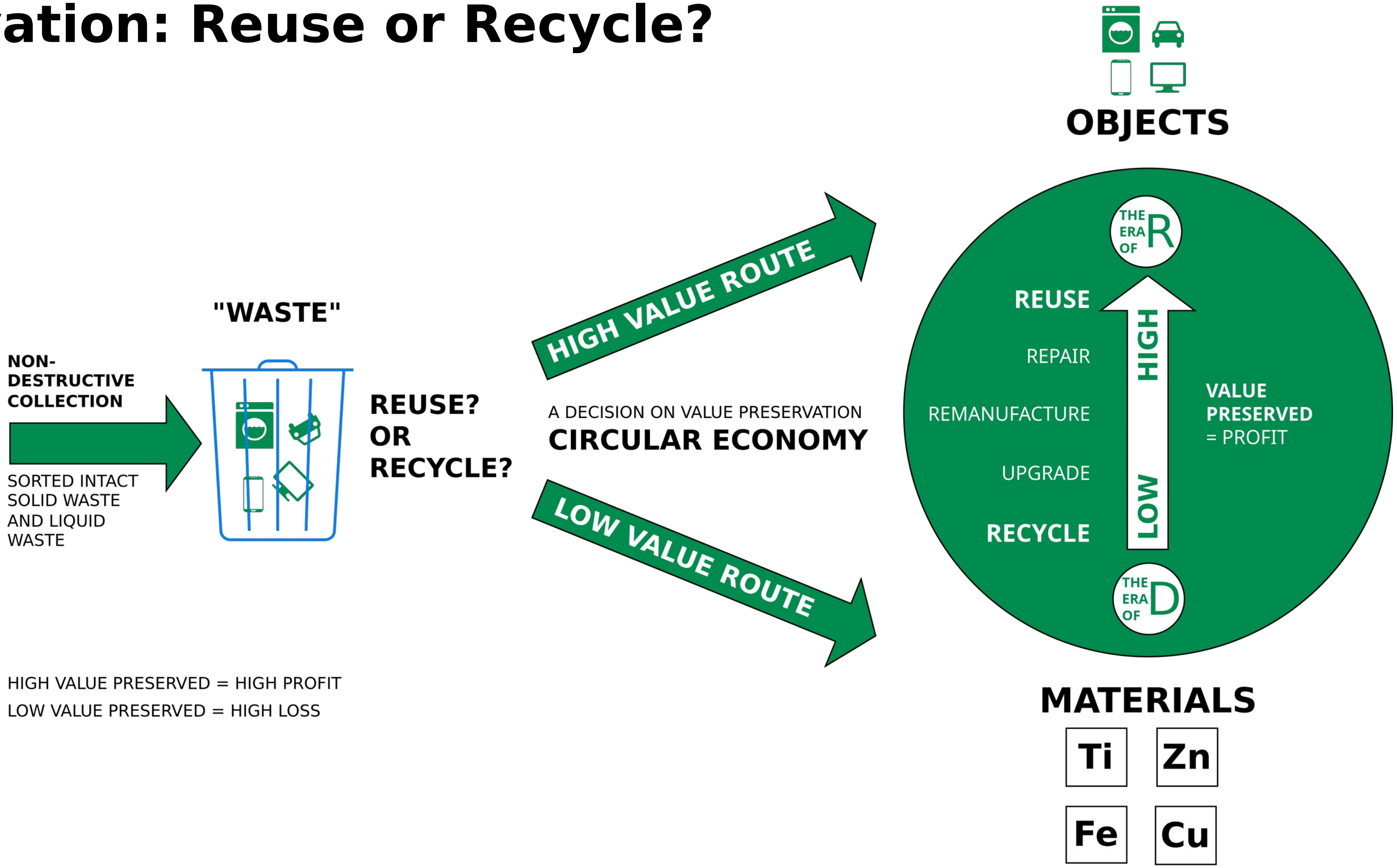
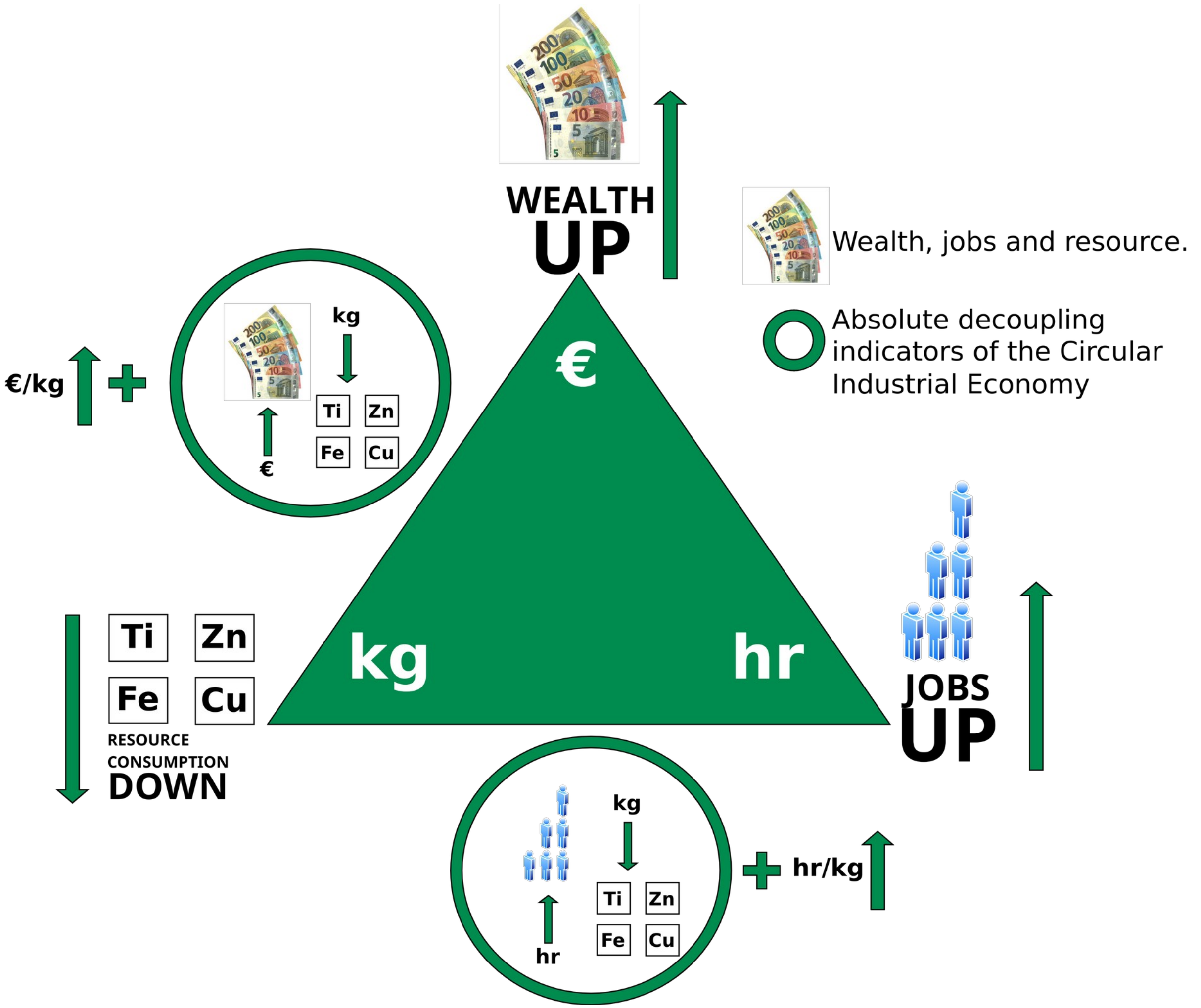


Image adapted from Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

The two absolute decoupling indicators of the CIE monitoring more wealth and jobs from less resource consumption

- **Linear Economy:** Low hr/kg (labor input per weight) ratios, coherent with mass production in highly mechanized processes, and low to medium €/kg (value per weight) ratios, in a range from basic materials like cement to smart goods like USB memory sticks



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- **Circular Economy:** Higher hr/kg and €/kg ratios for reuse, remanufacture and selling performance (goods as a service), in a group with new technologies, such as life sciences and nanotechnologies, which by nature produce dematerialized objects.

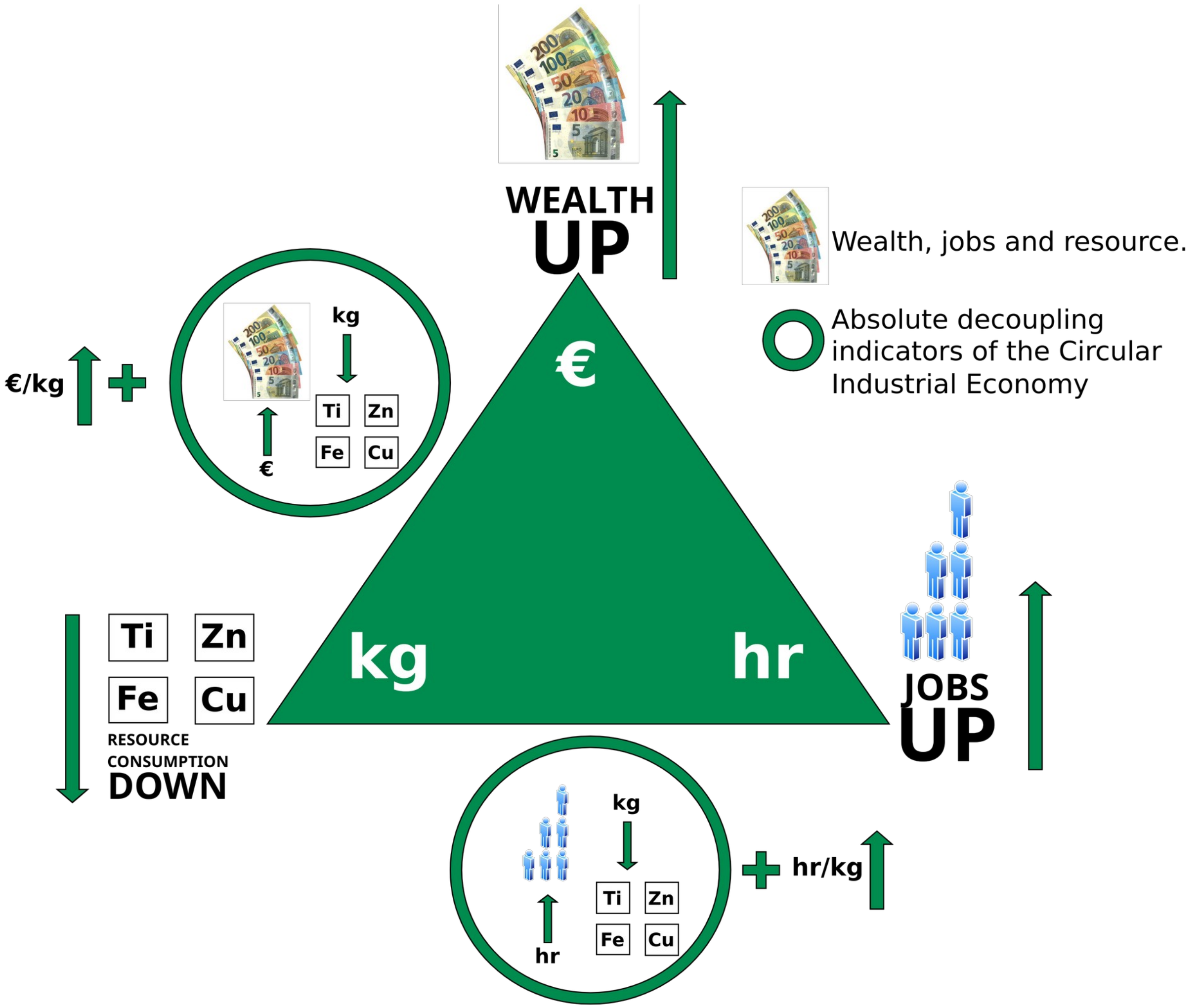
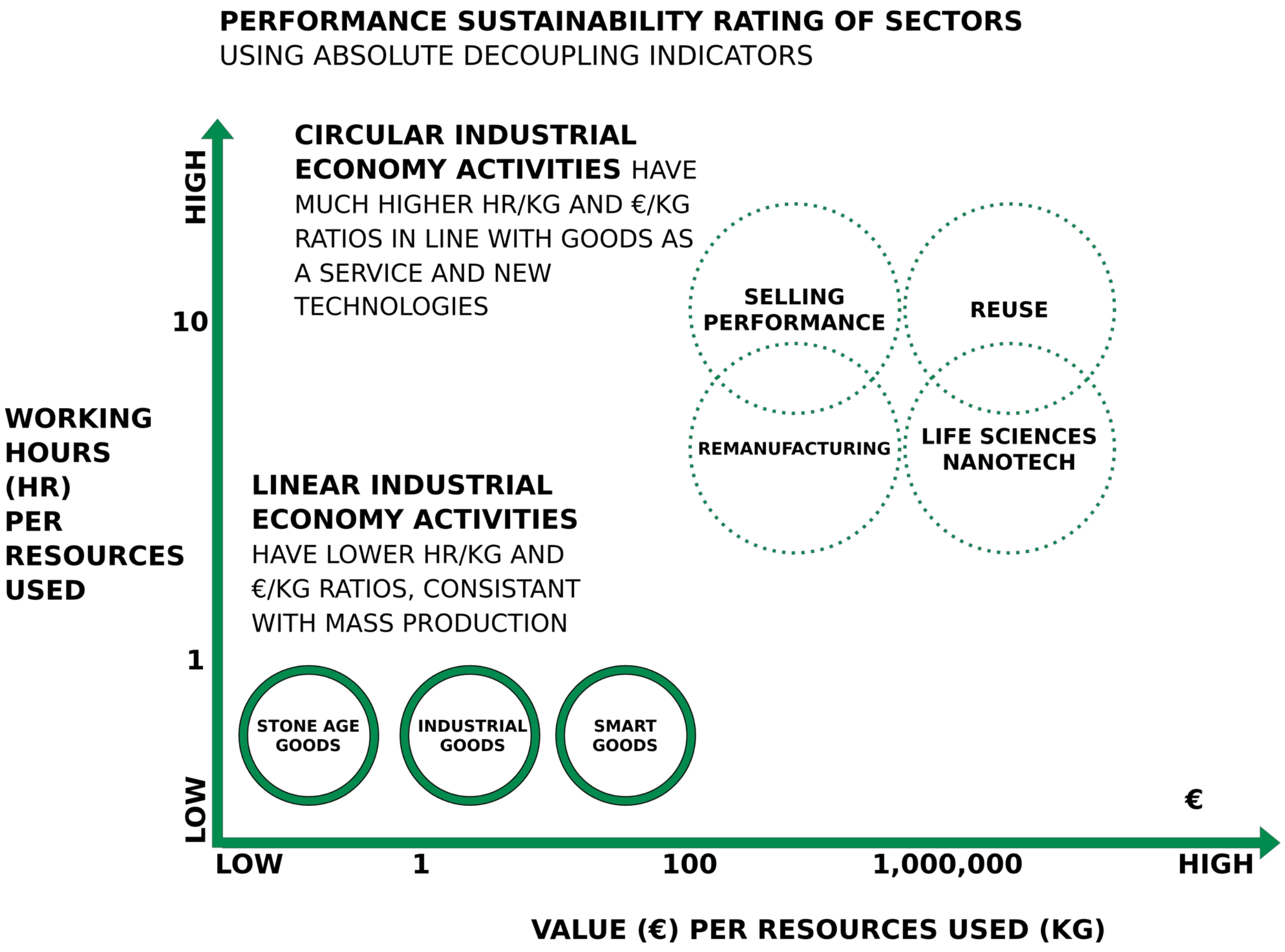


Image adapted from Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

Absolute decoupling indicators make the difference between the LIE and the CIE visible



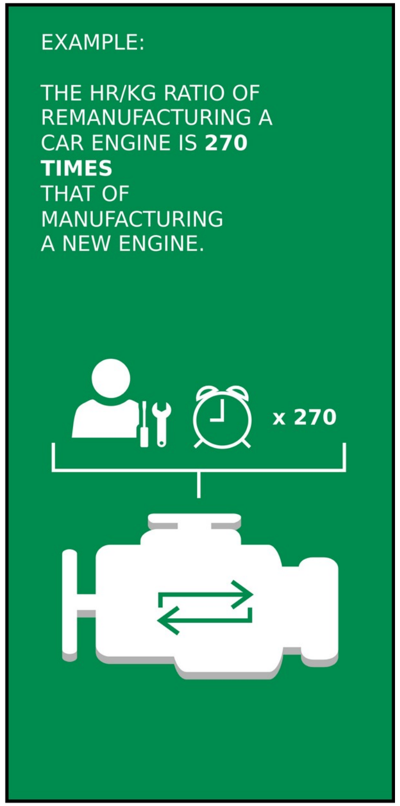


Image adapted from Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

PERFORMANCE ECONOMY

Performance Economy

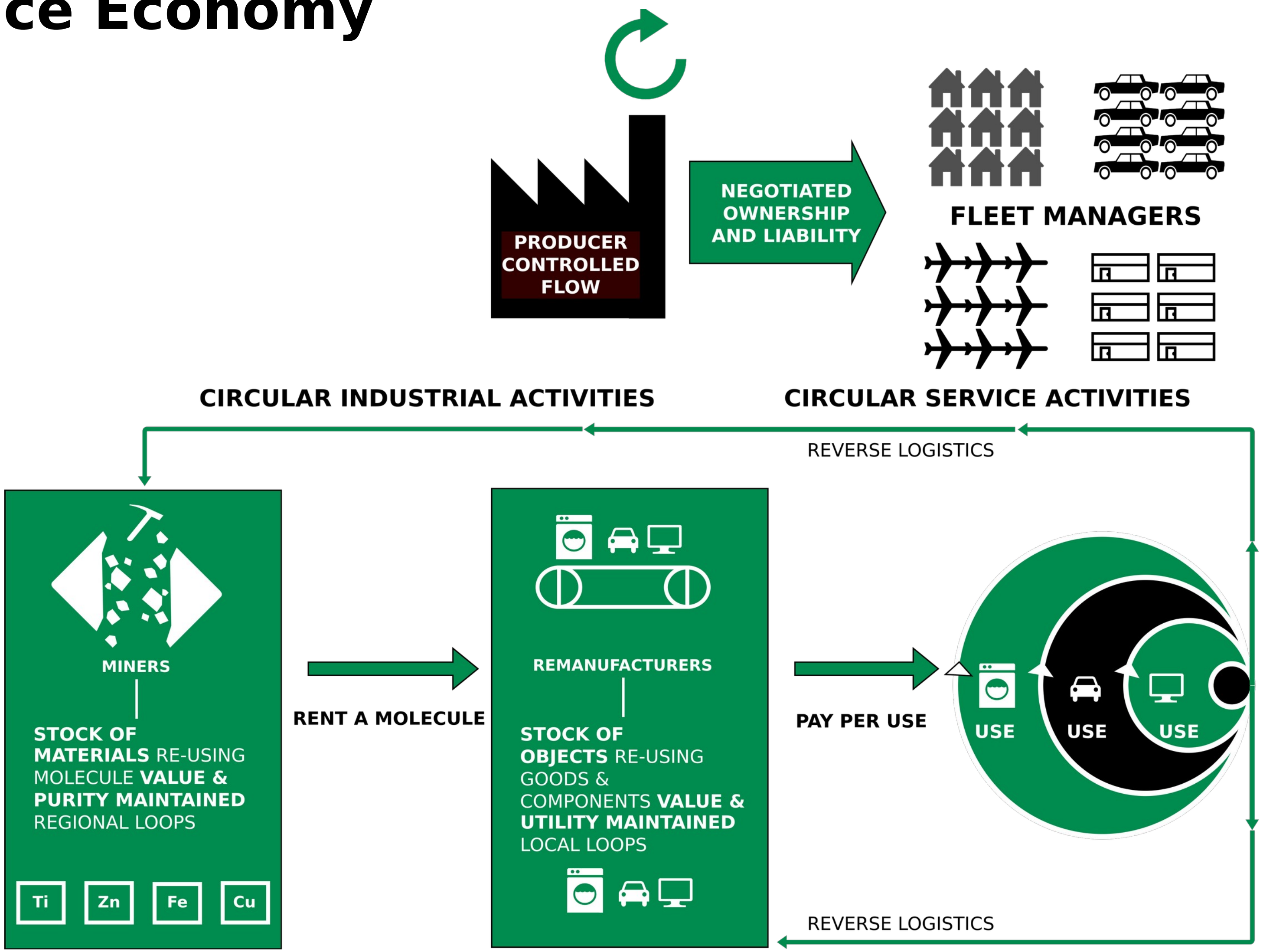


Image adapted from Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

Performance Economy – Definition

„The Performance Economy sells results instead of objects. Its economic actors may be manufacturers of durable objects or fleet managers operating them. In both cases, they sell the use of these objects as a service over the longest possible period of time and maximize their profits by exploiting both efficiency and sufficiency solutions. “

Walter R. Stahel (2019) – The Circular Economy: A User’s Guide.

Performance Economy – Most sustainable CE business model?

- Stahel argues:
  - "The Performance Economy of selling goods and molecules as a service, function guarantees or results and performance, is the most sustainable business model of the circular industrial economy because by internalising the costs of product liability, of risk and waste, it offers manufacturers a strong financial incentive to prevent losses and waste."

Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

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  - “It maximises the profit potential by exploiting sufficiency, efficiency and systems solutions.”

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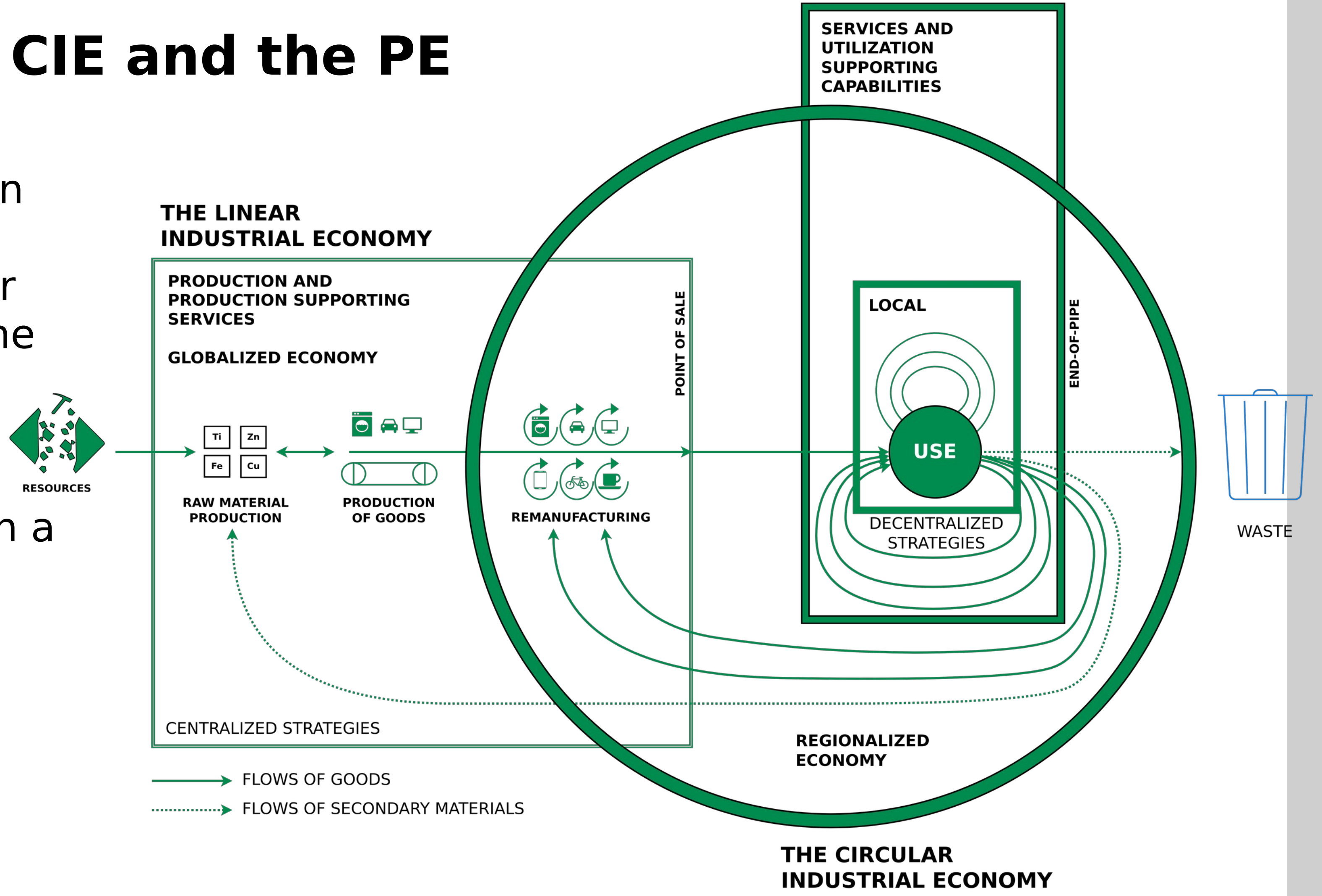
  - “It maximises the profit potential by exploiting sufficiency, efficiency and systems solutions.”
  - “In addition, by maintaining the ownership of objects and embodied resources, it creates long-term corporate and national resource security at low cost.”

Walter R. Stahel (2019) – The Circular Economy: A User’s Guide.

Situating the LIE, the CIE and the PE

- **Circle:** Managing the utilisation or use phase of stocks of manufactured objects and their components, by maintaining the value and quality of infrastructure, buildings, investment goods, equipment and durable consumer goods in a local or regional economy



Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

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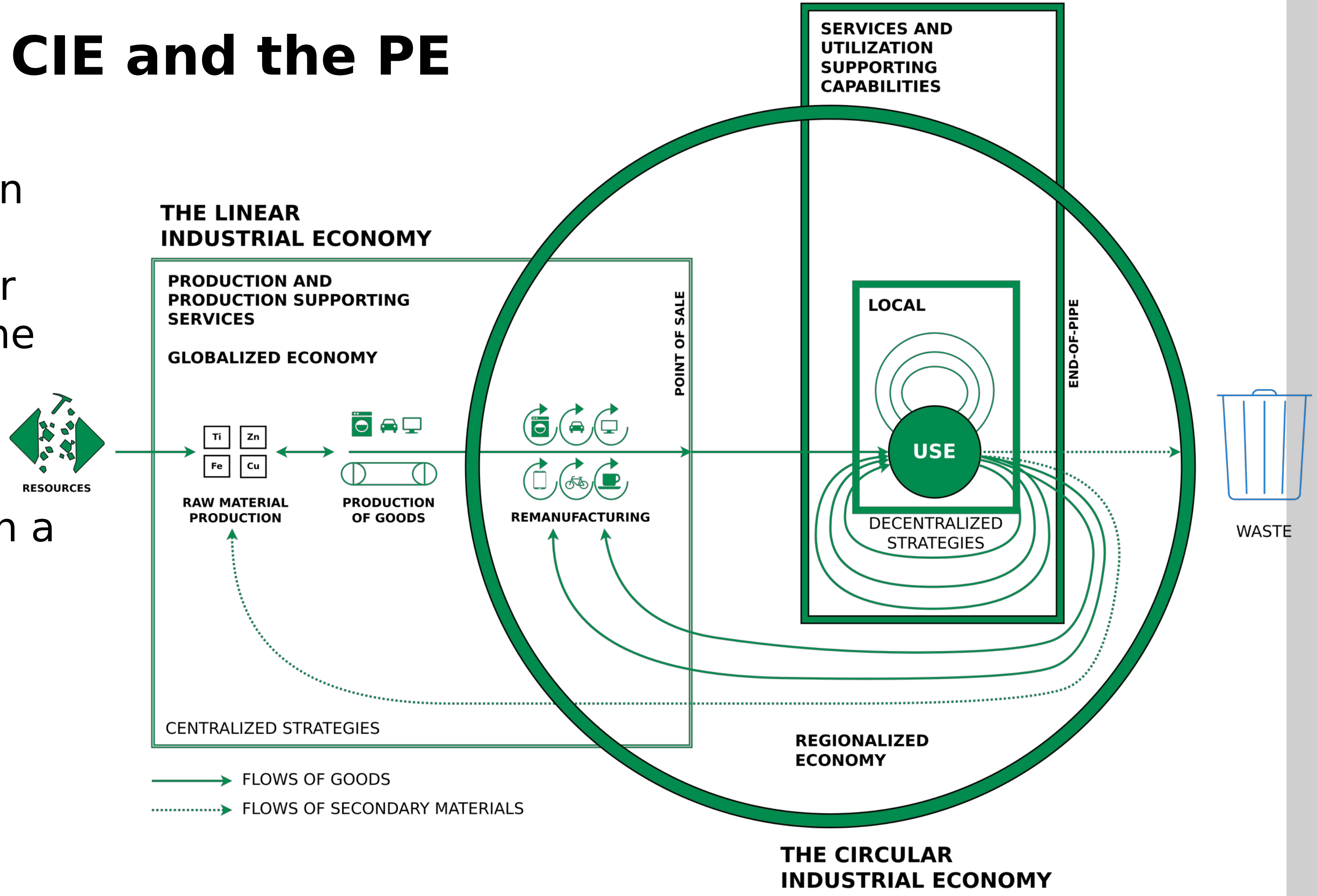
- **Small square:** Local use-focused PE



Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

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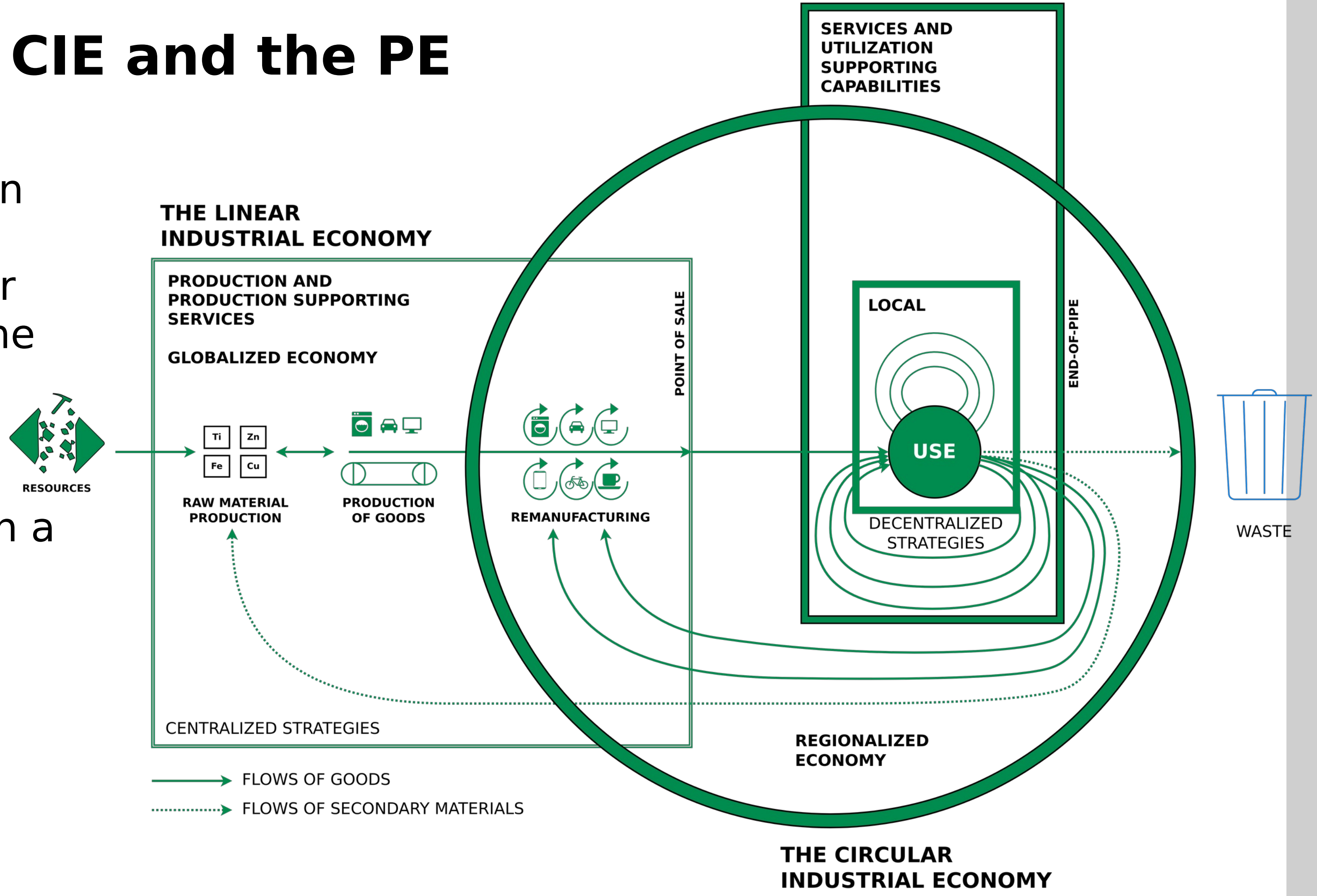
- **Small square:** Local use-focused PE
- **Big square:** Flows of used materials returning to the raw material producer to recover molecules and atoms in a globalised economy



Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

EMERGING TECHNOLOGIES FOR THE CIRCULAR ECONOMY

The Nature of Technology

- In the past many new technologies have emerged and disrupted existing economical models.

Arthur, Brian (2011) – The Nature of Technology: What It Is and How It Evolves.

The Nature of Technology

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- B. Arthur stipulates that an *economy is an expression of its technologies*

Arthur, Brian (2011) – The Nature of Technology: What It Is and How It Evolves.

The Nature of Technology

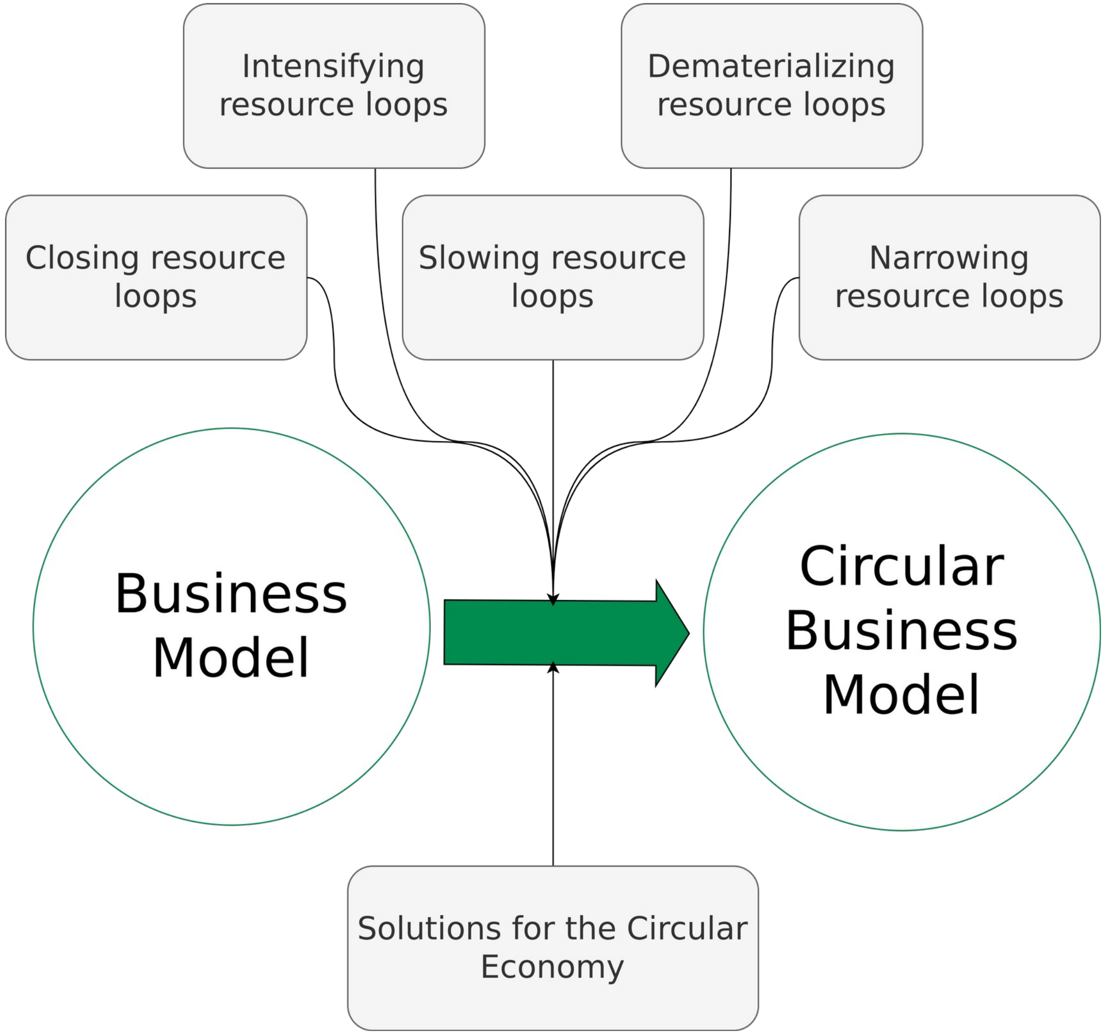
- In the past many new technologies have emerged and disrupted existing economical models.

- B. Arthur stipulates that an *economy is an expression of its technologies*
  - Thus, it can be argued that the current unsatisfying state of the Circular Economy reflects a lack of sufficiently developed technologies that express themselves within the CE.
  - Or, more precisely – difficulties of the stakeholders in combining the technologies that are required to enable the CE.

Arthur, Brian (2011) – The Nature of Technology: What It Is and How It Evolves.

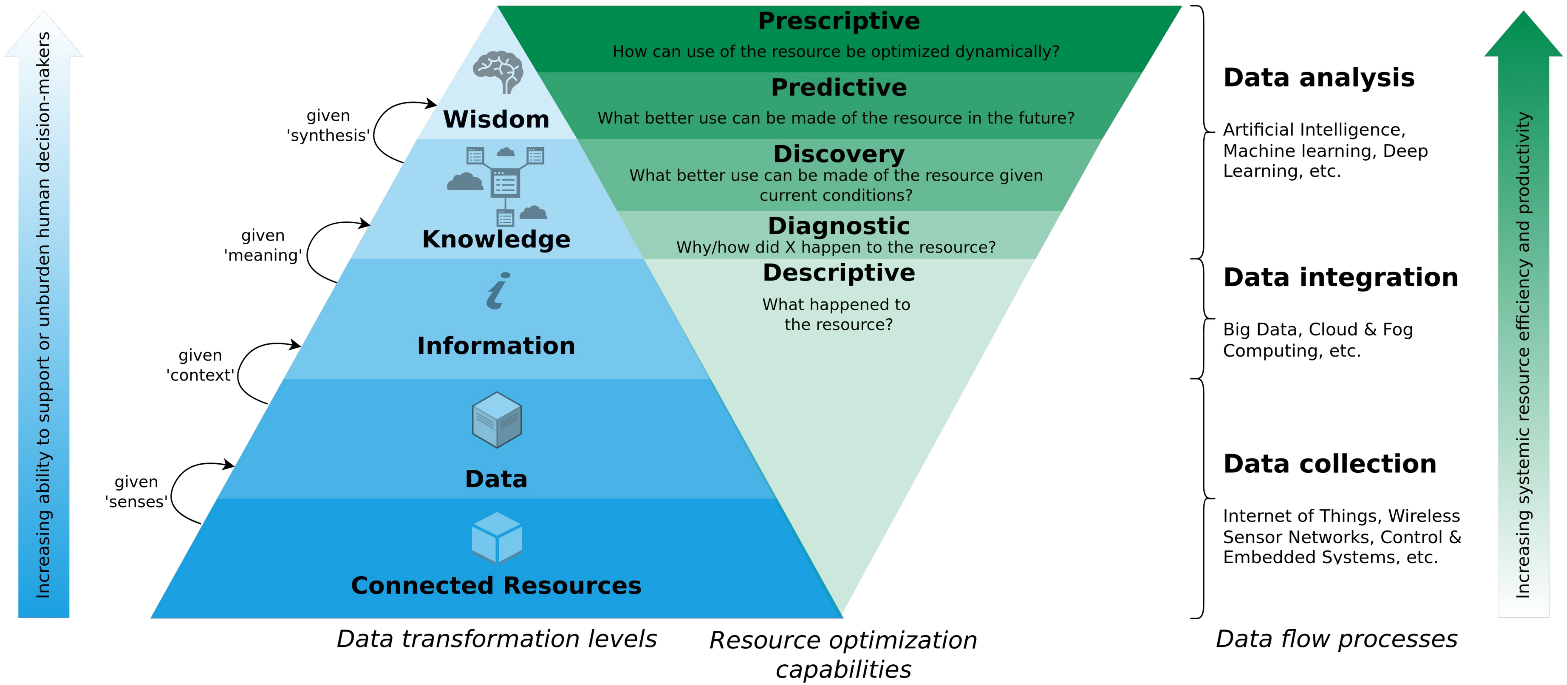
DIGITAL CIRCULAR ECONOMY AND BUSINESS MODELS

Circular Economy Business Models



Geissdoerfer et al. (2018) – Business models and supply chains for the circular economy.

#1: A Data-Driven Smart Circular Economy Framework



Kristoffersen et al. (2020) – The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies.

#2: Performance Economy and/to Sharing Economy

Walter R. Stahel (2019) – The Circular Economy: A User's Guide.

EXAMPLE 1– RESELL?

Resell and Reuse of IT Devices

- Momox.co.uk
- Ebay-Kleinanzeigen.de
- Rebuy.de

https://www.ebay-kleinanzeigen.de
https://www.momox.co.uk
https://www.rebuy.de

EXAMPLE 2 – FUTURE RESOURCES

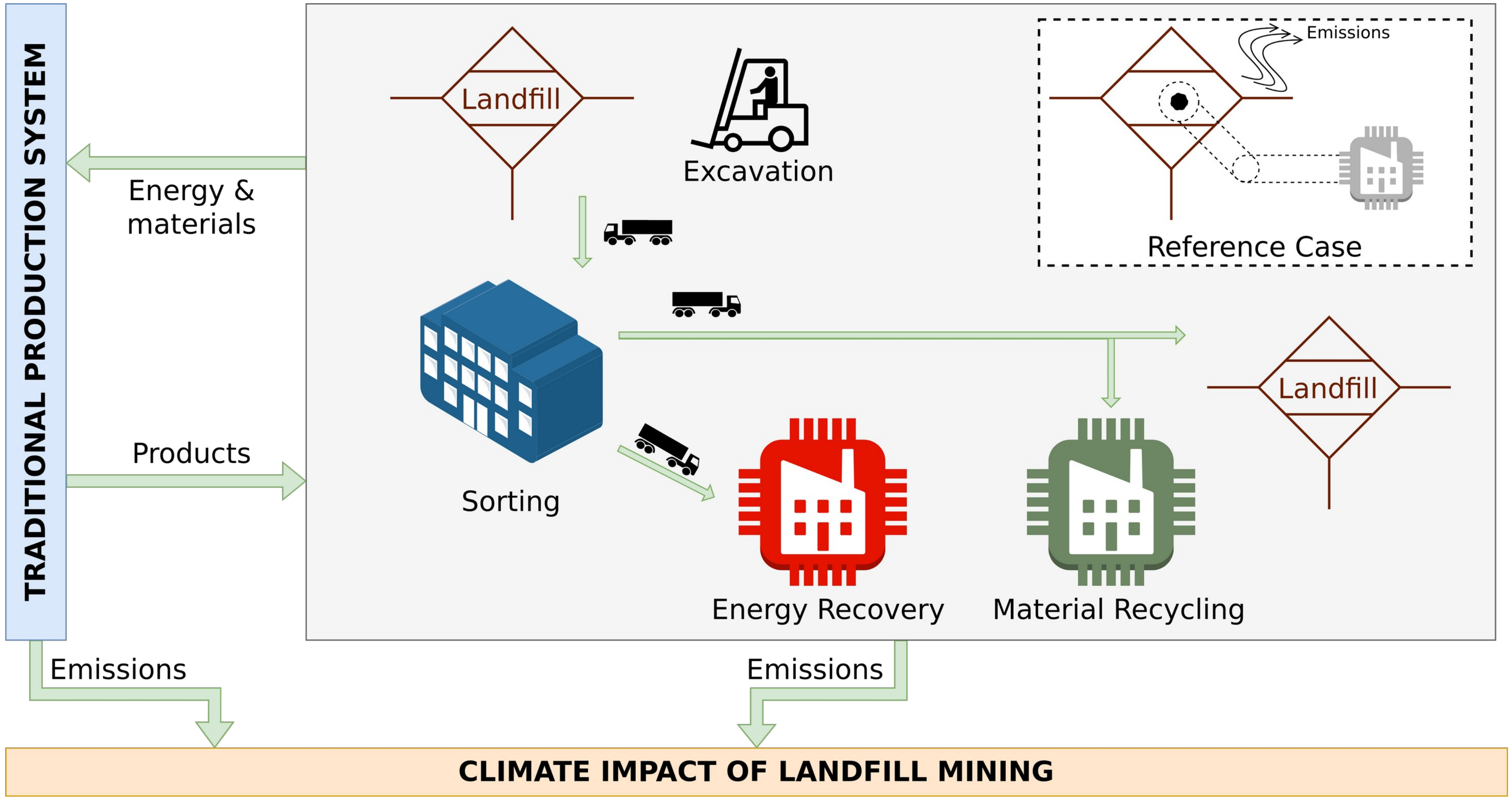
Buildings as Material Banks (BAMB)

- Integrating “materials passports” with reversible building design to optimise *Circular Industrial Value Chains*.

- Aims of BAMB:
  - Prevention of construction and demolition waste.
  - Reduction of virgin resource consumption and the development towards a circular economy through industrial symbiosis.
  - Addressing the challenges mentioned in the Work Programme on Climate action, environment, resource efficiency and raw materials

https://cordis.europa.eu/project/id/642384

Landfill Mining



Laner et al. (2016) – Quantitative Analysis of Critical Factors for the Climate Impact of Landfill Mining

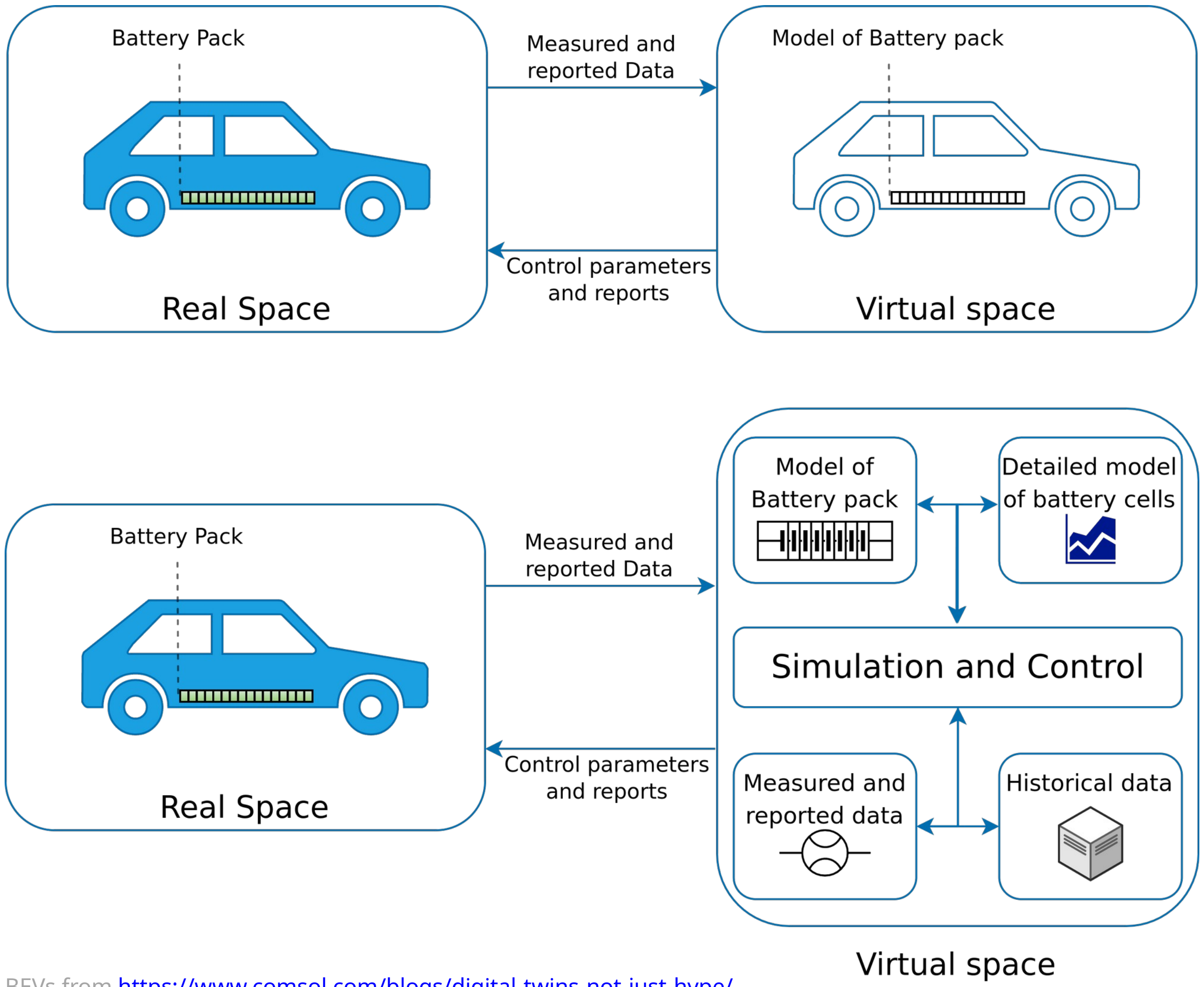
EXAMPLE 3 – DIGITAL TWINS

Definitions

No.	Ref	Year	Definition of Digital Twin
1	[16–18]	2010 and 2012	An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems.
2	[19]	2012	A cradle-to-grave model of an aircraft structure's ability to meet mission requirements, including submodels of the electronics, the flight controls, the propulsion system, and other subsystems
3	[20]	2012	Ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used to assess the aircraft's ability to meet mission requirements
4	[23]	2013	Coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge
5	[21]	2013	Ultra-high fidelity physical models of the materials and structures that control the life of a vehicle
6	[24]	2013	Structural model which will include quantitative data of material level characteristics with high sensitivity
7	[25]	2015	Very realistic models of the process current state and its behavior in interaction with the environment in the real world
8	[22]	2015	Product digital counterpart of a physical product
9	[26]	2015	Ultra-realistic multi-physical computational models associated with each unique aircraft and combined with known flight histories
10	[27]	2015	High- fidelity structural model that incorporates fatigue damage and presents a fairly complete digital counterpart of the actual structural system of interest
11	[28]	2016	Virtual substitutes of real world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services
12	[29]	2016	Digital representation of a real world object with focus on the object itself
13	[30]	2016	The simulation of the physical object itself to predict future states of the system

Negri et al. (2017) – A Review of the Roles of Digital Twin in CPS-based Production Systems – https://doi.org/10.1016/j.promfg.2017.07.198.

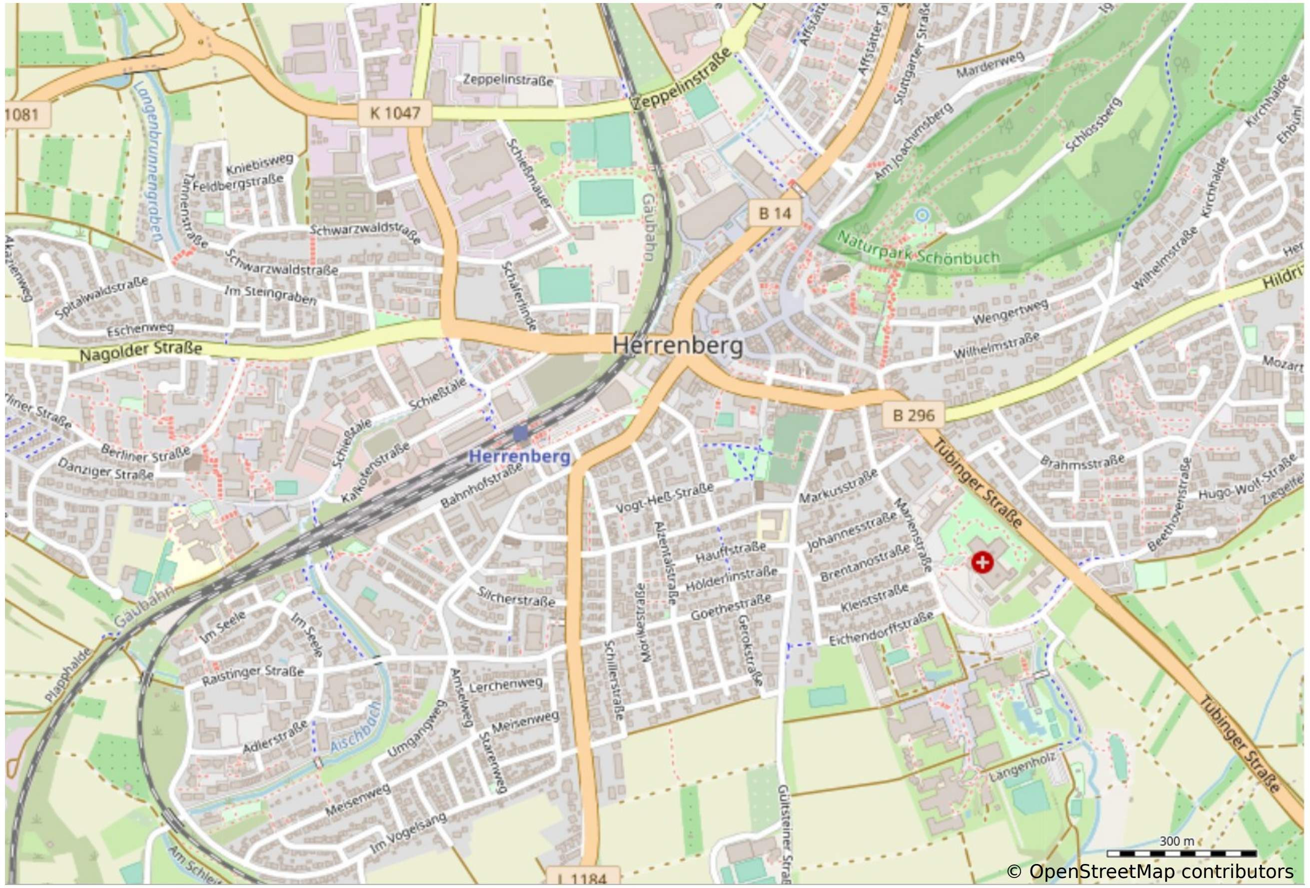
Example 1: Automotive Industry



The digital twin concept exemplified on a battery pack of a BEV.

Image adapted for BEVs from https://www.comsol.com/blogs/digital-twins-not-just-hype/

Example 2: Smart Cities

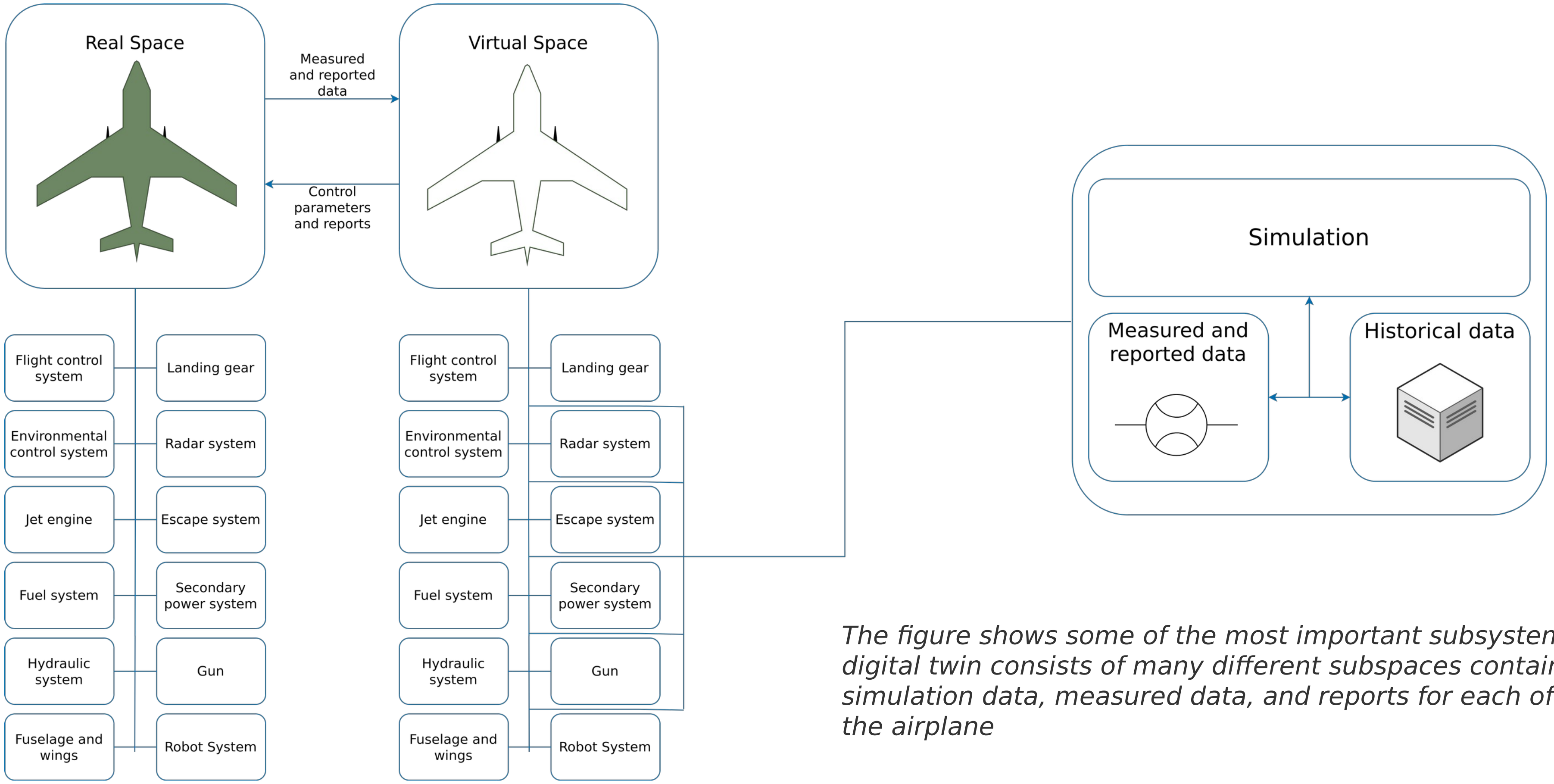


- Digital Twin of Herrenberg

- Mathematical street network model with space syntax
  - Used to indicate high/low potentials of traffic.
- Sensor network
  - Temperature
  - Humidity
  - Particulate Matter
- Air-flow simulation
  - Simulation and combination of data relates emissions to potential volume of traffic using wind, humidity, temperature and particulate matter data.
- 3D Visualization of the above using Virtual Reality (VR)

Dembski, Fabian, et al. "Urban digital twins for smart cities and citizens: the case study of Herrenberg, Germany." *Sustainability* 12.6 (2020): 2307

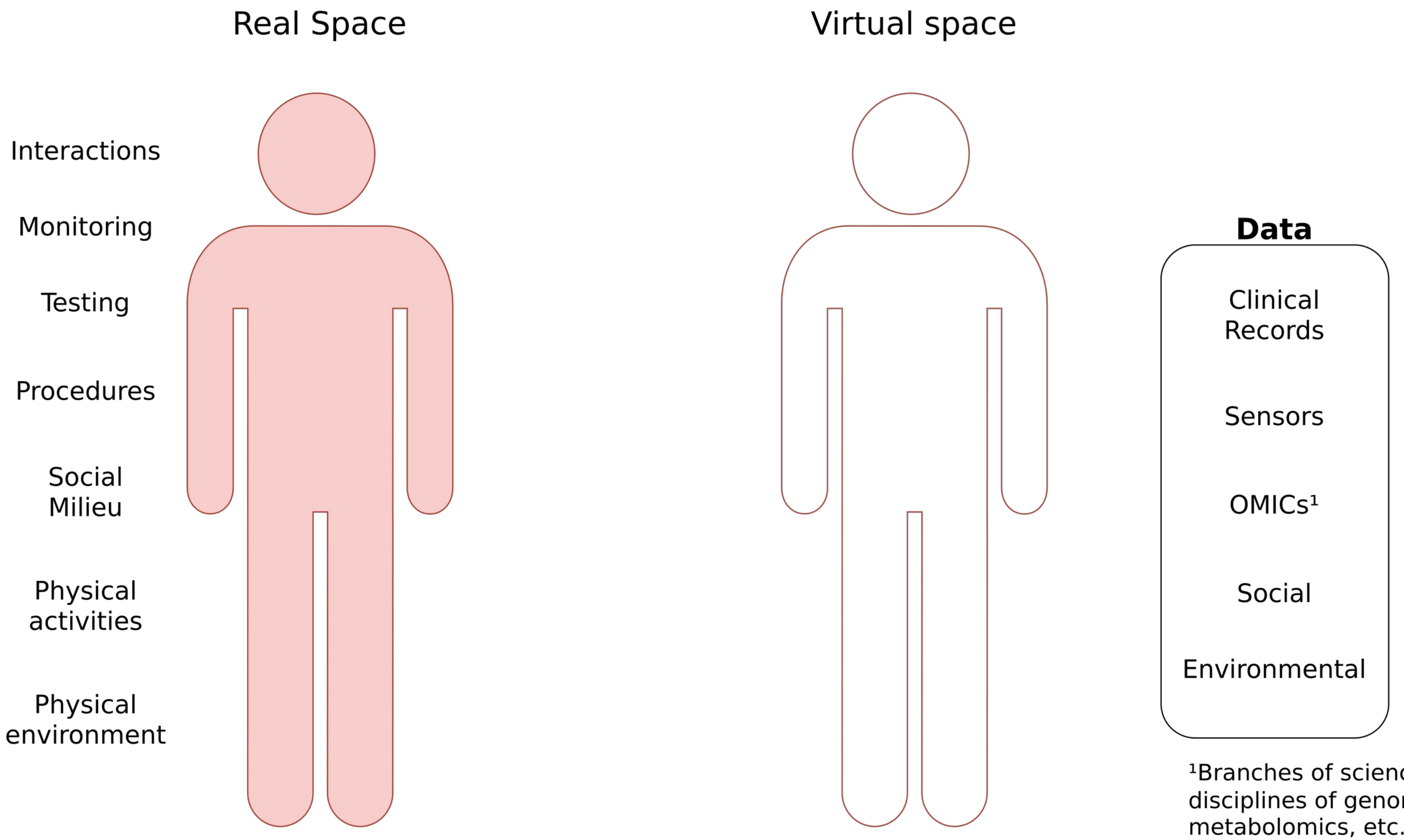
Example 3: Aviation and Aerospace



The figure shows some of the most important subsystems in a fighter jet. A digital twin consists of many different subspaces containing models, simulation data, measured data, and reports for each of the subsystems of the airplane

Image recreated from: https://www.comsol.com/blogs/digital-twins-not-just-hype/

Example 4: Human Medicine



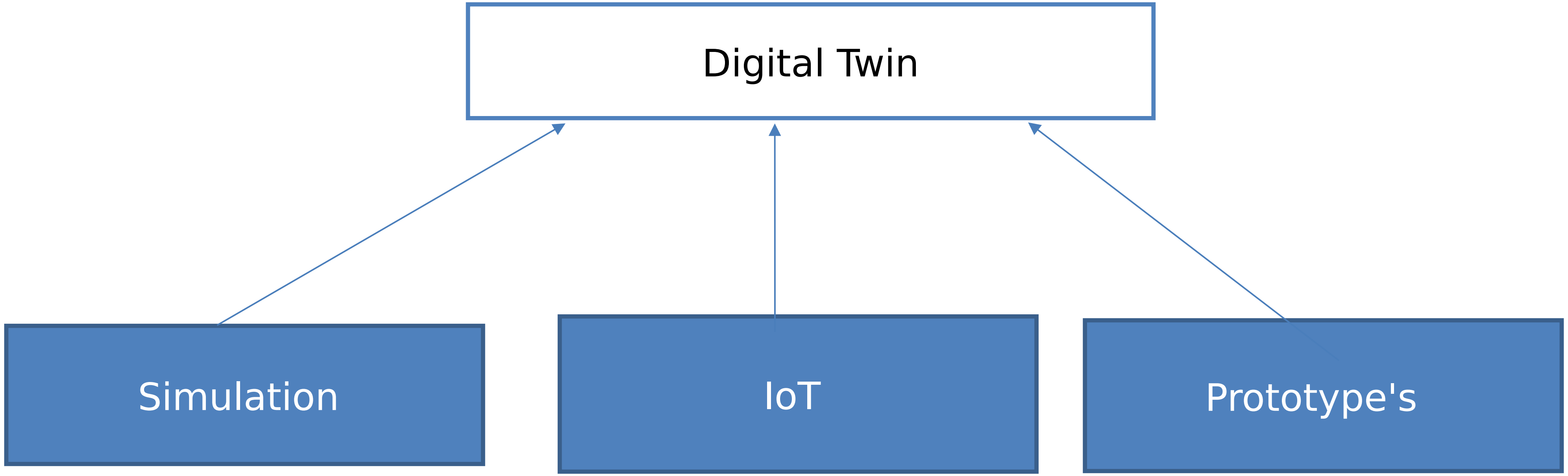
[1]Branches of science composed of disciplines of genomics, proteomics, metabolomics, etc.

Digital Twin for patient-specific care

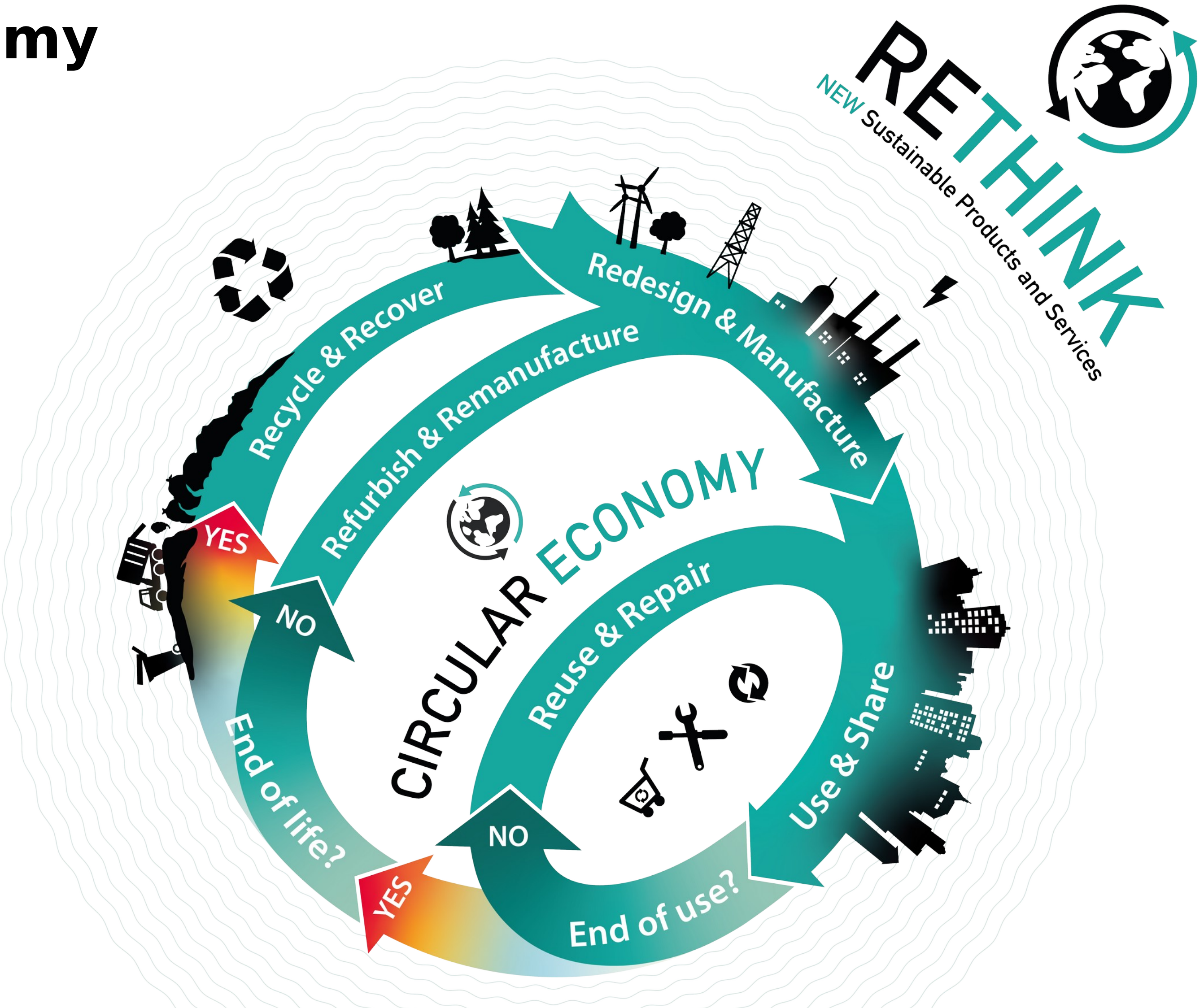
Image adapted from: Rao, Dattaraj Jagdish, and Shraddha Mane. "Digital Twin approach to Clinical DSS with Explainable AI." *arXiv preprint arXiv:1910.13520* (2019).

Digital Twins vs. Other Concepts

- Digital twins are often compared to be synonymous with simulation, prototype, IoT, etc.



Circular Economy



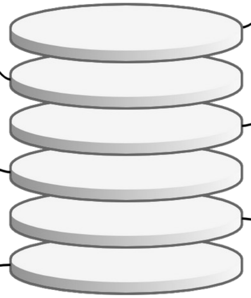
Center for Digital Technologies (DIGIT) (2022) – https://www.digit-research.de/fileadmin/DIGIT/Presse_und_News/Downloads/Grafikpaket_Reallabor_DCE_Kreislaufmodell_V2_ccby.zip – CC BY 4.0.

Use Cases (1): Supply Chain Transparency

Product Usage
What is it for? Where will it be used?
How? Is it a Direct Material? Does it meet specifications?
Will it suffice? What are the concerns?
What are the risks? Are there alternatives?

Procurement Data
Purchasing approval? Is the vendor approved?
Is it importable? Payment terms supported?
Supply risks?

Facility Information
Can we use it? Store it?
Where exactly? How much?
Do we adhere to standards?
Have we adopted appropriate Codes?
Applied labels and signage?



Composition Information
What substances does it contain?
Are any of them regulated? Restricted? Banned?
Do we have acceptable disclosure from the Vendor?

Health and Safety Information
What are the risks? Hazards?
Can we mitigate these?
Do we have appropriate controls in place?
Do we need to train our staff?
Do we need to provide instructions?

Environmental Data
What are the recyclability/ disposal considerations?
Release to Air/Water/Land? Waste contractor required?
Special process?
Does target market have adequate processes, infrastructure or contractors to handle this?
What are the related Environmental Impacts?

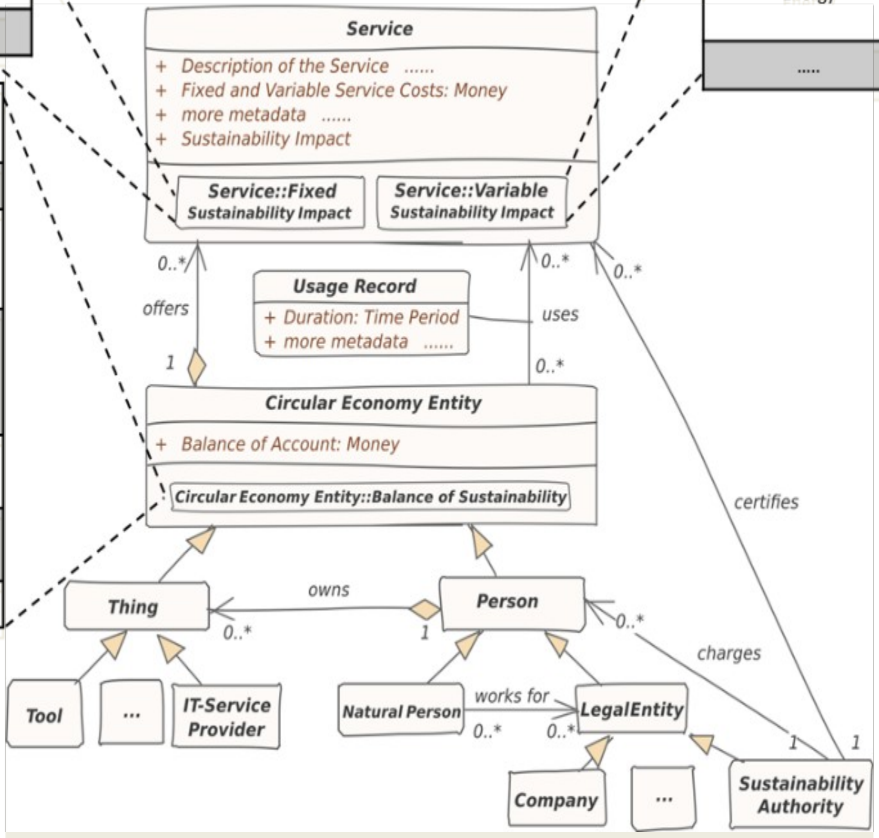
Relevant Information can be gathered, updated and accessed via a digital twin. Thus creating transparency and traceability.

Based on https://fslci.org/wp-content/uploads/2018/Slides/Sessions/Session_5_Prox.pdf

Use Cases (2): Sustainability Impact Factor

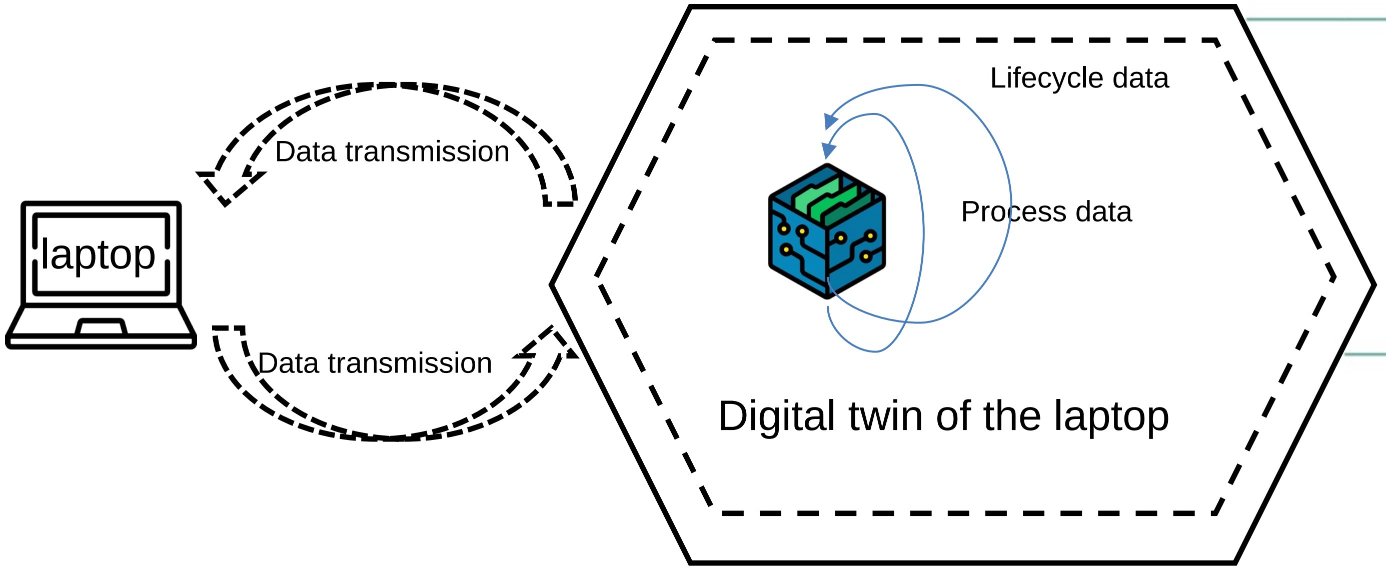
Amount of Impact		More...
50 kg CO2		.....
1 kg steel, 0.01 kg rare earth materials		.....
.....		.....

CO2 Impact		Environmental Impact		More...	
Debt	Credit	Debt	Credit	Debt	Credit
-10 kg Co2		0.5kg steel		.....	
	+5 kg CO2		+0.001 kg rare earth materials	.....	.....
-20 kg CO2		.....	.....	.....	.....
.....	.....	.....	.....	.....	.....
Total: -20 kg CO2		Total:		Total:	



Amount of Impact	Per use/ Per hour	More ...
52 kg CO2	Hour (H)	.....
Energy	Energy Amount/Hour (H)	.....
.....	.....	.....

Use Case (3): Increasing the Longevity of Electronics

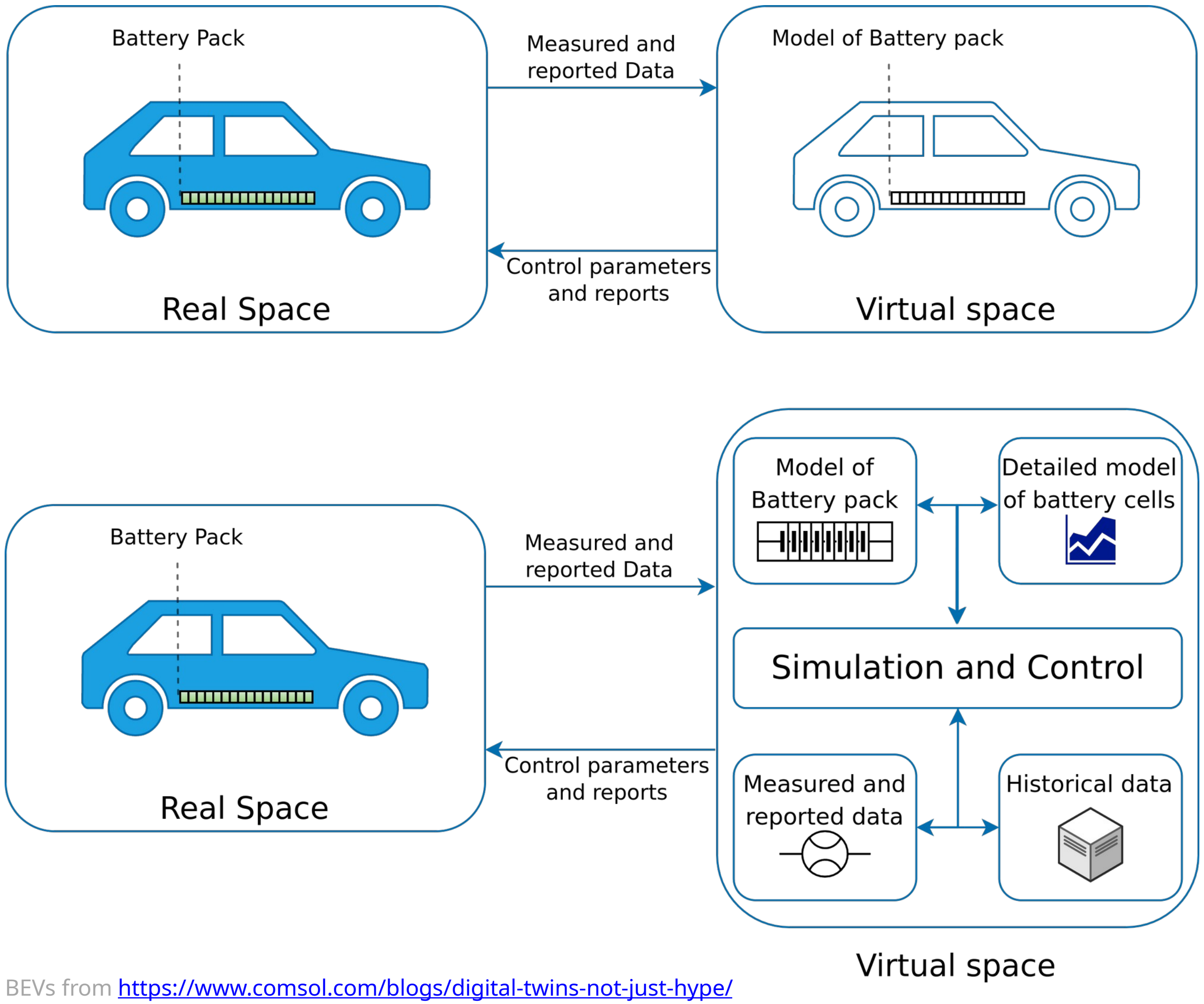


- Scenario 1 – Resell
  - *Buyers can access data* from the twin and *determine* if the laptop/product will *serve their requirements.*

- Scenario 2 - Repair
  - Repairers can *access the twins data* to *determine* the *problem*, rather then analyze it by themselves. This would save the repair time and cost.

More Transparency, reducing repair costs and traceability, products could be easily leased or shared

Use Case (4): Battery Electric Vehicles



The digital twin concept exemplified on a battery pack of a BEV.

Image adapted for BEVs from https://www.comsol.com/blogs/digital-twins-not-just-hype/

EXAMPLE 4 – ELECTRIC VEHICLE LIFE CYCLE ASSESSMENT (LCA)

LCA – Motivation

LCA – Motivation

Battery Electric Vehicles (EV)

Or

Internal Combustion Engine Vehicles

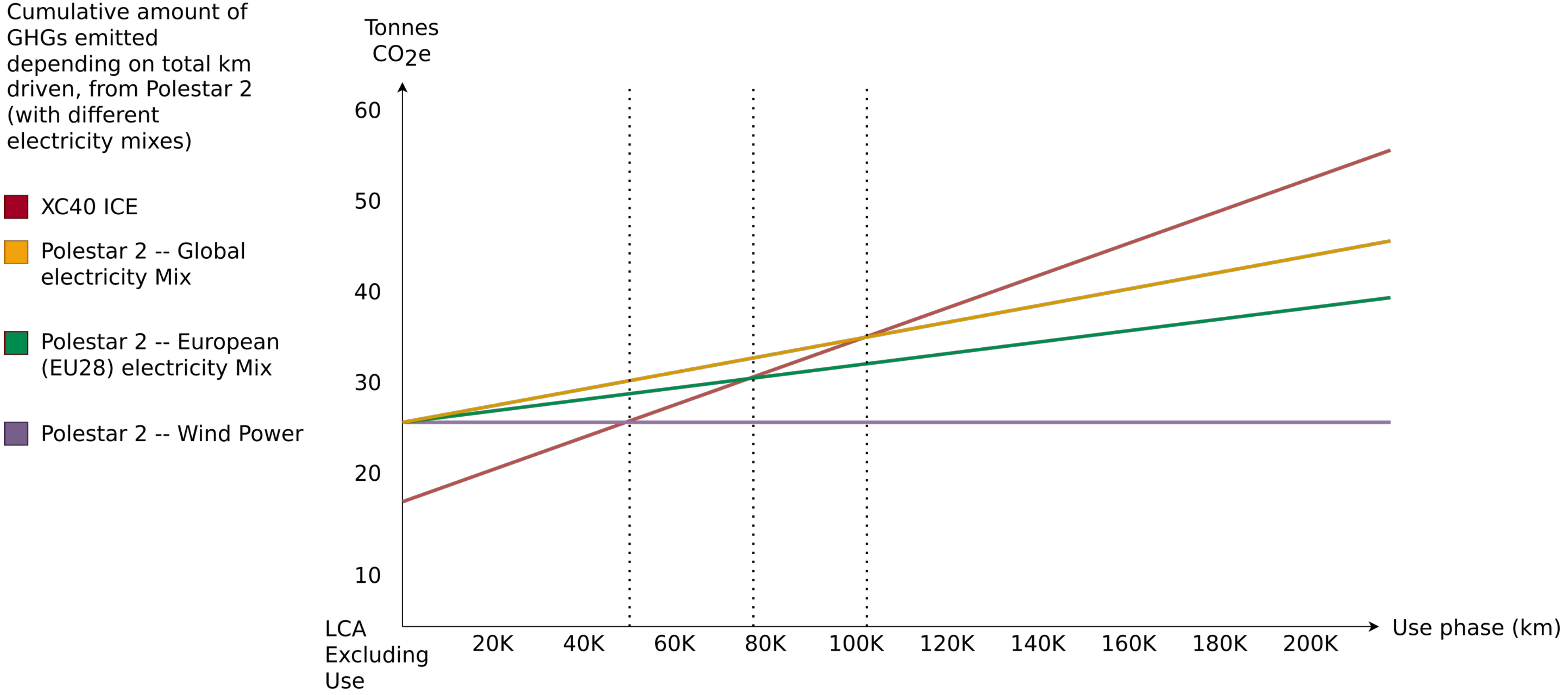
EV Break-Even Point?

What is the **break-even** point (in km) after which an EV would have caused fewer emissions than an Internal Combustion Engine (ICE?)

a. 0 – 50.000km
b. 50.000 – 100.000km
c. 100.000 – 150.000km
d. 150.000 – 200.000km
e. After 200.000km

Life Cycle Assessment – Polestar 2

Cumulative amount of GHGs emitted depending on total km driven, from Polestar 2 (with different electricity mixes)



Number of kilometers driven at break-even between Polestar 2 with different electricity mixes in the use phase of XC40 ICE (petrol)

Electric mix	Break-even (km)
Polestar 2 -- Global electricity Mix	112,000
Polestar 2 -- European (EU28) electricity Mix	78,000
Polestar 2 -- Wind Power	50,000

Polestar (2020) – Life Cycle Assessment – Carbon Footprint of Polestar 2.

Further Resources

- Baccini et al. (2012) – Metabolism of the Anthroposphere: Analysis, Evaluation, Design
- Deutscher Bundestag (1994): Bericht der Enquete-Kommission „Schutz des Menschen und der Umwelt − Bewertungskriterien und Perspektiven für umweltverträgliche Stoffkreisläufe in der Industriegesellschaft“ – Link
- Meadows (1972) – The Limits to Growth
- Meadows, Randers and Meadows (2004) – Limits to Growth – The 30-Year Update
- Walter R. Stahel (2019) – The Circular Economy: A User's Guide
- Website of the Ellen MacArthur Foundation – Link

Emerging Technologies for the Circular Economy

Lecture 3: Lifecycle Assessment (LCA)

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Questions?