Emerging Technologies for the Circular Economy

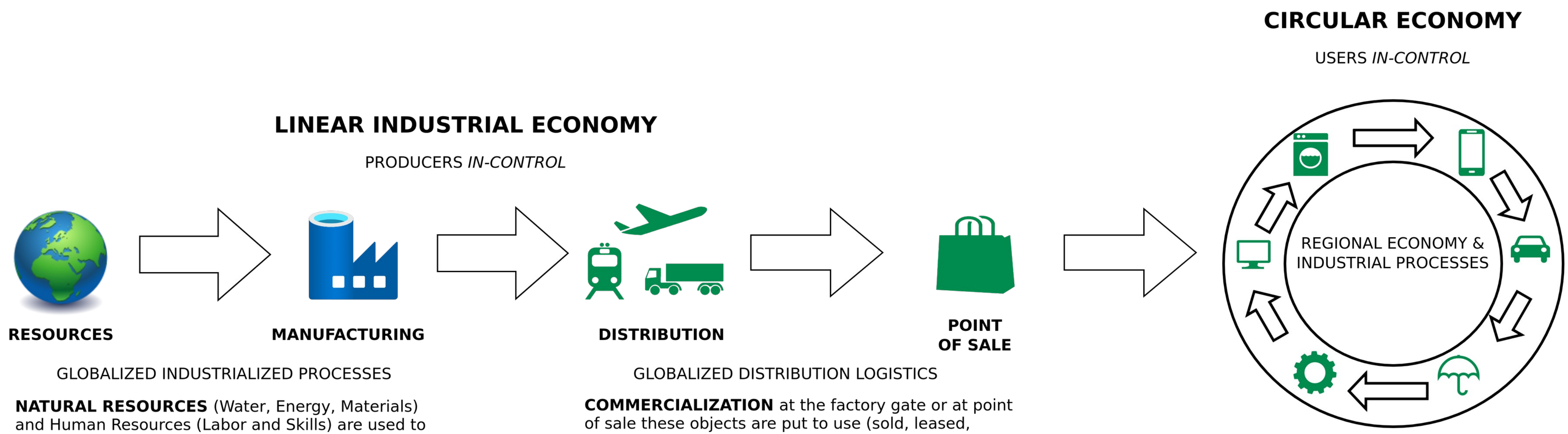
Lecture 3: Circular Economy II

Prof. Dr. Benjamin Leiding (Clausthal)
M.Sc. Arne Bochem (Göttingen)
M.Sc. Anant Sujatanagarjuna (Clausthal)

License

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

The Linear (Industrial) Economy



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).

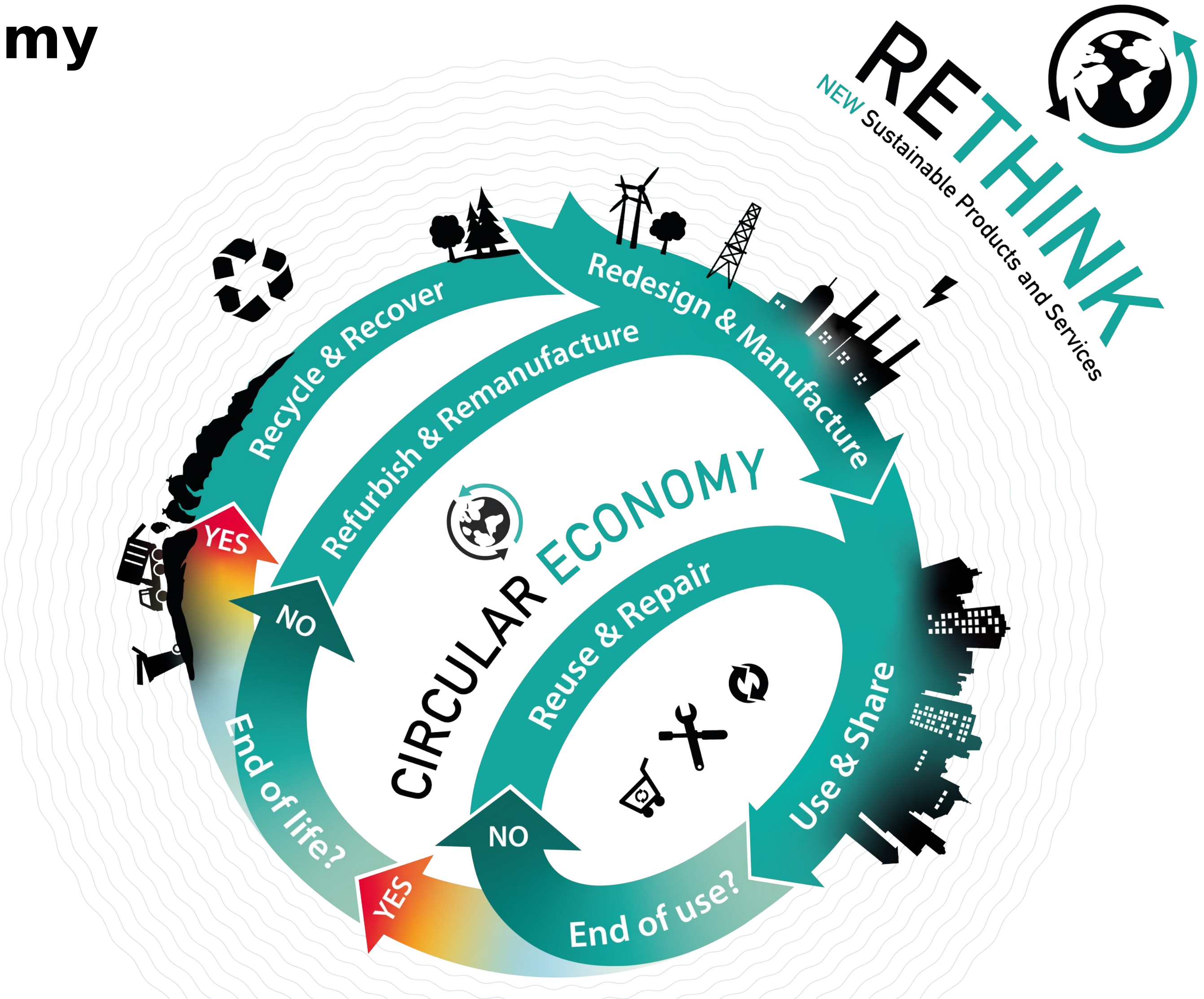
GLOBALIZED DISTRIBUTION LOGISTICS

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

... 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.

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.

EXAMPLE 2 – ELECTRIC VEHICLE LIFE CYCLE ASSESSMENT (LCA)

LCA – Motivation

LCA – Motivation

Battery Electric Vehicles (EV)

Or

Internal Combustion Engine Vehicles

Material Flow

„A material flow is the path of a material from its extraction as a raw material through the various stages of refinement to the final product stage, the use/consumption of the product, and - if applicable - its reuse/recovery up to its disposal."

Deutscher Bundestag (1994): Bericht der Enquete-Kommission „Schutz des Menschen und der Umwelt − Bewertungskriterien und Perspektiven für umweltverträgliche Stoffkreisläufe in der Industriegesellschaft". Deutscher Bundestag. Bonn (Drucksache, 12/8260).

Material Flow Management

„Material flow management is the goal-oriented, efficient use of materials, material streams and energy. The goals are given by ecological and economical areas and by observing social aspects."

Deutscher Bundestag (1994): Bericht der Enquete-Kommission „Schutz des Menschen und der Umwelt − Bewertungskriterien und Perspektiven für umweltverträgliche Stoffkreisläufe in der Industriegesellschaft". Deutscher Bundestag. Bonn (Drucksache, 12/8260).

Material Flow Analysis (MFA)

- Which material flows are relevant?

Deutscher Bundestag (1994): Bericht der Enquete-Kommission „Schutz des Menschen und der Umwelt − Bewertungskriterien und Perspektiven für umweltverträgliche Stoffkreisläufe in der Industriegesellschaft". Deutscher Bundestag. Bonn (Drucksache, 12/8260).

Material Flow Analysis (MFA)

- Which material flows are relevant?
- In which processes and by which actors are these materials used?

Deutscher Bundestag (1994): Bericht der Enquete-Kommission „Schutz des Menschen und der Umwelt − Bewertungskriterien und Perspektiven für umweltverträgliche Stoffkreisläufe in der Industriegesellschaft". Deutscher Bundestag. Bonn (Drucksache, 12/8260).

Material Flow Analysis (MFA)

- Which material flows are relevant?
- In which processes and by which actors are these materials used?
- In what quantities are the materials used, extracted from the environment and discharged into the environment?

Deutscher Bundestag (1994): Bericht der Enquete-Kommission „Schutz des Menschen und der Umwelt − Bewertungskriterien und Perspektiven für umweltverträgliche Stoffkreisläufe in der Industriegesellschaft". Deutscher Bundestag. Bonn (Drucksache, 12/8260).

Life Cycle Assessment (LCA)

The life cycle assessment is an instrument that allows for a holistic, systematic recording of environmental impacts and an evaluation of a balance object in order to enable the comparison of alternatives. Balance objects can be products, processes, companies or behaviors.

Bieletzke (1999): Simulation der Ökobilanz – Modelltheoretische Analyse ökonomischer und ökologischer Auswirkungen

MFA vs. LCA

MFA vs. LCA

- MFA is a component of the LCA

MFA vs. LCA

- MFA is a component of the LCA
- MFA explicitly does not include any environmental assessment

MFA vs. LCA

- MFA is a component of the LCA
- MFA explicitly does not include any environmental assessment
- MFA is for the qualitative and quantitative assessment of material flows, while in the LCA is additionally performed the environmental assessment through the quantification of environmental effects

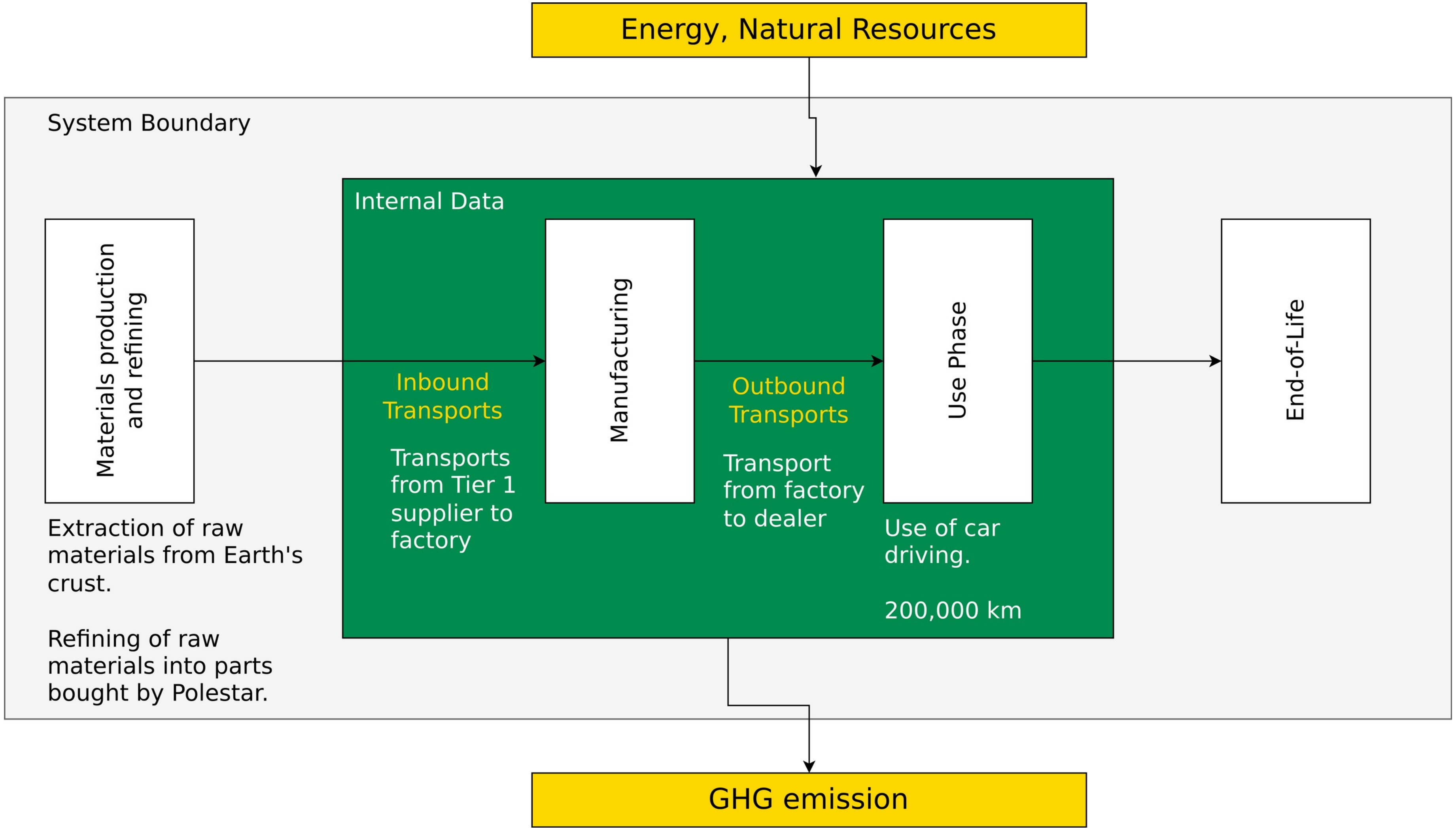
LCA – Motivation

Battery Electric Vehicles (EV)

Or

Internal Combustion Engine Vehicles

Life Cycle Assessment – Polestar 2



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

EV Break-Even Point?

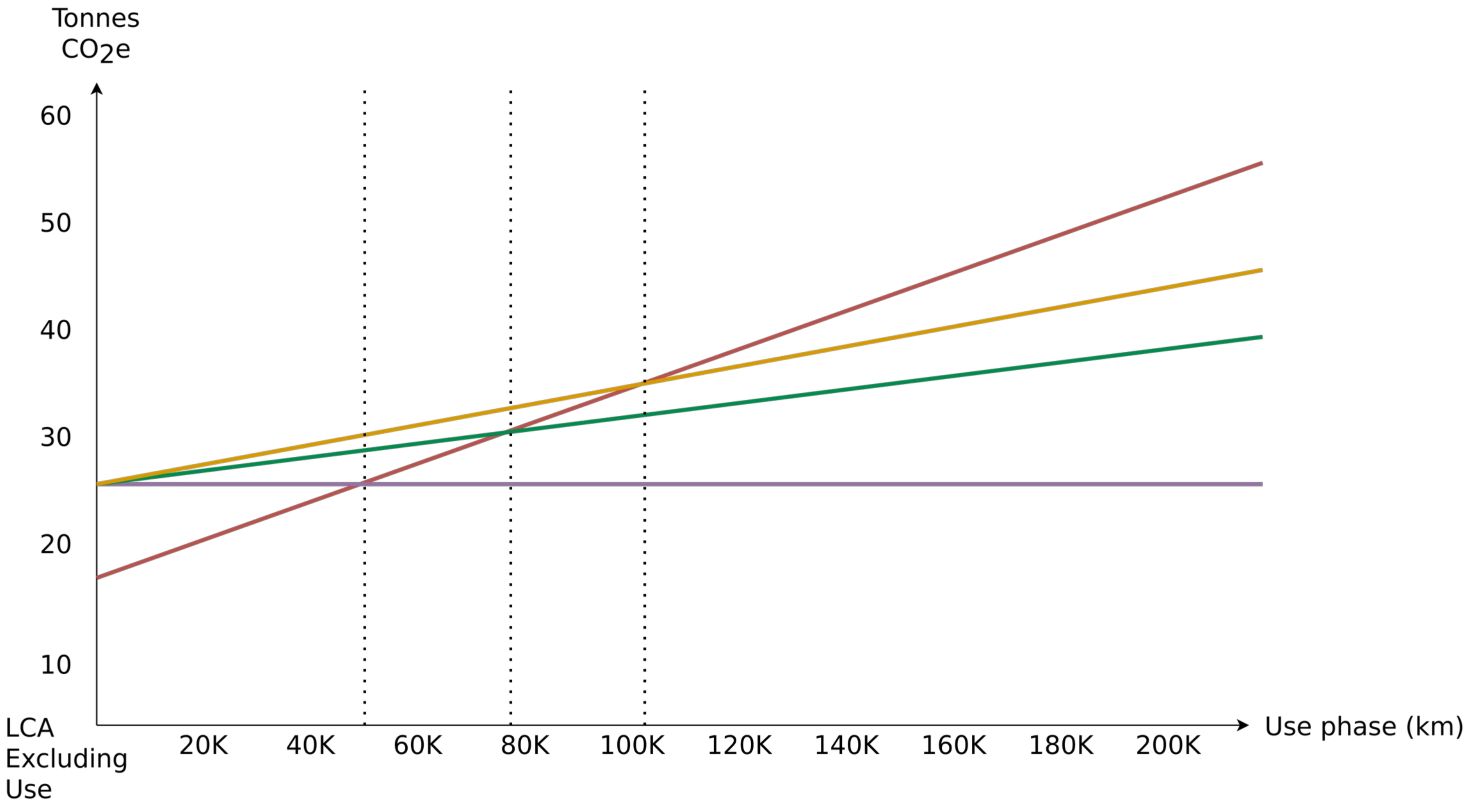
What is the **break-even** point (in km) after which an EV would have caused fewer emissions than an Internal Combustion Engine (ICE?)

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)

- XC40 ICE
- Polestar 2 -- Global electricity Mix
- Polestar 2 -- European (EU28) electricity Mix
- Polestar 2 -- Wind Power



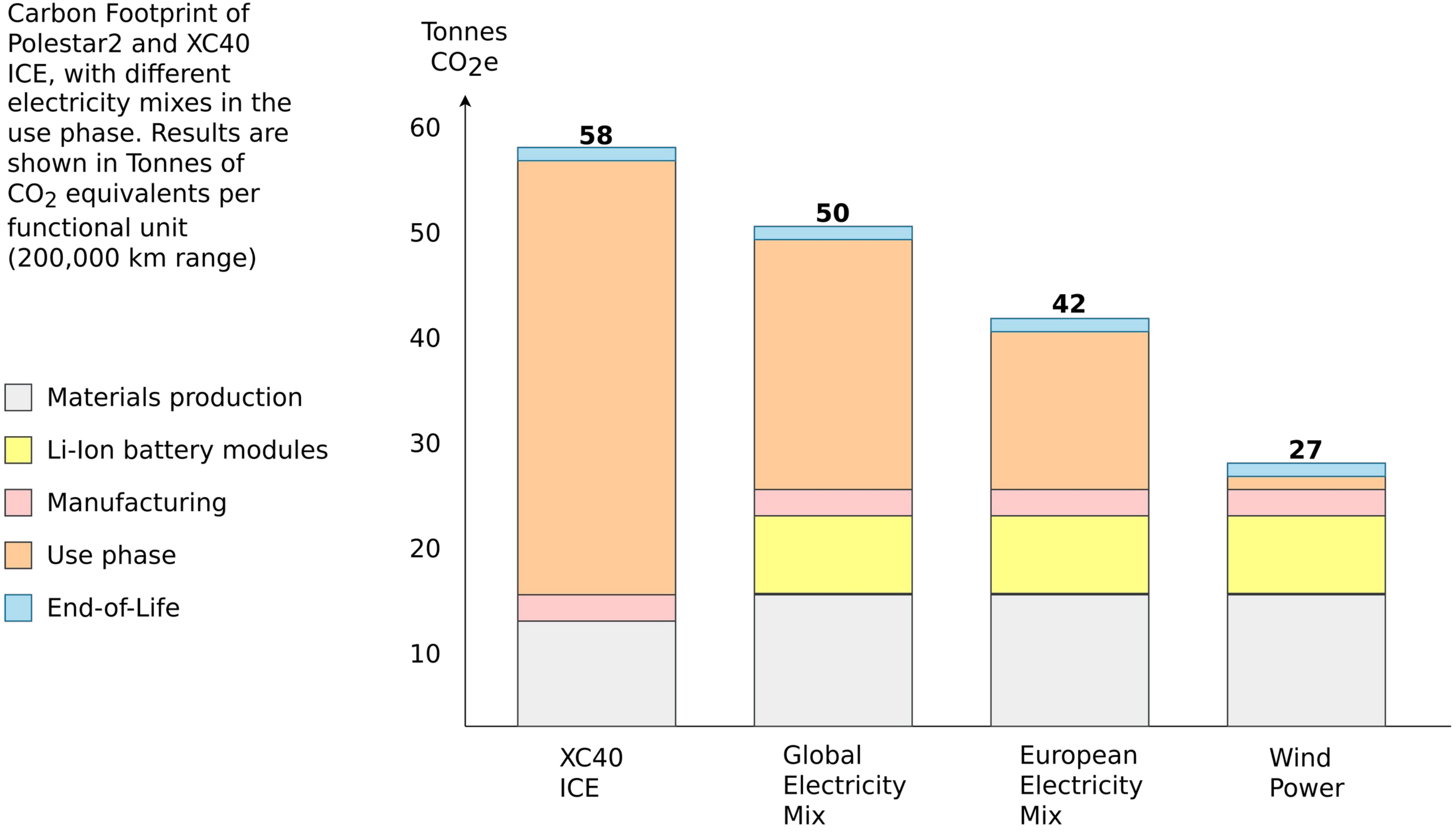
Number of kilometers driven at break-even between Polestar 2 with different electricity mixes in the use phase of XC40 ICE (petrol)

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.

Life Cycle Assessment – Polestar 2

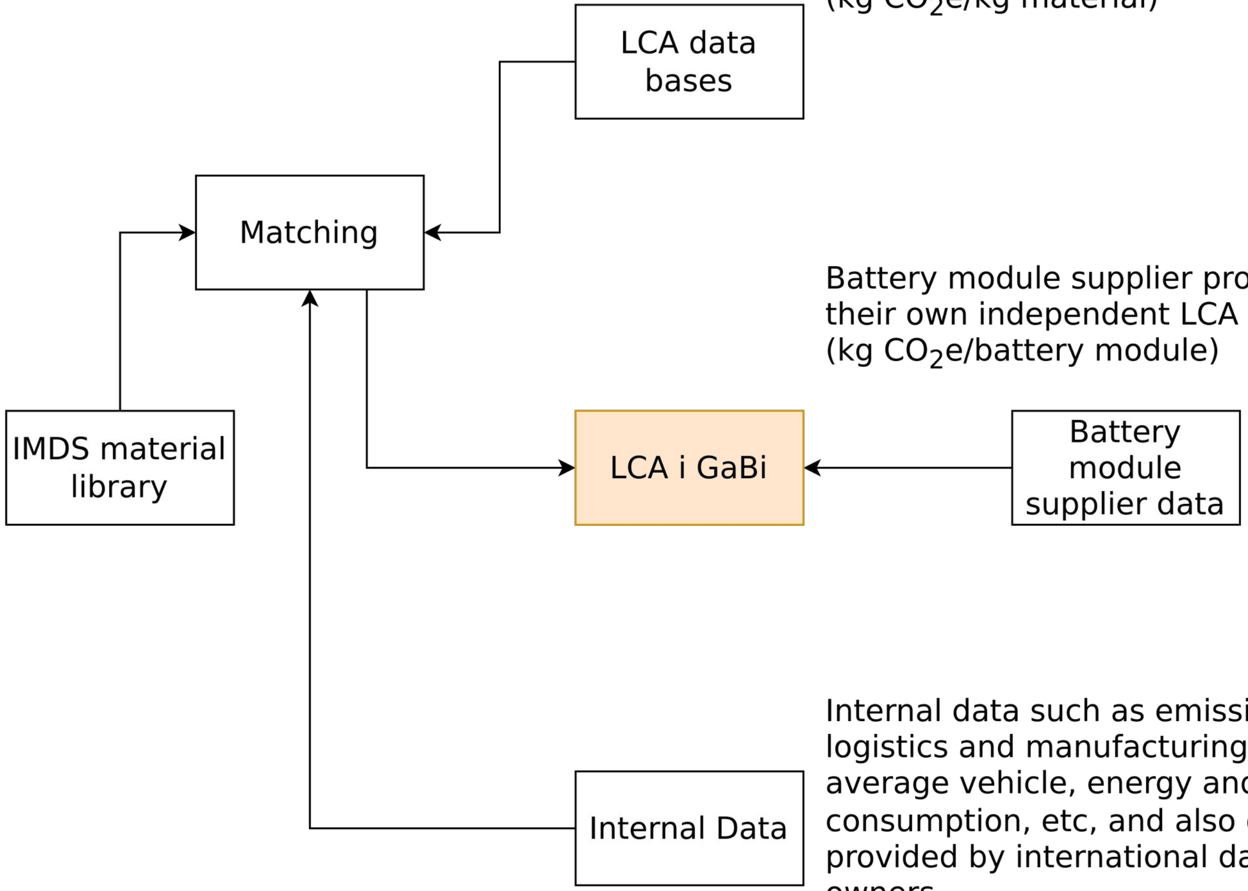
Carbon Footprint of Polestar2 and XC40 ICE, with different electricity mixes in the use phase. Results are shown in Tonnes of CO_2 equivalents per functional unit (200,000 km range)



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

Life Cycle Assessment – Polestar 2

Databases contain data for a large variety of materials, production, logistics, energy from cradle to material, e.g., wrought aluminium, copper wire.
(kg CO_2e/kg material)



Battery module supplier provides their own independent LCA data
(kg CO_2e/battery module)

IMDS material data per component in the BoM representing the Polestar2. The ~10,000 incoming materials are aggregated into ~70 materials (kg material)

Internal data such as emissions from logistics and manufacturing per average vehicle, energy and fuel consumption, etc, and also data provided by international data owners

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

LCA – Result

Critical Discussion

- Example LCA based on a report by Polestar → Polestar produces EVs → biased?
- Various studies indicate varying numbers with respect to the CO2 footprint of EVs and internal combustion engine cars, especially in the context of LCAs

Critical Discussion

- Example LCA based on a report by Polestar → Polestar produces EVs → biased?
- Various studies indicate varying numbers with respect to the CO2 footprint of EVs and internal combustion engine cars, especially in the context of LCAs
- Therefore:
  - Check who authors/funds these studies
  - What are their interests?
  - Be critical – also while listening to us ;)

Critical Discussion

- Example LCA based on a report by Polestar → Polestar produces EVs → biased?
- Various studies indicate varying numbers with respect to the CO2 footprint of EVs and internal combustion engine cars, especially in the context of LCAs
- Therefore:
  - Check who authors/funds these studies
  - What are their interests?
  - Be critical – also while listening to us ;)
- Further literature:
  - Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA (2020) – European Commission – Link
  - TU-Eindhoven report – Link
  - Polestar report – Link
  - BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) report – Link
  - Bus case study Romania – Link
  - RWTH Aachen (synthetic fuels) – Link

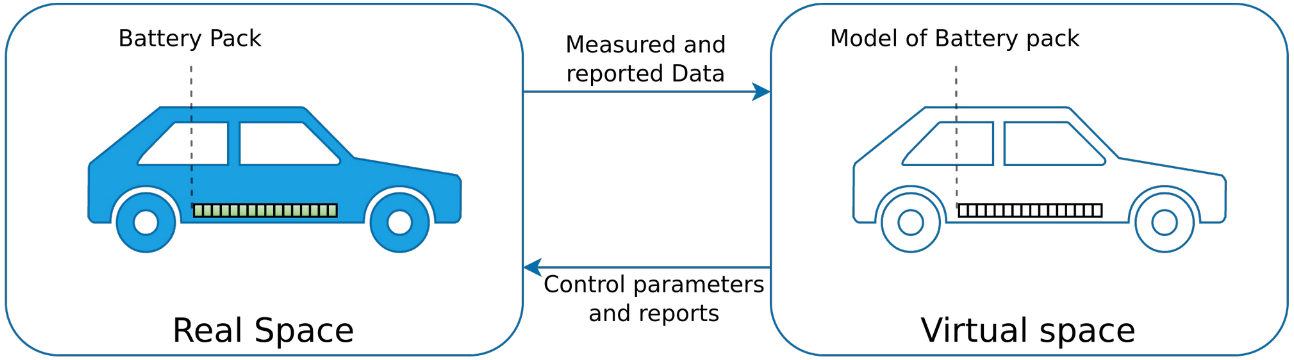
EXAMPLE 3 – DIGITAL TWINS

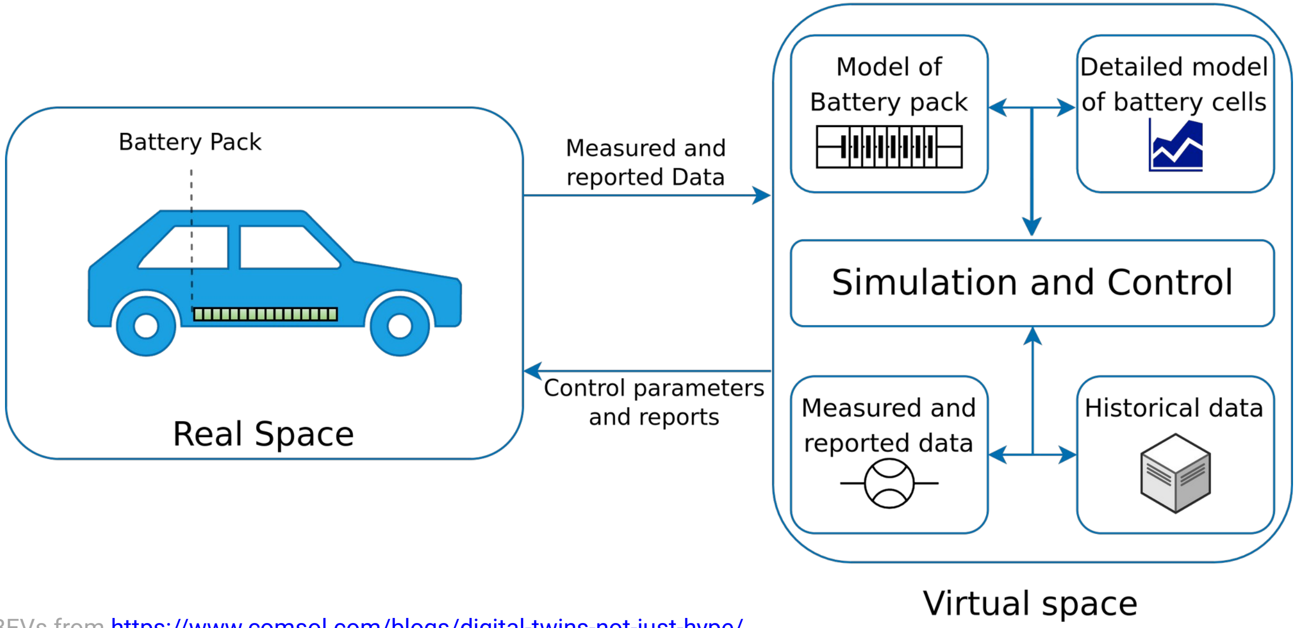
Definitions

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

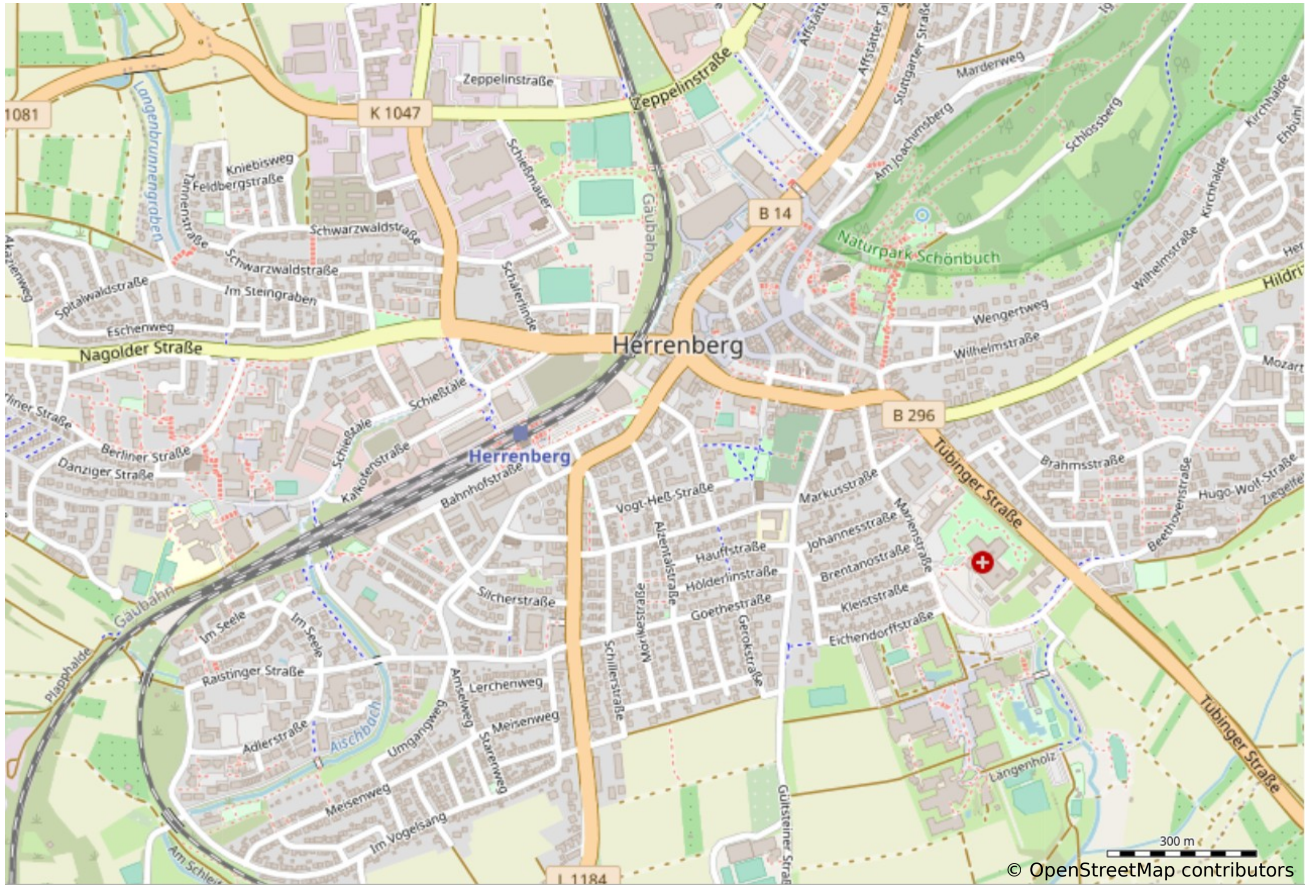




The digital twin concept exemplified on a battery pack of a BEV.

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

Example 2: Smart Cities

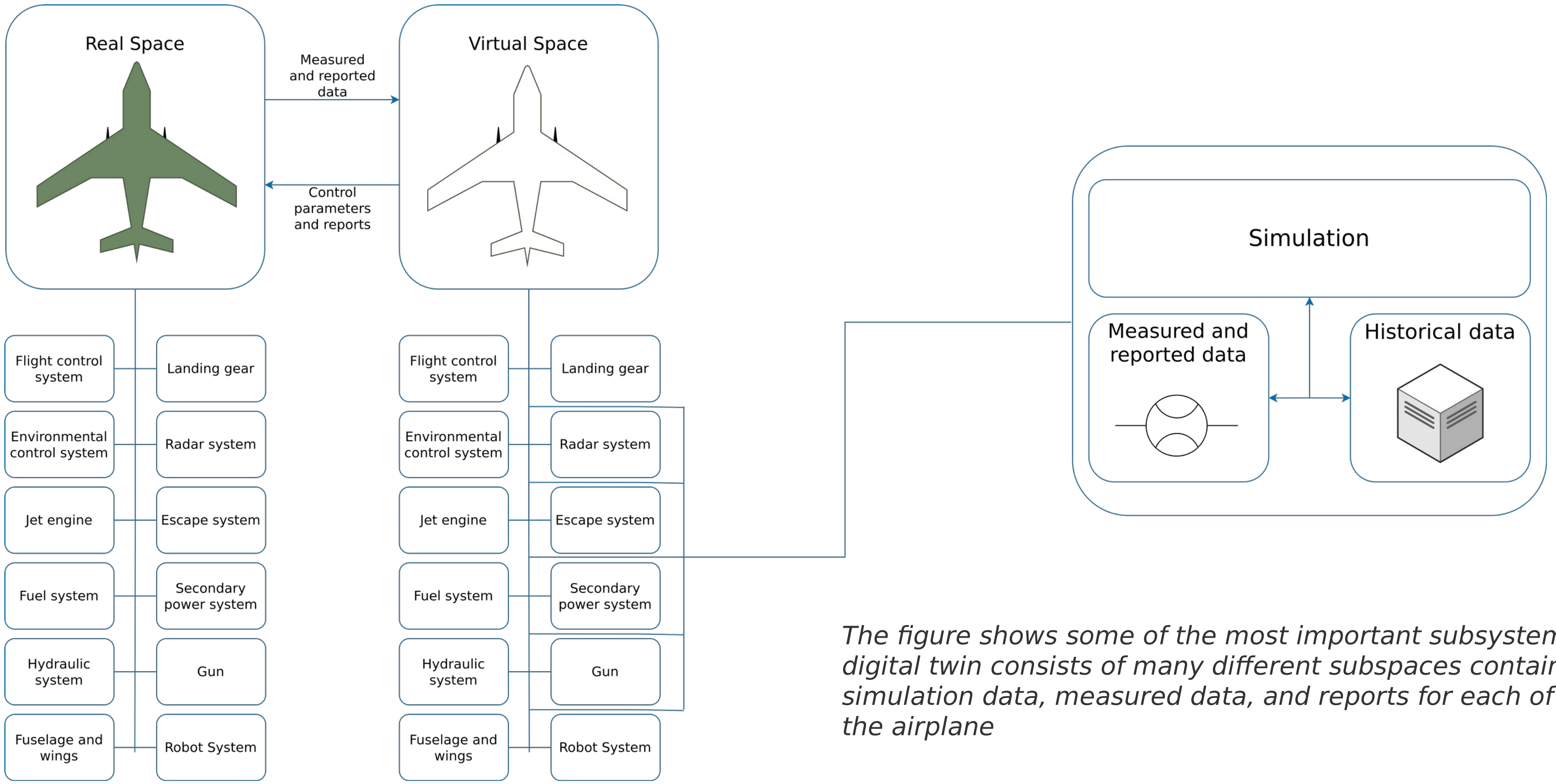


Digital Twin of Herrenberg

- 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

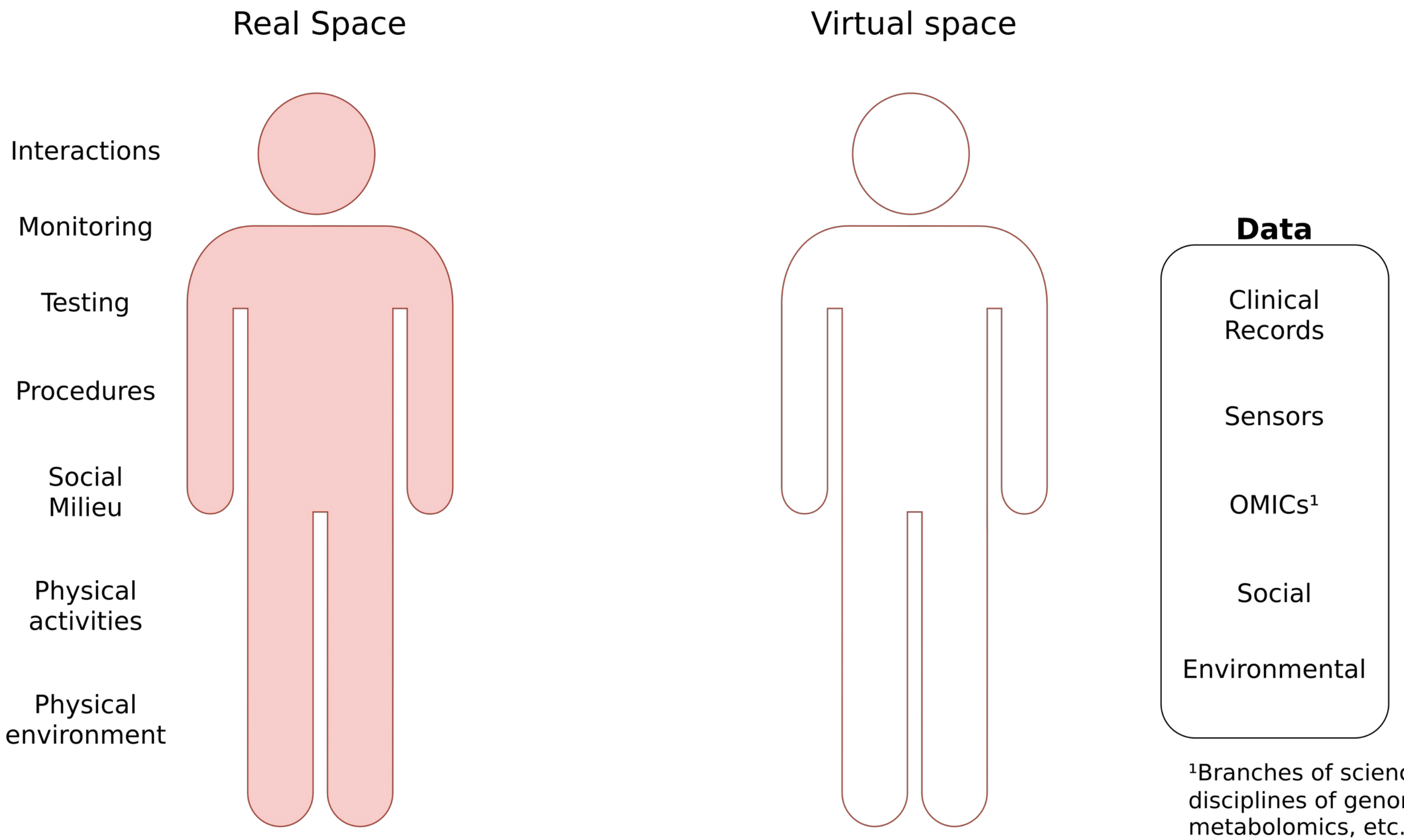
Example 3: Aviation and Aerospace



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



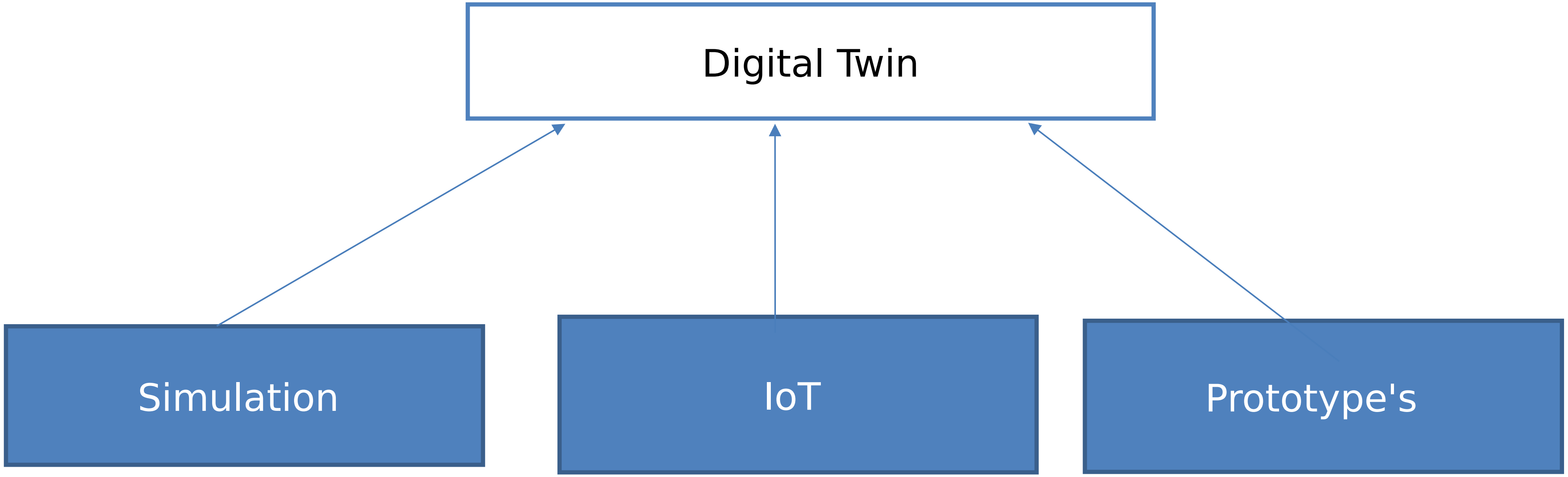
[1]Branches of science composed of disciplines of genomics, proteomics, metabolomics, etc.

Digital Twin for patient-specific care

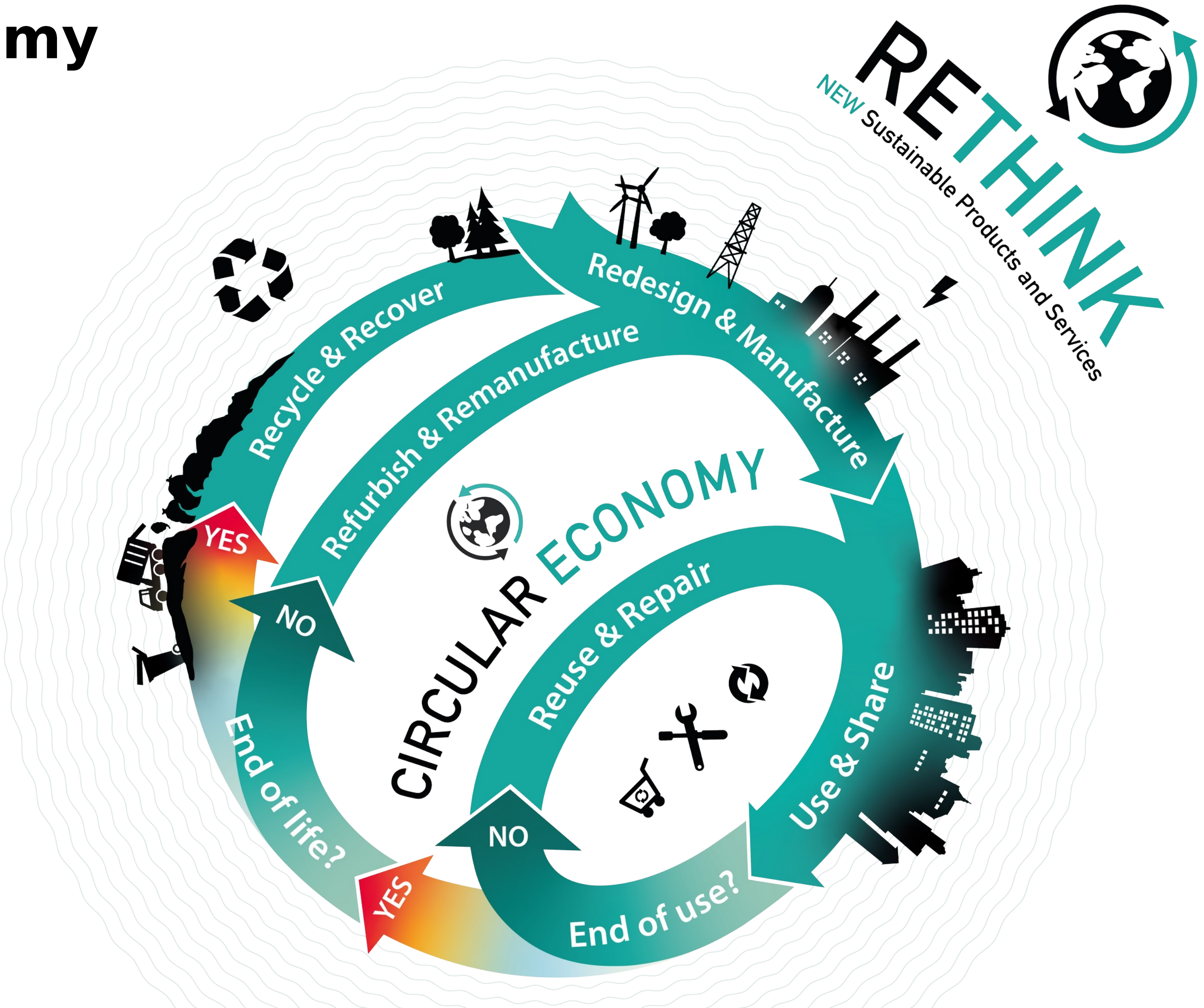
Image adapted from: Rao, Dattaraj Jagdish, and Shraddha Mane. "Digital Twin approach to Clinical DSS with Explainable AI." *arXiv preprint arXiv:1910.13520* (2019).

Digital Twins vs. Other Concepts

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



Circular Economy



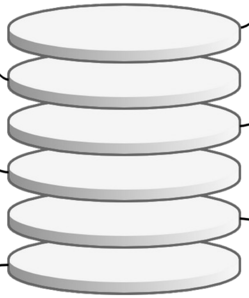
Center for Digital Technologies (DIGIT) (2022) – https://www.digit-research.de/fileadmin/DIGIT/Presse_und_News/Downloads/Grafikpaket_Reallabor_DCE_Kreislaufmodell_V2_ccby.zip – CC BY 4.0.

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.

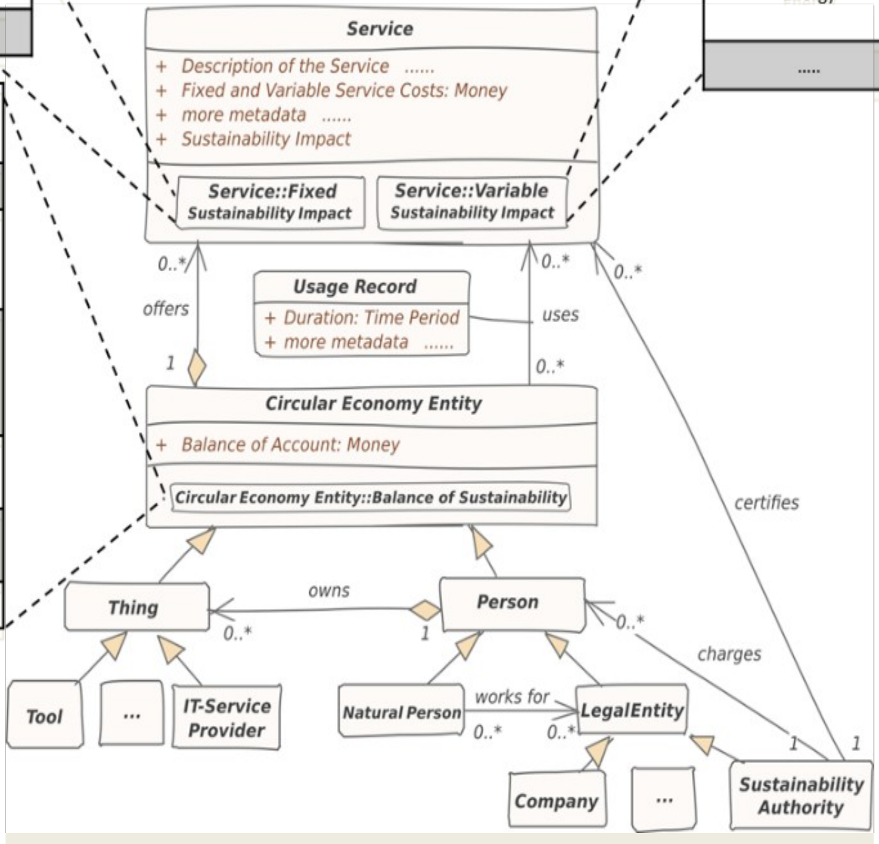
Based on https://fslci.org/wp-content/uploads/2018/Slides/Sessions/Session_5_Prox.pdf

Use Cases (2): Sustainability Impact Factor

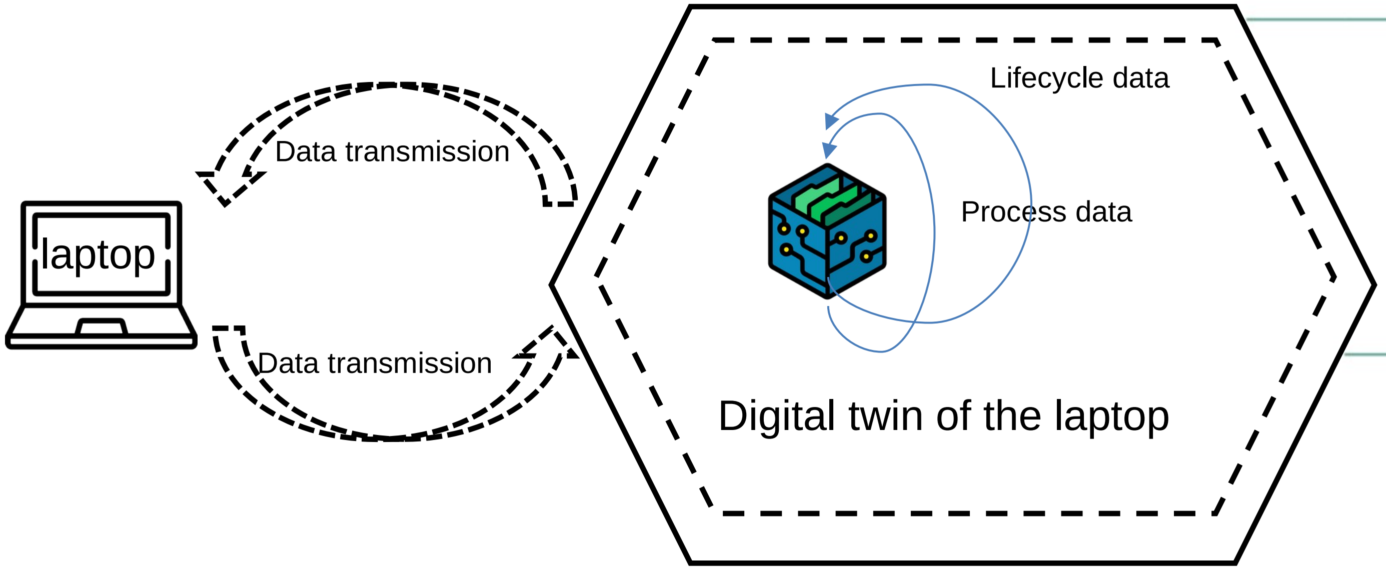
Amount of Impact		More...
50 kg CO2		.....
1 kg steel, 0.01 kg rare earth materials		.....
.....		.....

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)	.....
.....	.....	.....



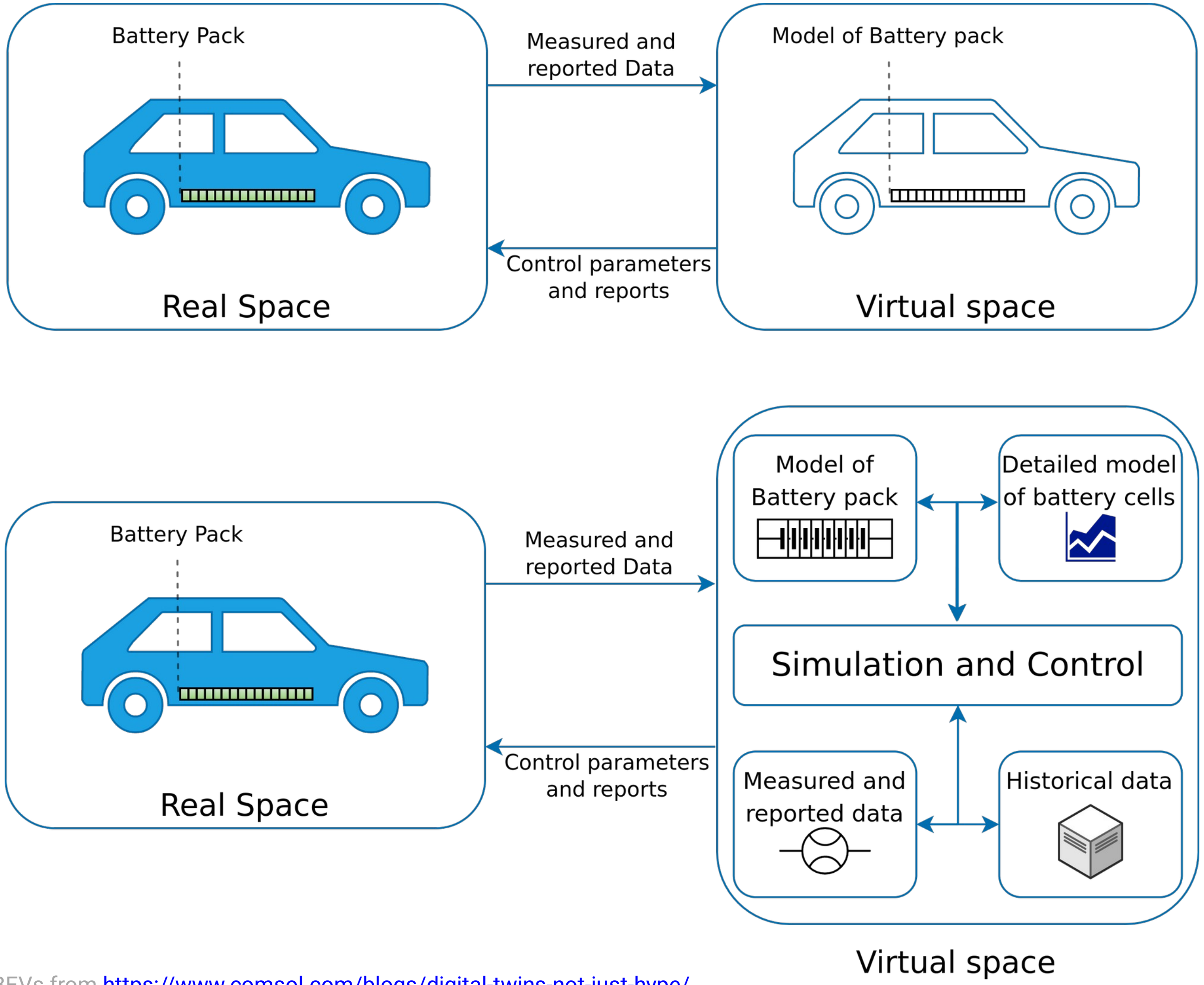
Use Case (3): Increasing the Longevity of Electronics



- 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.

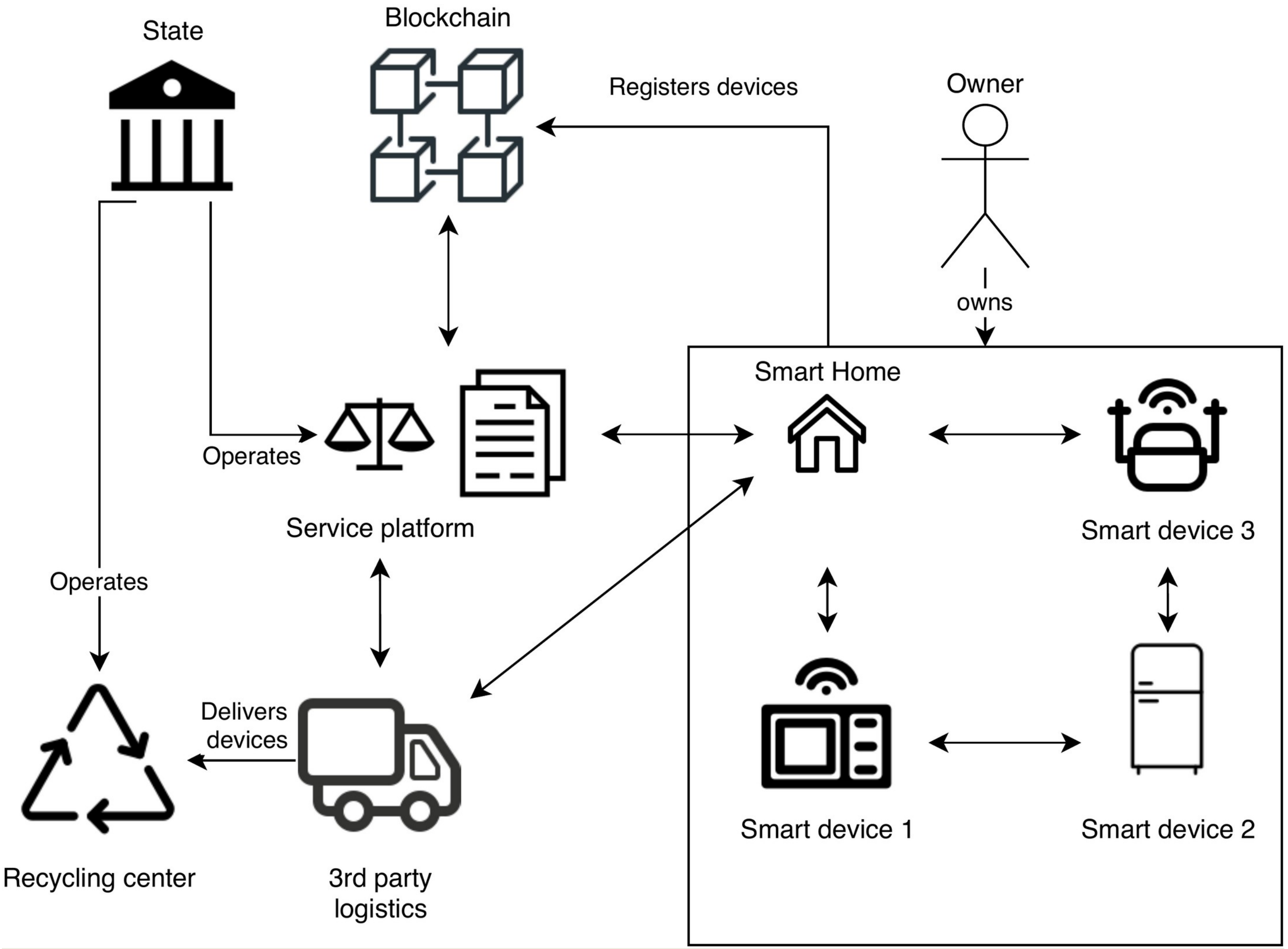
Image adapted for BEVs from https://www.comsol.com/blogs/digital-twins-not-just-hype/

EXAMPLE 4 – THE HITCHHIKER’S GUIDE TO THE END-OF-LIFE FOR SMART DEVICES

E-Waste at home – Why?

a. No e-waste at home.
b. Inconvenient disposal process.
c. Might need it later (backup solution).
d. Not sure how to dispose of the e-waste.
e. Other

Hitchhiking for E-Waste



S. Lawrenz and B. Leiding (2021) – The Hitchhiker's Guide to the End-of-Life for Smart Devices

EXAMPLE 5 – 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 6 – FUTURE RESOURCES

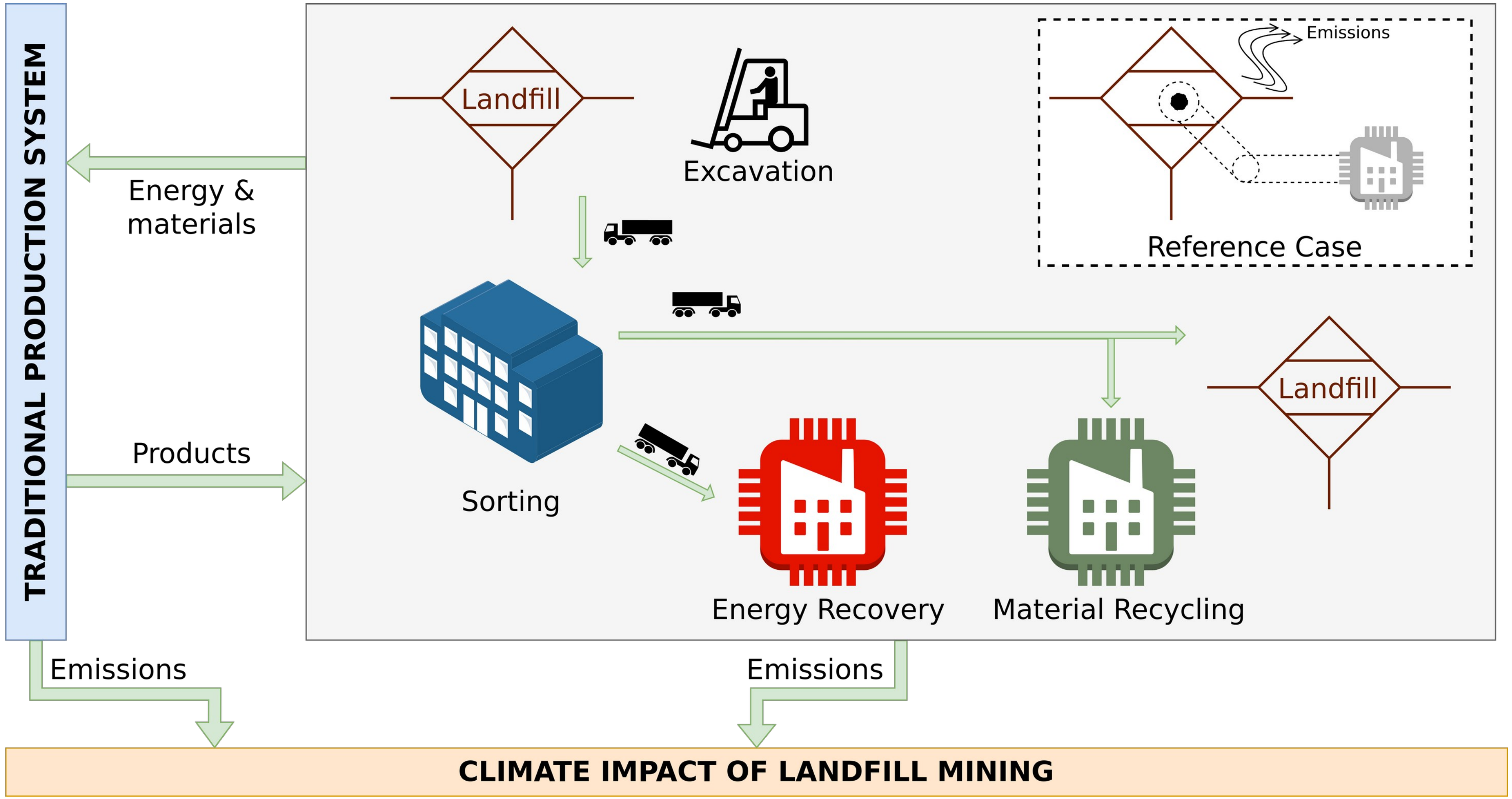
Buildings as Material Banks (BAMB)

- 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

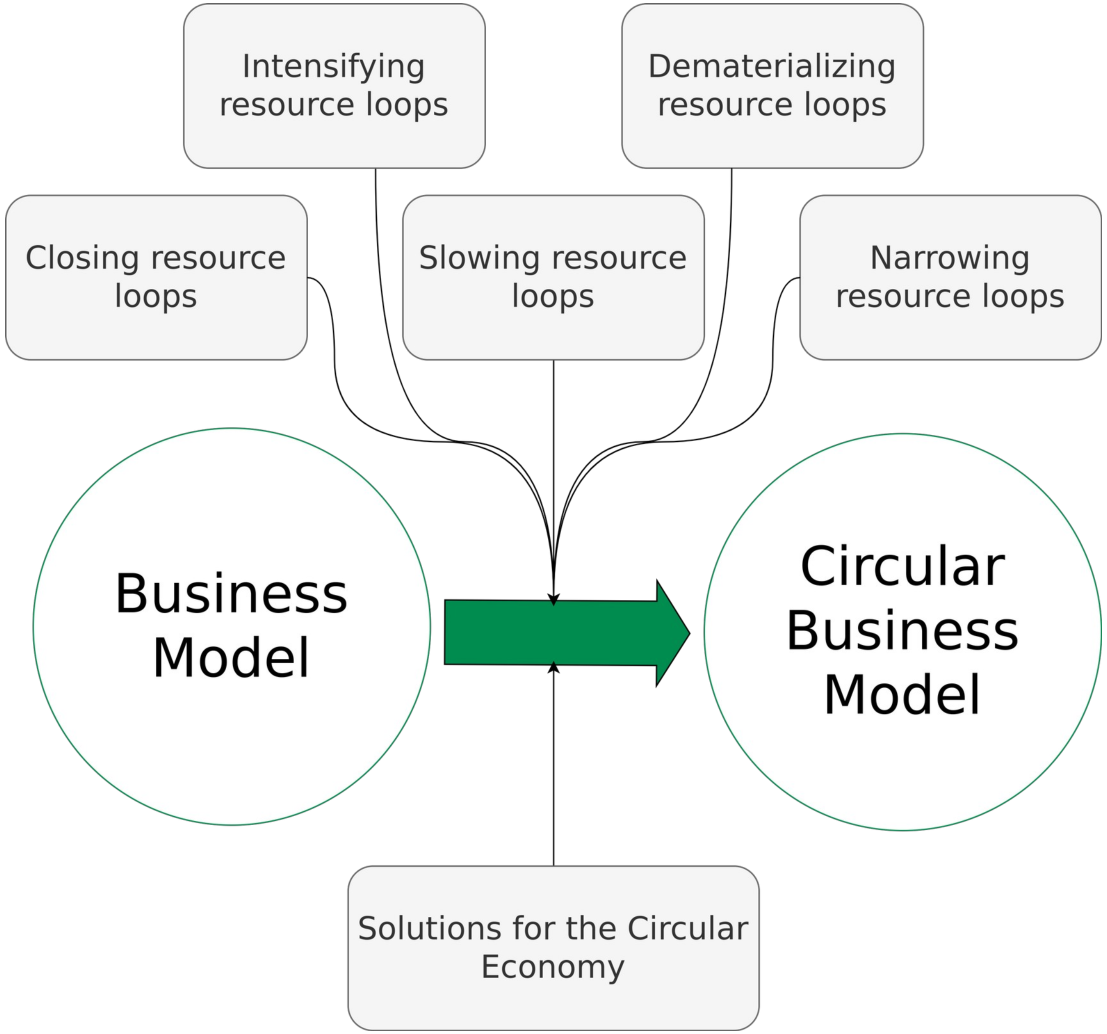
Landfill Mining



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

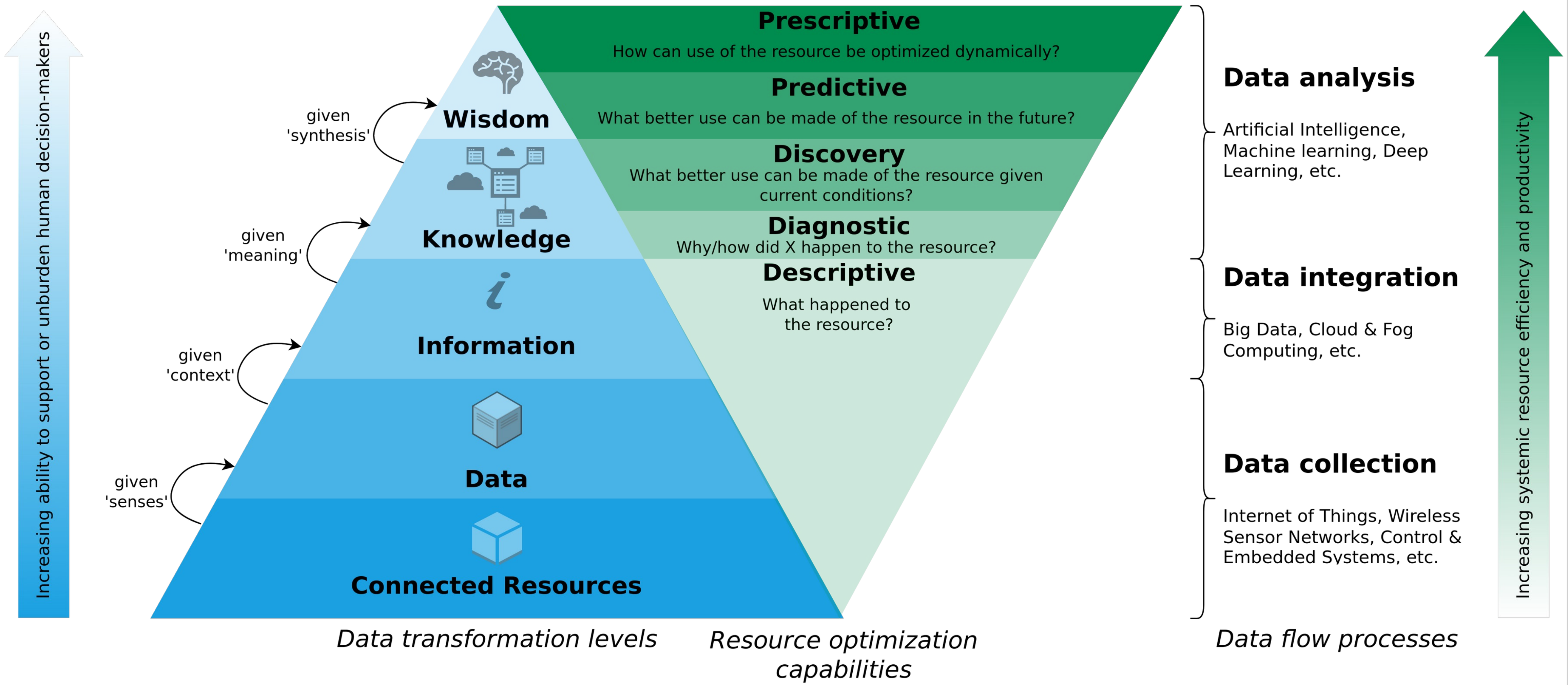
DIGITAL CIRCULAR ECONOMY AND BUSINESS MODELS

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.

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

- 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*

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 <u>the Circular Economy reflects a lack of sufficiently developed technologies</u> 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.

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
- Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA (2020) – European Commission – Link
- Polestar (2020) – Life Cycle Assessment – Carbon Footprint of Polestar 2 – Link

Questions?