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Research & Innovation for Smart Enterprises
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UNIVERSITÀ DEGLI STUDI DI BRESCIA

UNIVERSITÀ DI BRESCIA
LABORATORIO RISE
Research & Innovation for Smart Enterprises

Assessing the sustainability impacts of Circular Economy Supply Chains: a new framework and a simulation tool for the washing machine industry

DOCUMENT: Assessing the sustainability impacts of Circular Economy; **VERSION:** 1.0; **DATE:** 08/07/2021; **AUTHOR:** Gianmarco Bressanelli
STATE: final; **CIRCULATION:** restricted

AGENDA

1. Circular Economy and Circular Supply Chains: an introduction
2. A Framework for assessing the impacts of Circular Economy scenarios
3. Mathematical formulation, simulation tool and application to the washing machine industry
4. Discussion of results, implications and key takeaways

But first…

BRESCIA
(AND UNIVERSITY OF BRESCIA – UNIBS)

But first…

BRESCIA
(AND UNIVERSITY OF BRESCIA – UNIBS)

CORRIERE DELLA SERA

Industria, Brescia prima provincia d'Europa: vale 10,1 miliardi

Al secondo posto Bergamo, poi la provincia tedesca dello Wolfsburg

- Metals
  - Steel, aluminium, brass…
- Automotive components
- Textiles
- Electronics

But first…

RISE LABORATORY (@UNIBS)

Our competences areas ▲

But first…

RISE LABORATORY (@UNIBS)

UNIVERSITÀ DEGLI STUDI DI BRESCIA

4 University Areas:
- Economics
- **Engineering**
- Law
- Medicine

Our competences areas ▲

But first…

RISE LABORATORY (@UNIBS)

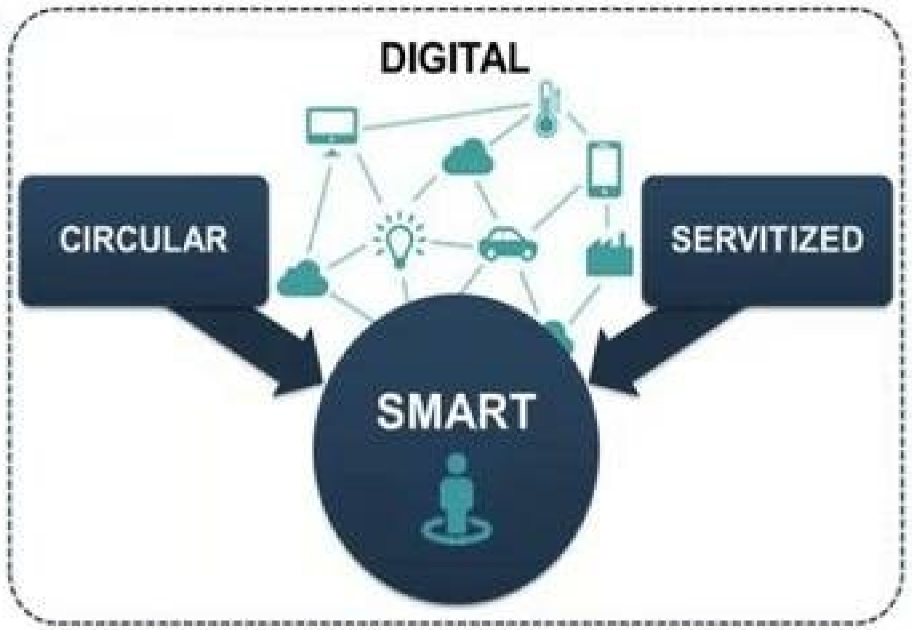
UNIVERSITÀ DEGLI STUDI DI BRESCIA

RISE Research & Innovation for Smart Enterprises

4 University Areas:
- Economics
- **Engineering**
- Law
- Medicine

Operations and supply chain management

Rise LAB Vision: we believe that the **supply chain** of the future will be ***circular***, ***digital*** and ***servitized***. Therefore we focus our research and dissemination activities mainly towards these three themes.



Our Vision ▲

Our competences areas ▲

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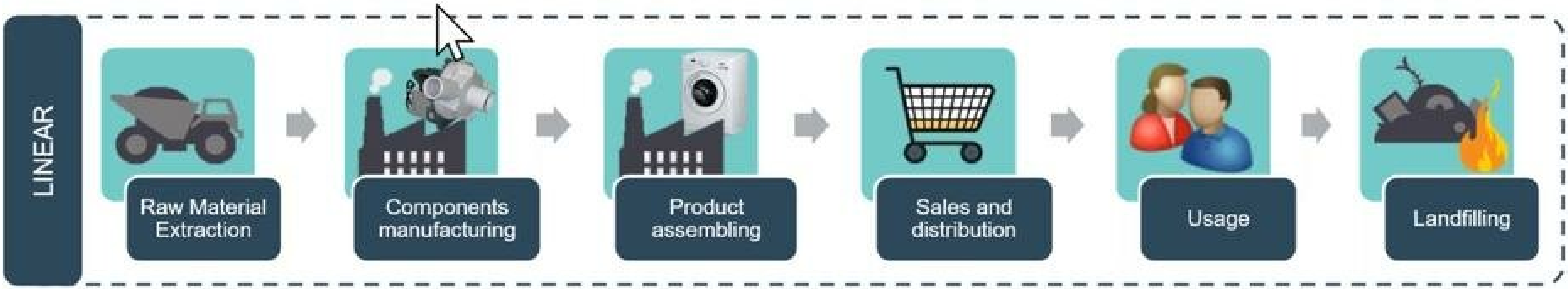
TODAY'S ECONOMY… AND ITS LIMITATIONS

The currently most-adopted production and consumption model is

LINEAR



3. Resources availability

1. Waste generation

2. Climate Change

1. WASTE GENERATION

- Waste Generation
- Climate Change
- Resources availability

Globally: 50 million tonnes of e-waste each year

Equivalent of almost 4.500 Eiffel Towers

E-waste:
€ 48 Billion/y in EU

Furniture:
9 million tons/y in EU

Textiles:
1 truck / second worldwide

Biodiversity loss

Emissions

Pollution

European Commission

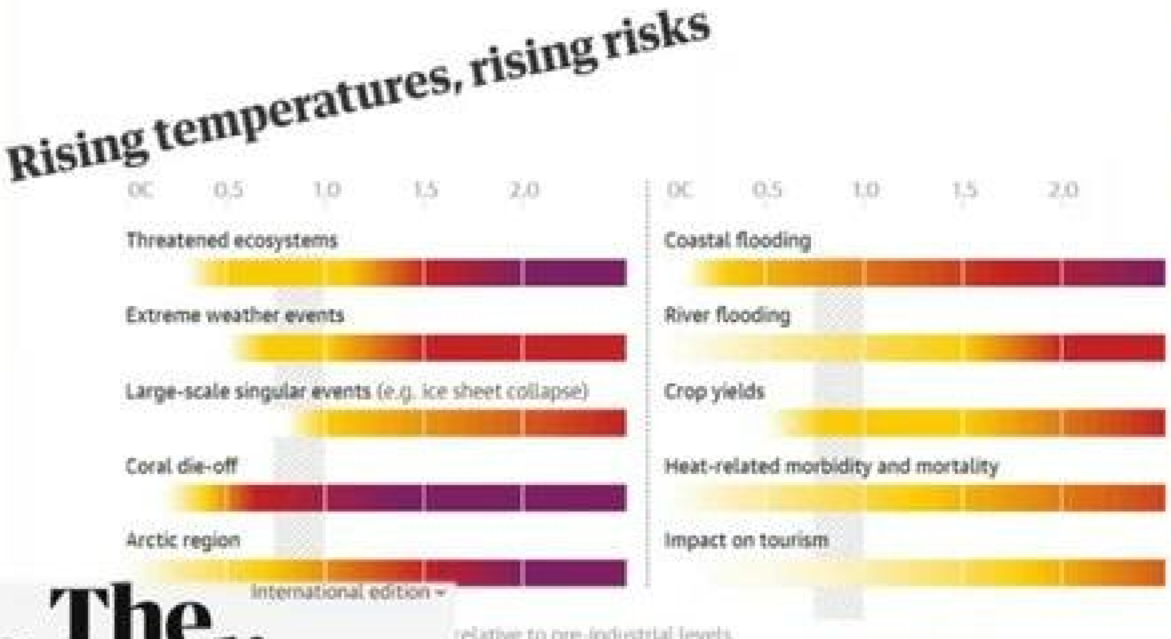
2. CLIMATE CHANGE

Waste Generation
Climate Change
Resources availability

Climate change

https://www.theguardian.com/environment/2018/oct/08/global-warming-must-not-exceed-15c-warns-landmark-un-report

We have 12 years to limit climate change catastrophe, warns UN



International edition

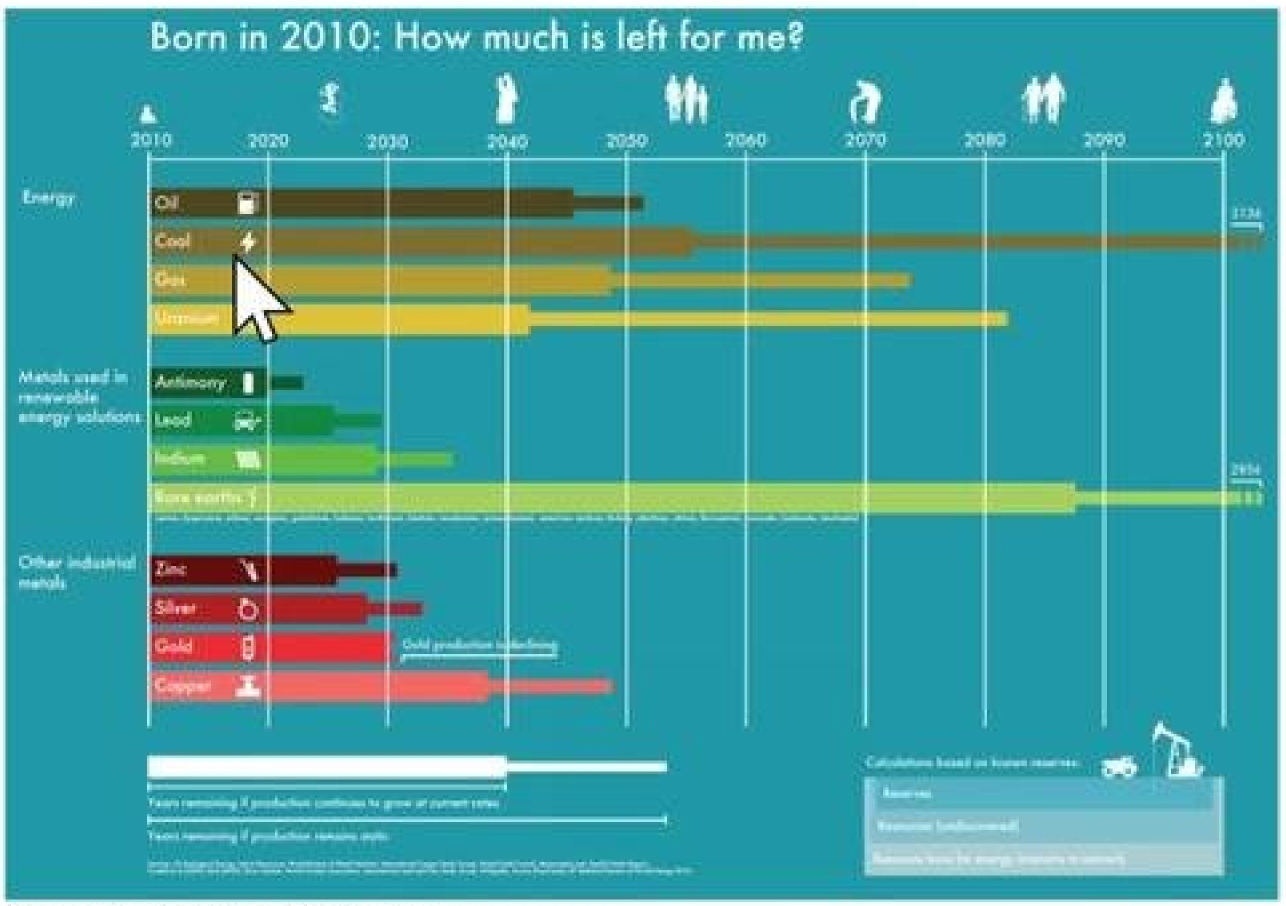
The Guardian

▲ A firefighter battles a fire in California. The world is currently 1C warmer than preindustrial levels. Photograph:

Waste Generation
Climate Change
Resources availability

3. RESOURCES AVAILABILITY

ENVIRONMENTAL…

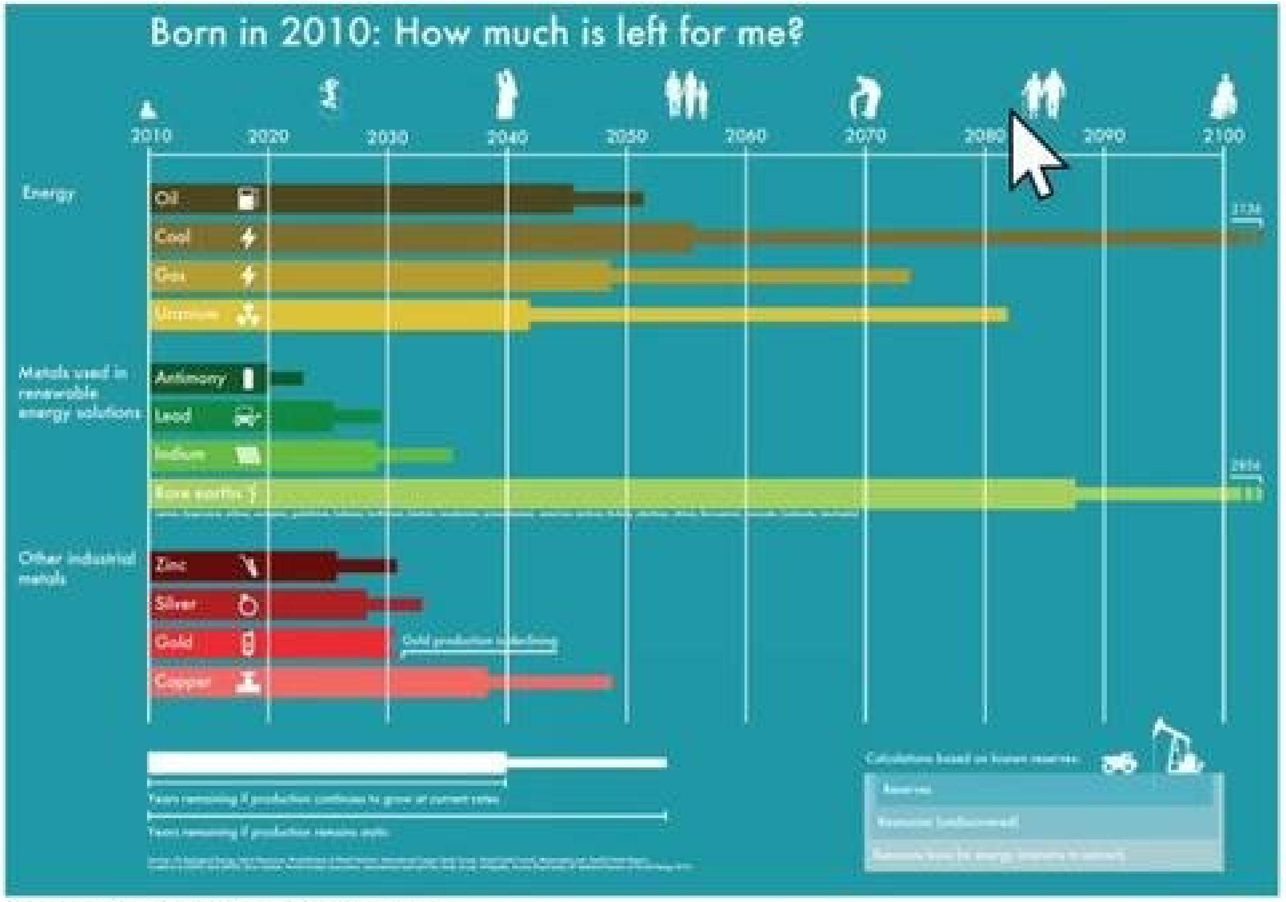


https://www.vlaanderen-circulair.be/nl

3. RESOURCES AVAILABILITY

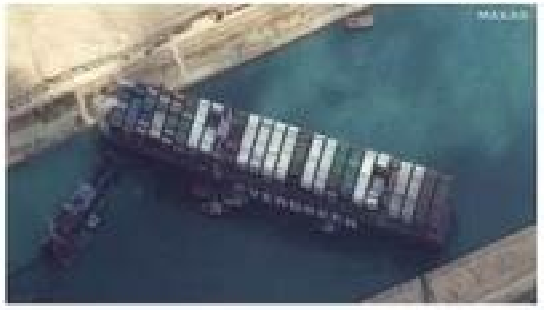
Waste Generation
Climate Change
Resources availability

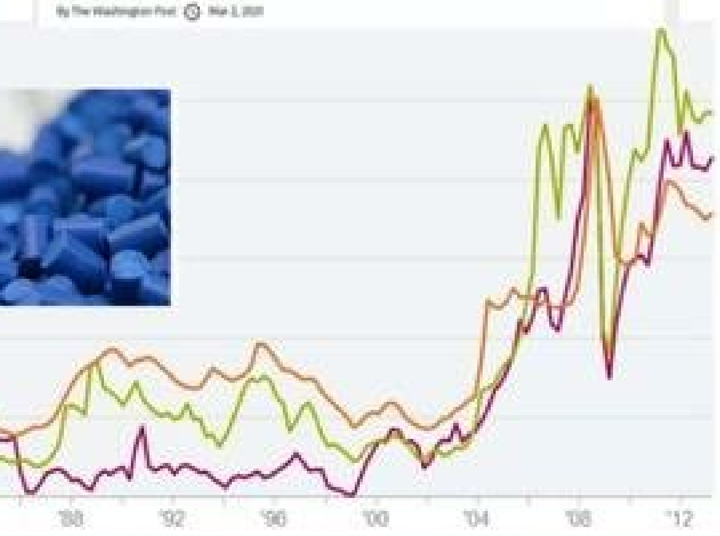
ENVIRONMENTAL…



https://www.vlaanderen-circulair.be/nl

…AND ECONOMIC ISSUE!

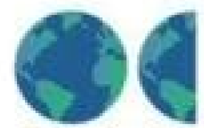




3. RESOURCES AVAILABILITY

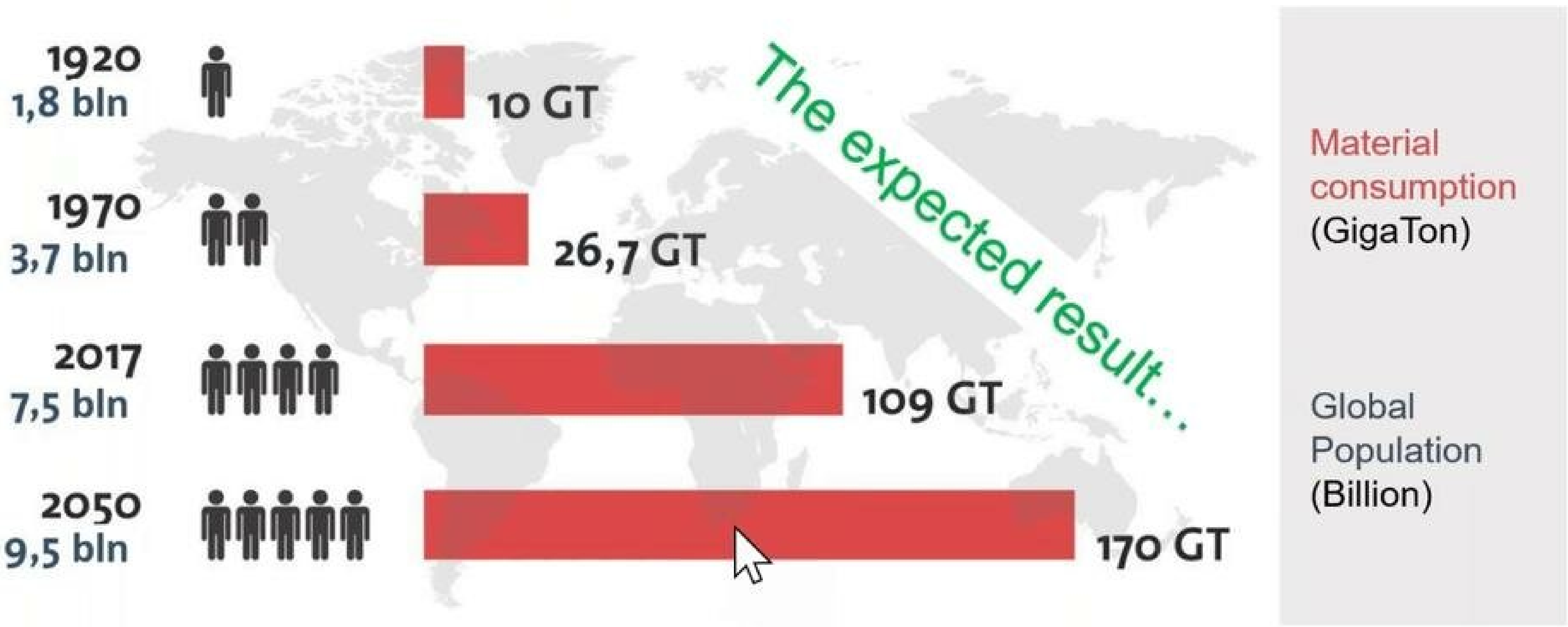
Waste Generation
Climate Change
Resources availability

Global: 29th July (1.75 Earths)

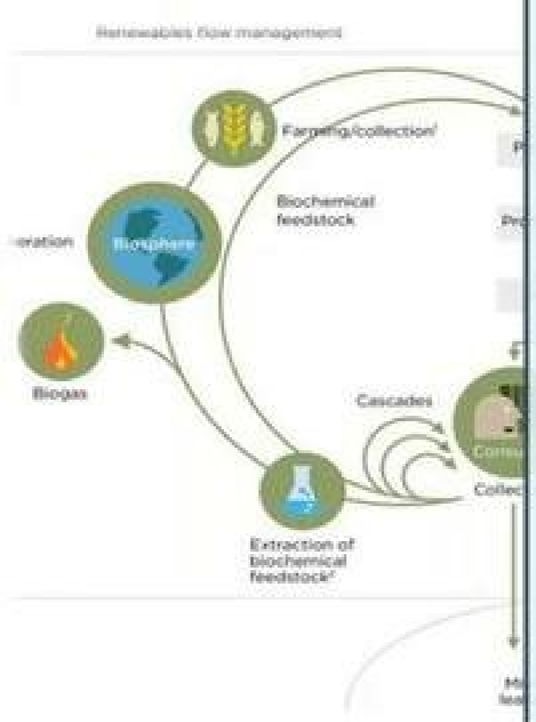


http://www.footprintcalculator.org/

… AND THE GLOBAL POPULATION?

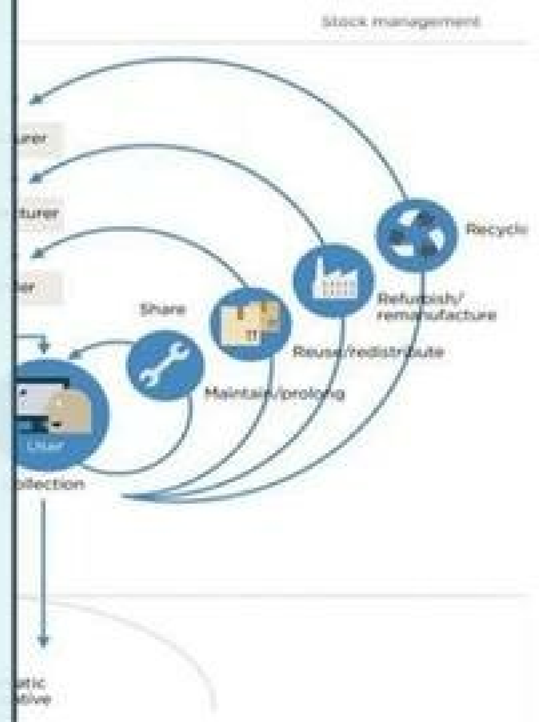


A POSSIBILE ANSWER… CIRCULAR ECONOMY



CIRCULAR ECONOMY

- **Circular Economy** is an industrial system **restorative** and **regenerative** by design
- Implemented by **one or more supply chain actors** through **one or more of the four building blocks** (circular product design, servitised business models, reverse logistics and enablers)
- In order to replace the end-of-life concept with **reducing**, alternatively **reusing**, **remanufacturing** and **recycling** materials in production, distribution and consumption processes
- For both **technical** and **biological** materials
- With the aim to accomplish **sustainable development**
- Operating at the **micro, meso and macro level**



Source: Bressanelli et al. (2019) Challenges in supply chain redesign for the Circular Economy, *International Journal of Production Research*; Ellen MacArthur Foundation 2012; Kirchherr et al. (2017) Resources Conservation and Recycling 127:221-232

A POSSIBILE ANSWER… CIRCULAR ECONOMY

Source of CE value creation

- ▲ Increase Resource Usage
- ▲ Increase Resource efficiency
- ▲ Increase product life
- ▲ Increase components life
- ▲ Increase materials life
- ▲ Close the loop

THE «4R» SCHEME OF CIRCULAR ECONOMY

THE INERTIA PRINCIPLE

By Walter Stahel

Do not repair
what is not broken

Do not remanufacture
something that can be repaired

Do not recycle
a product that can be remanufactured

Replace or treat only the smallest possible part
in order to maintain the existing economic value

Source: Bocken et al., (2017)

HOW TO IMPLEMENT CIRCULAR ECONOMY IN COMPANIES? – BULDING BLOCKS

Products Design

Business Models

Supply Chain

Enablers and system conditions (system thinking)

Bressanelli et al. (2021) Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: a literature review

PRODUCT DESIGN

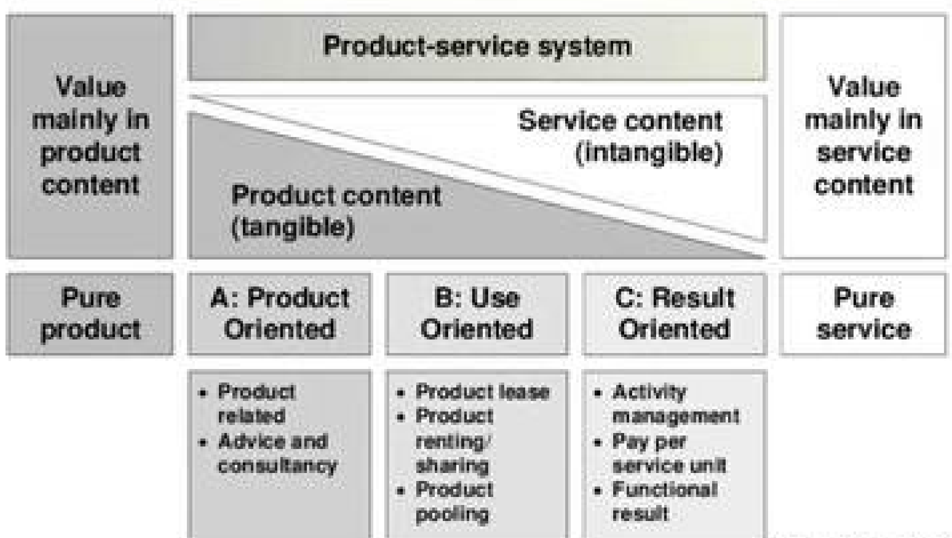
Circular Design

- Design for Durability
- Green materials choice (e.g. biodegradable)
- Modularity and Standardization
- Maintenance
- Upgradability
- Design for disassembly
- Design for Attachment and Trust
- Design for sustainable behaviour

FAIRPHONE

https://www.fairphone.com/it/

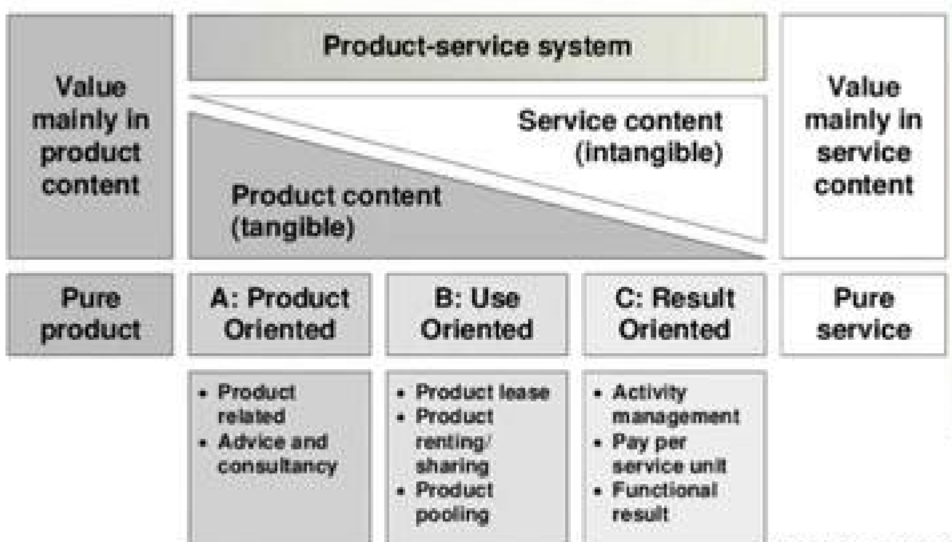
BUSINESS MODELS



Tukker et al., 2015

https://mudjeans.eu/

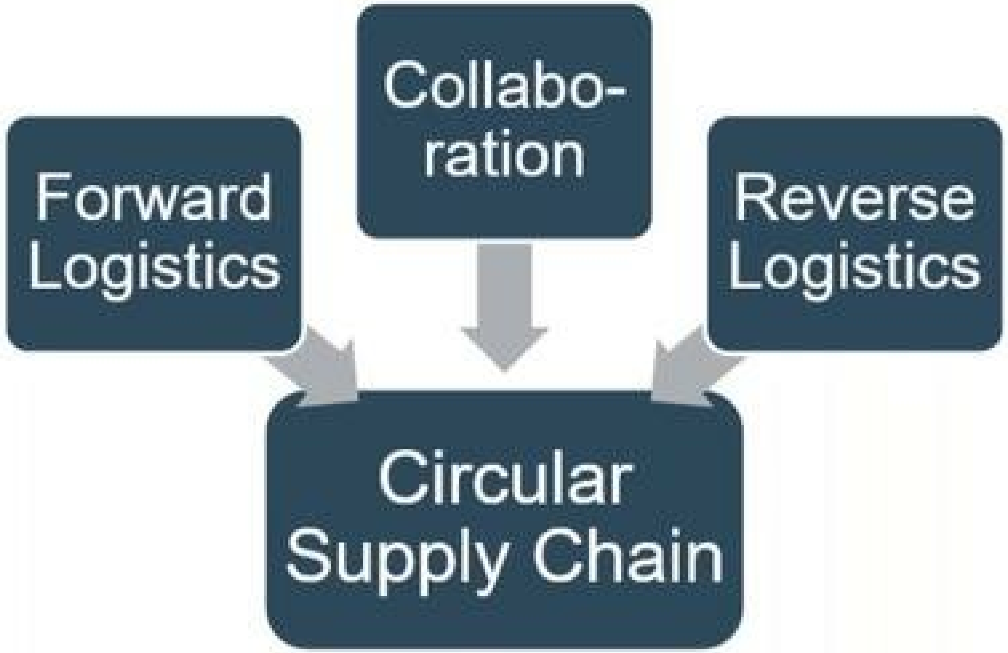
BUSINESS MODELS



Tukker et al., 2015

https://mudjeans.eu/

SUPPLY CHAIN



Integrated management of the forward-reverse processes, activites, resources, infrastructures, actors

From cost-focused supply chain to value-focused supply chain

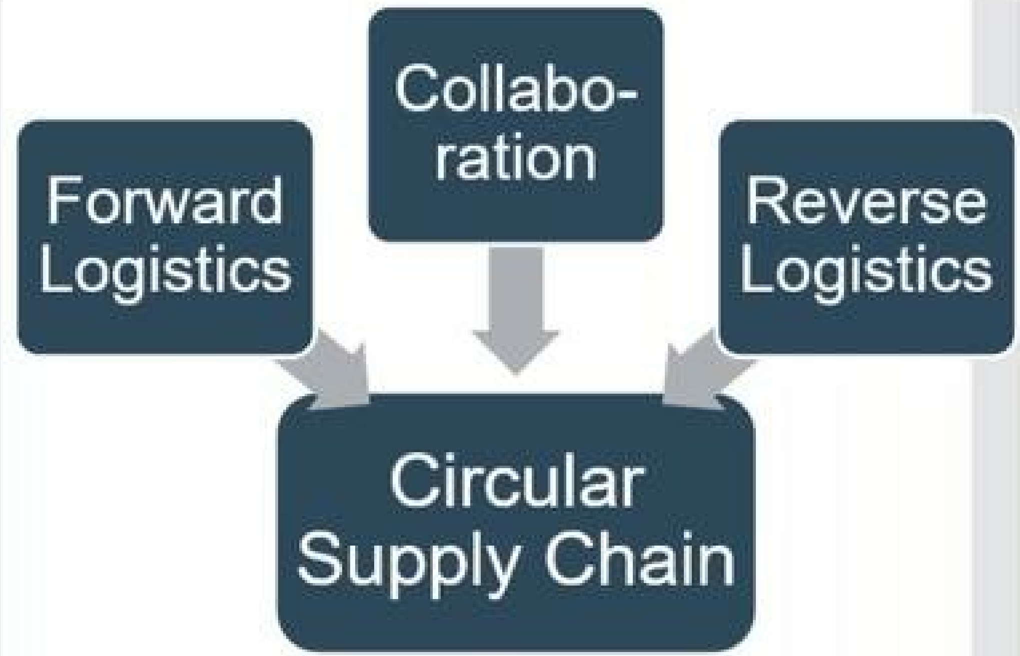
Source: https://www.ri-generation.com/it/

SUPPLY CHAIN

astelav

RI-GENERATION
ELETTRODOMESTICI CHE FANNO BENE

Giving second-life to household appliances



Integrated management of the forward-reverse processes, activites, resources, infrastructures, actors

From cost-focused supply chain to value-focused supply chain

Source: https://www.ri-generation.com/it/

ENABLERS DIGITALIZATION

sustainability

Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies

Gianmarco Bressanelli *, Federico Adrodegari, Marco Perona and Nicola Saccani

RISE Laboratory, Department of Mechanical and Industrial Engineering, University of Brescia, Brescia 25123, Italy

DIGITAL TECHNOLOGY			FUNCTIONALITY	LIFE CYCLE PHASE	SOURCE OF CIRCULAR VALUE CREATION		
IoT	BIG DATA	3D	Improving circular product design	Begin of Life		Extend lifespan	Close the loop
IoT			Product monitoring (status, usage, etc.)	Middle of Life (Usage)	Increase resource efficiency		
		3D	Technical assistance and repair			Extend lifespan	
IoT	BIG DATA		Predictive Maintenance			Extend lifespan	
IoT	BIG DATA		Optimization of the product usage		Increase resource efficiency		
IoT		3D	Upgrade (digital and physical)		Increase resource efficiency	Extend lifespan	
IoT	BIG DATA		Regeneration (tracking)	End of Life			Close the loop

Bressanelli et al. (2018) Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies

DIGITALIZATION AS ENABLER

IoT & Tires-As-A-Service

IOT & BIG DATA TO REDUCE FUEL CONSUMPTION

Michelin in 2013 opened Michelin Solutions, a division to design, develop and market services (**tires-as-a-service**) for commercial vehicles

EFFIFUEL: **IoT sensor-based** system to collect and analyze **Big Data** such as fuel consumption, tire pressure, temperature, speed, position

Significant savings for customers: reduction in **fuel consumption** of € 3,200 / year (equal to 2.1% of the TCO) and savings for 8 tons of **CO2 emissions**

Source: https://rctom.hbs.org/submission/michelin-tires-as-a-service/

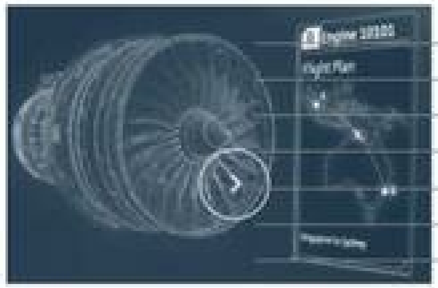
DIGITALIZATION AS ENABLER

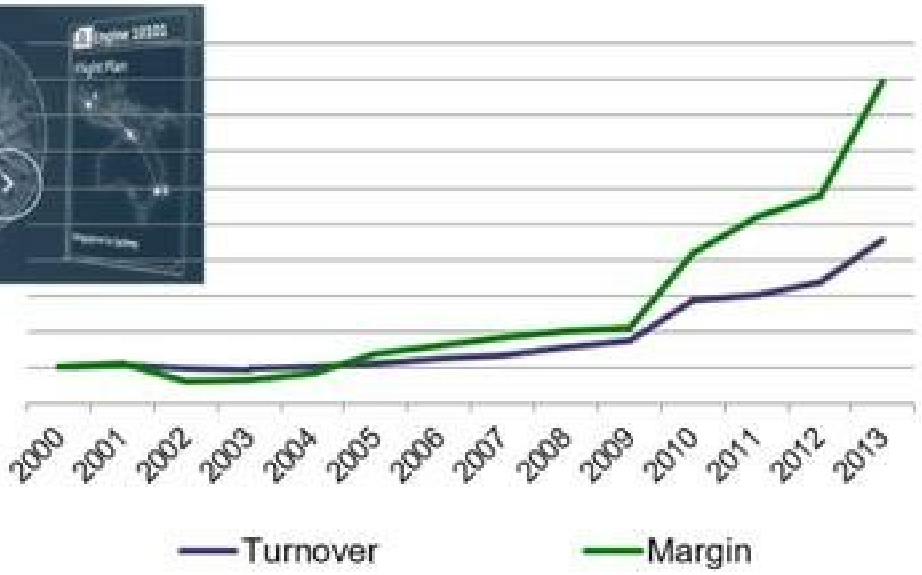
Value Creation

TOTAL CARE PROGRAMME: customers pay only for the flying hours

Product redesign	Spare parts management optimization
Advanced Analytics	Predictive maintenance

IOT & BIG DATA TO PROVIDE ADVANCED SERVICES





https://www.rolls-royce.com/products-and-services/civil-aerospace.aspx

DIGITALIZATION AS ENABLER

3D Printing

- Mission: repair (instead of substituting) small household appliances
- Aim: guarantee 10 years of useful life
- 3D printing directly in the Technical Assistance Centres
- Spare parts availability (also for out-of-production products)
- Product Upgrade

Groupe SEB
Repair, instead of Replace

Source: https://www.youtube.com/watch?v=4gHHG4ibr-A

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PRACTICE AND RESEARCH GAPS

"Circular Economy initiatives are not sustainable per se"

Practice

PRACTICE AND RESEARCH GAPS

"Circular Economy initiatives are not sustainable per se"

- **Limited application in practice**
  Companies are struggling with the implementation of Circular Economy into supply chains and a **limited application** of the Circular Economy concept is observed in practice

- **Is it profitable?**
  One of the main factors hindering the implementation of Circular Economy is the **uncertainty regarding the potential benefits** that can be gathered from such a transition.

Practice

- **Assessment: lack of systemic perspective**
  Works dealing with the assessment of Circular Economy impacts do not simultaneously evaluates and quantifies in a **systemic and holistic manner** the benefits

- **Assessment: lack of knowledge on results**
  Whether Circular Economy can – or cannot – be a **Win-Win-Win-Win strategy** able to provides net benefits to the environment; to the society; to supply chain economics and to users' finances is still an open question

Literature

OBJECTIVE AND RESEARCH QUESTIONS

Obj

To identify, assess and quantify the main **economic, environmental and social impacts of a Circular Economy transition** in a systemic and holistic perspective, in a way to also outline the most promising **Circular Economy Levers** and/or **Circular Economy Enabling Factors**

OBJECTIVE AND RESEARCH QUESTIONS

Obj

To identify, assess and quantify the main **economic, environmental and social impacts of a Circular Economy transition** in a systemic and holistic perspective, in a way to also outline the most promising **Circular Economy Levers** and/or **Circular Economy Enabling Factors**

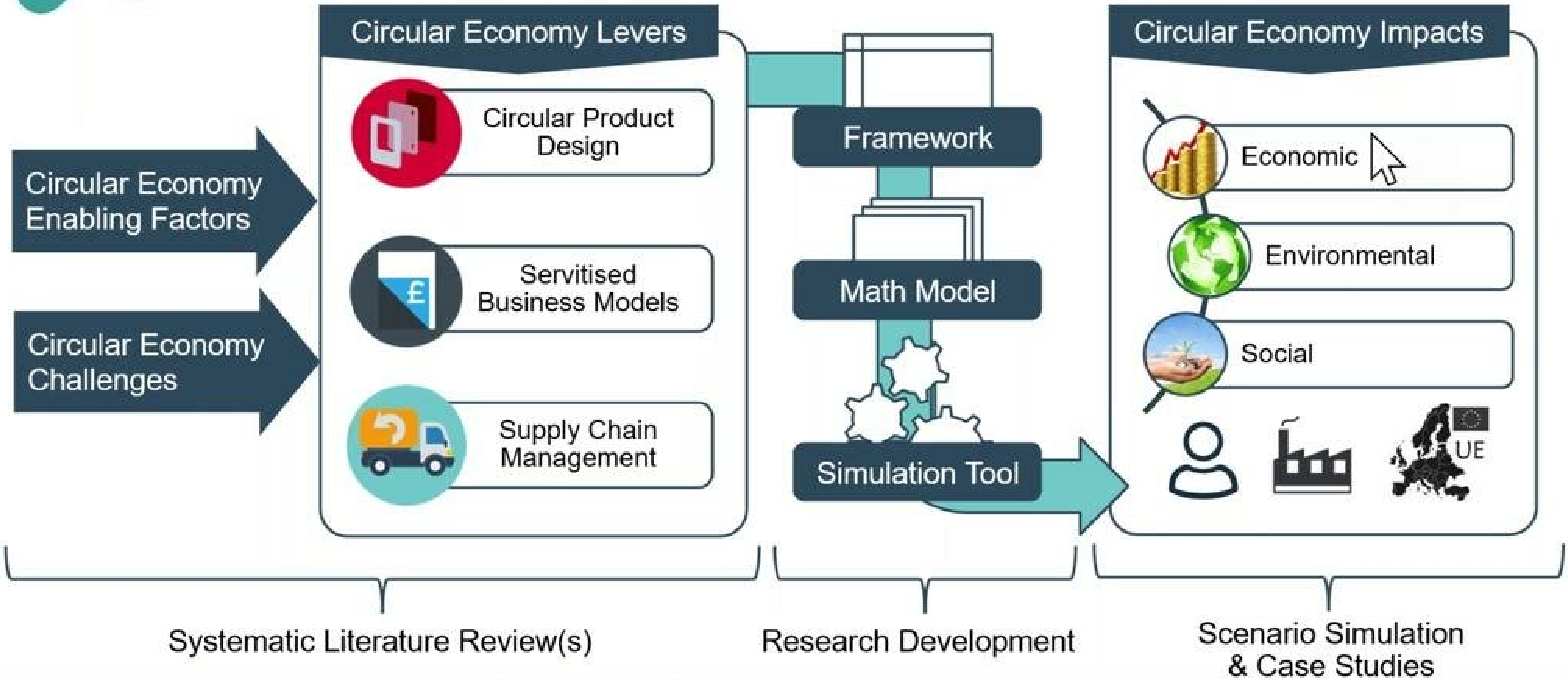
RQ1

How the potential effects of a Circular Economy transition can be:
- estimated ex-ante?
- evaluated ex-post?

RQ2

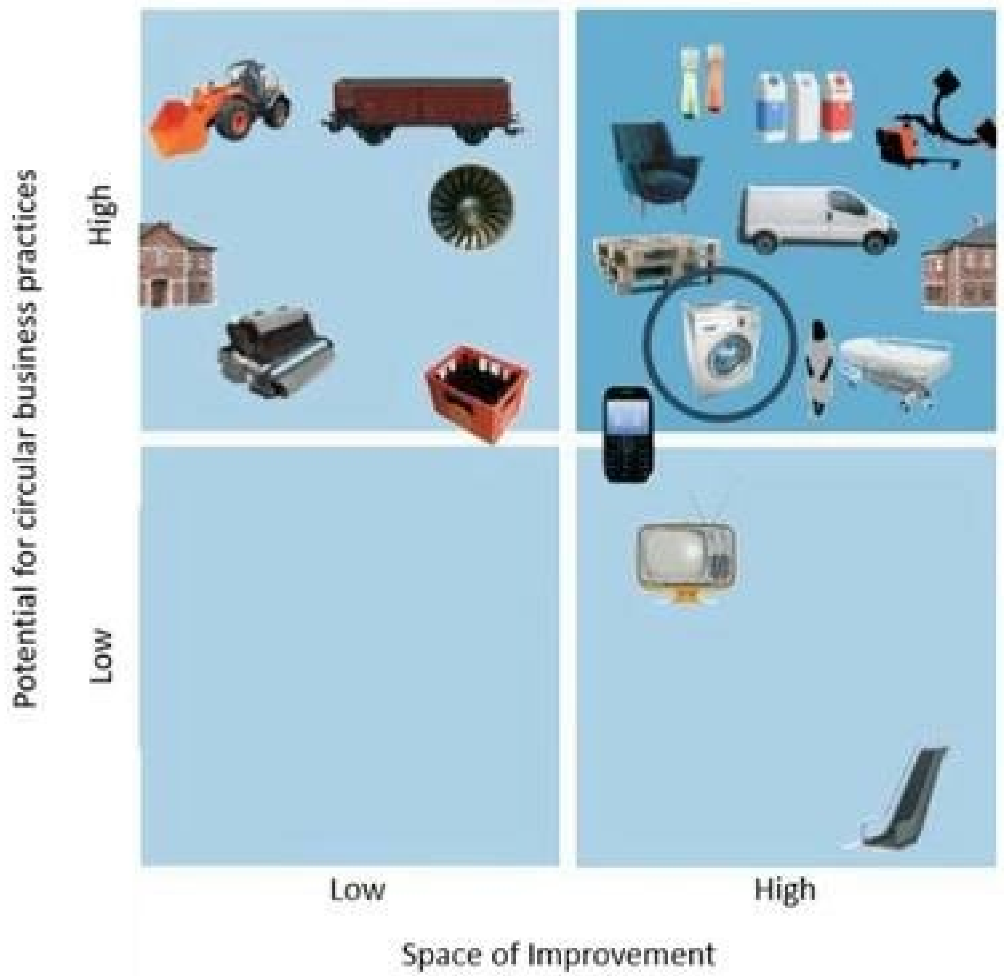
Which are the most promising Circular Economy Levers and Enabling Factors from an environmental, social and economic perspective, and what are the potential benefits achievable?

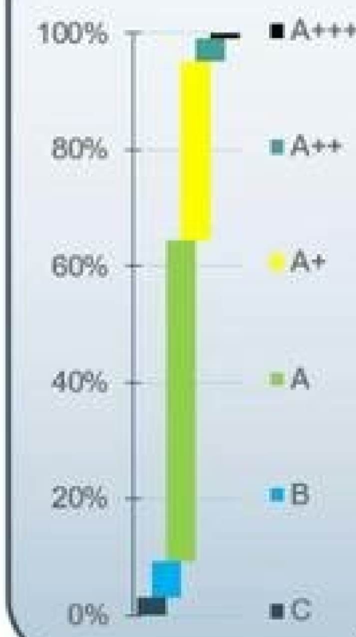
OVERALL RESEARCH PROCESS AND METHODOLOGY



THE APPLICATION: THE WASHING MACHINE INDUSTRY

THE APPLICATION: THE WASHING MACHINE INDUSTRY





LHA collected at EOL:
45 %
in Italy in 2020

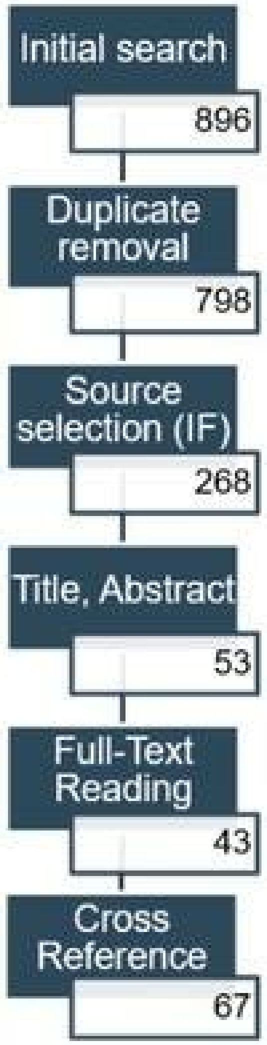
https://www.tandfonline.com/doi/full/10.1080/00207543.2018.1542176

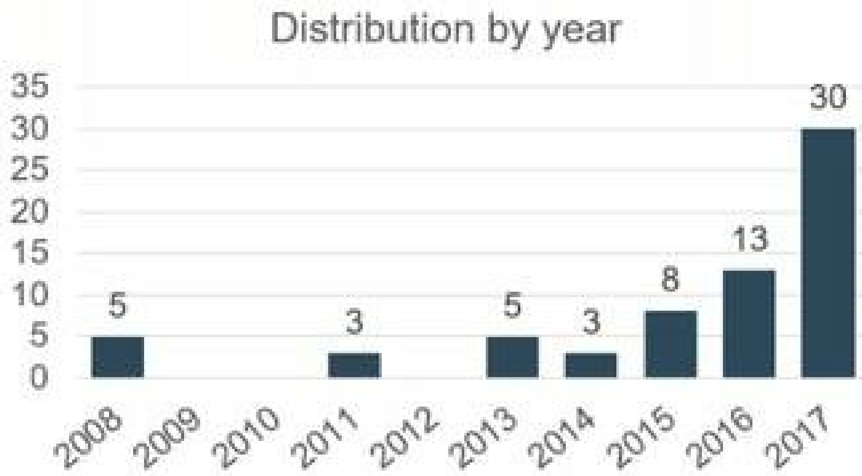
LITERATURE REVIEW #1
CHALLENGES IN SUPPLY CHAIN REDESIGN FOR THE CE

OBJ: To identify and provide a categorization of challenges for supply chain redesign for the Circular Economy

- Systematic Literature Review
- November-December 2017
- Scopus

Search string	N° Papers
Circular Economy AND Barrier	69
Circular Economy AND Obstacle	24
Circular Economy AND Challenge	239
Closed loop supply chain AND Barrier	10
Closed loop supply chain AND Obstacle	9
Closed loop supply chain AND Challenge	93
Green supply chain AND Barrier	124
Green supply chain AND Obstacle	20
Green supply chain AND Challenge	308
Total	**896**

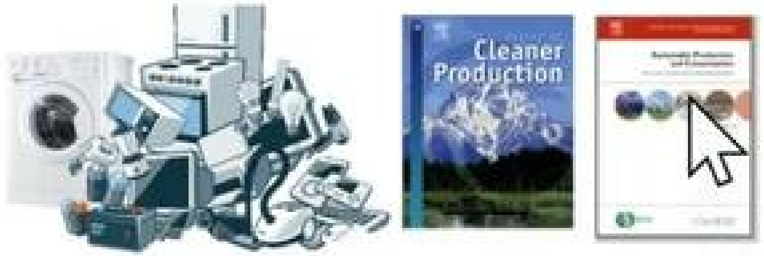


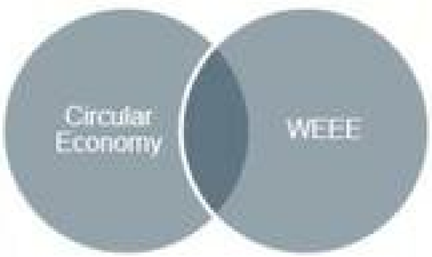


Findings

- Emerging phenomenon that is gaining momentum
- Multidisciplinary characteristics
- Lack of systemic and holistic perspectives

LITERATURE REVIEW #2 & #3
CIRCULAR ECONOMY & WEEE

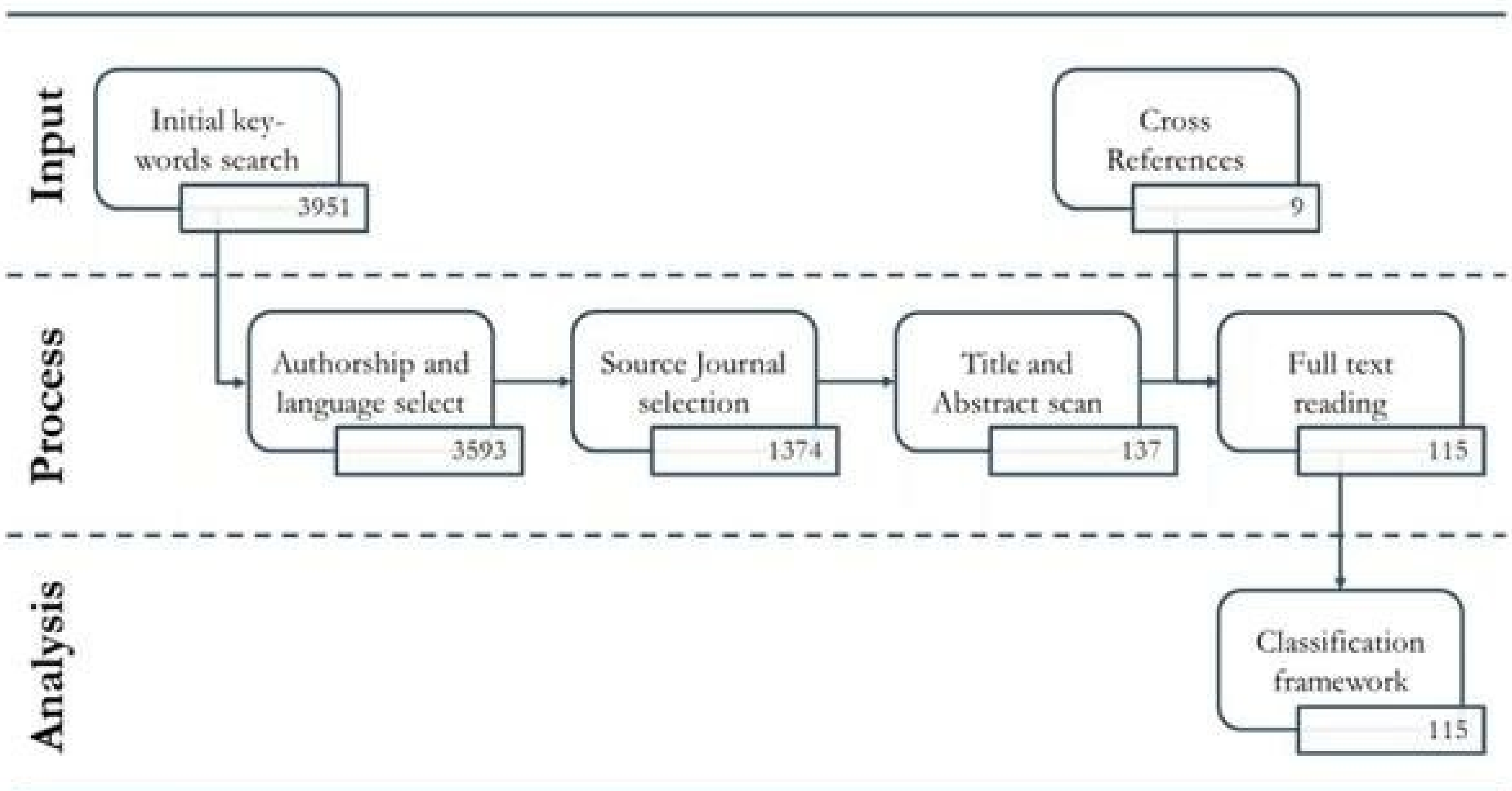




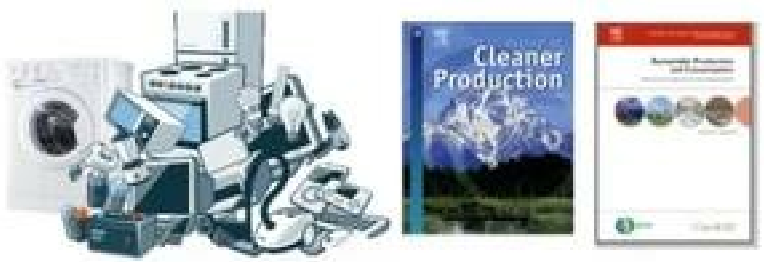
To explore the **state-of-the-art** of **Circular Economy** in the **WEEE industry** to spot research gaps, define a research agenda and future research directions

Keywords Set 1 – Circular Economy
Circular economy; Durability; Eco-eff*; Sustainab*; Closed-loop; Reverse supply chain; Reverse logistics; Reus* OR re-us*; Remanuf* OR re-manuf; Refurbish*; Disassembly; Repair; Eco-design; Shar*; Product-service system

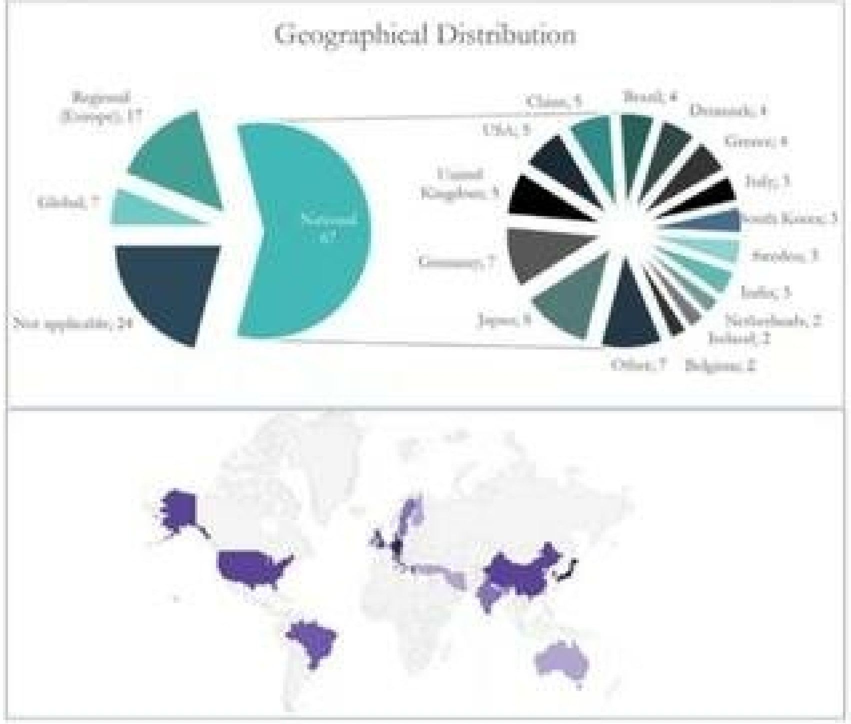
Keywords Set 2 – WEEE
WEEE; EEE; Appliance; Washing Machine; Laundry

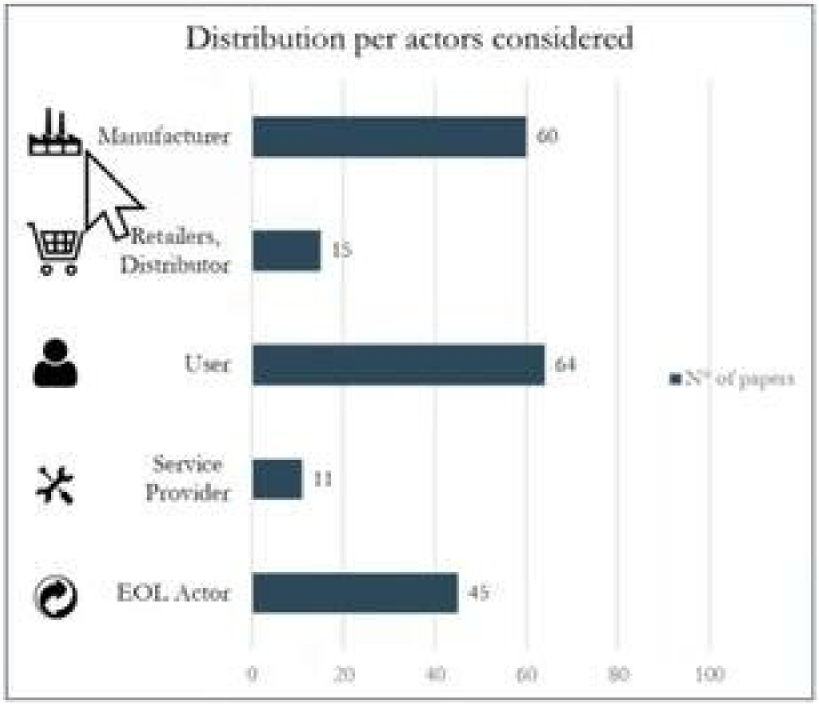


LITERATURE REVIEW #2 & #3
CIRCULAR ECONOMY & WEEE



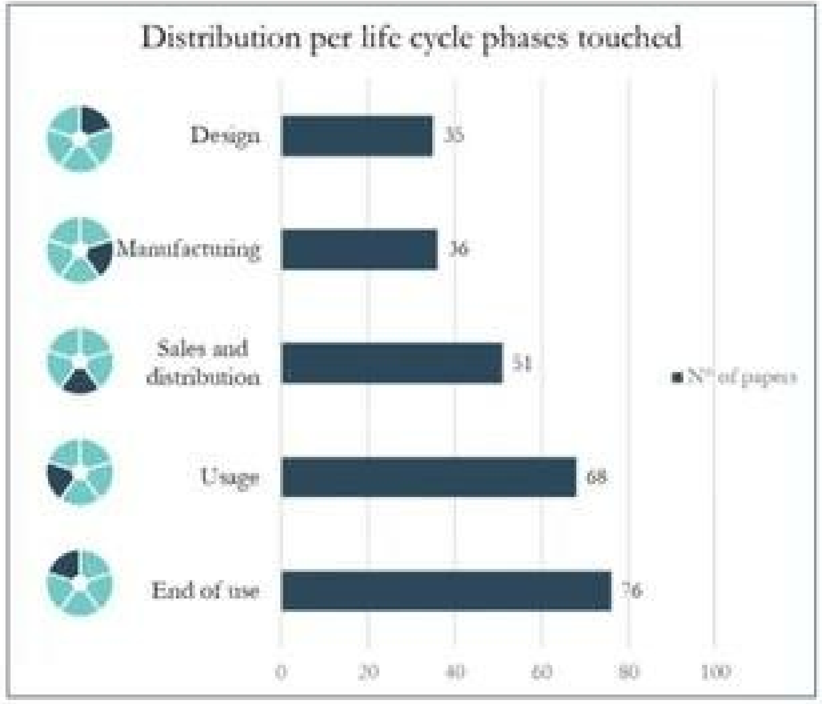
▼ Geographical distribution





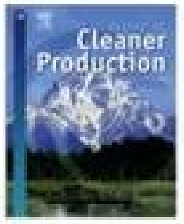
▲ Supply Chain Actors

▼ Supply Chain Phases



Lack of systemic and holistic perspective when addressing Circular Economy in the WEEE industry, in terms of: Supply Chain actors, life cycle phases, R-Strategies, CE Levers, CE Enabling Factors and especially **Benefits**

LITERATURE REVIEW #2 & #3
CIRCULAR ECONOMY & WEEE



G. Bressanelli, D.C.A. Pigosso, N. Saccani et al.

Journal of Cleaner Production 298 (2021) 126819

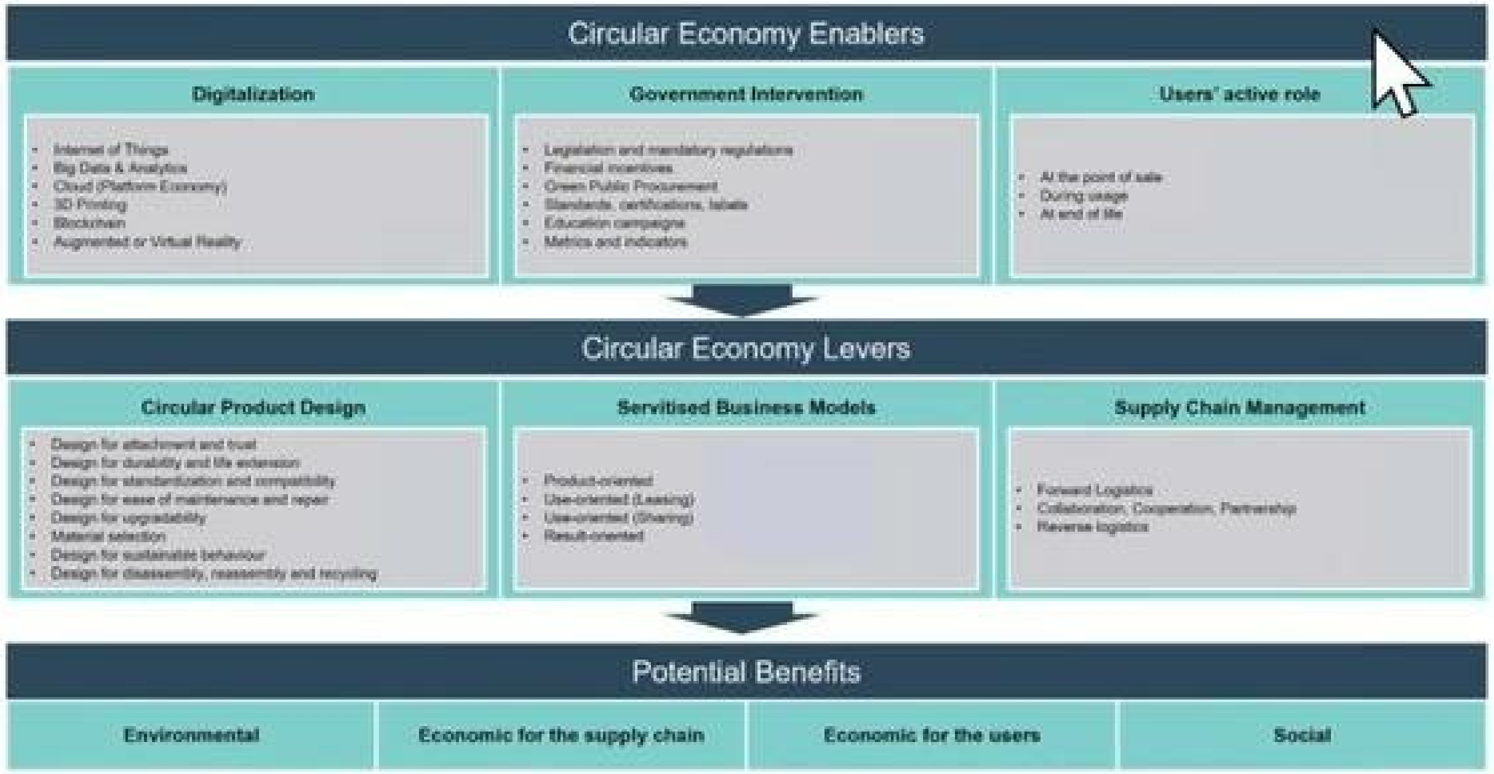
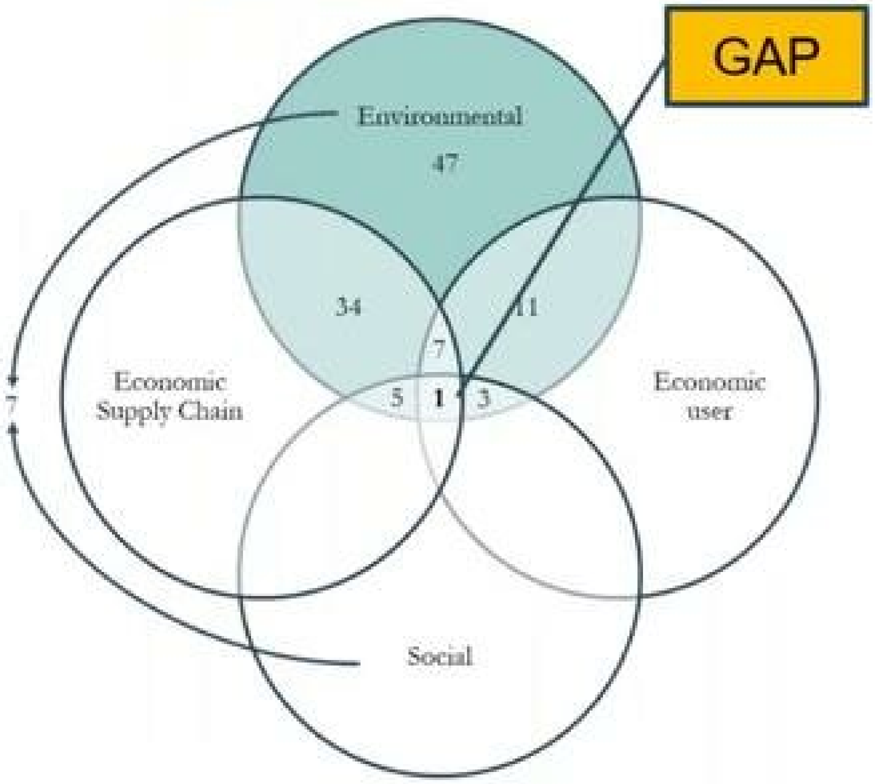


Fig. 4. Research framework.



▲ Circular Economy Benefits

Lack of systemic and holistic perspective when addressing Circular Economy in the WEEE industry, in terms of: Supply Chain actors, life cycle phases, R-Strategies, CE Levers, CE Enabling Factors and especially **Benefits**

LITERATURE REVIEW #2 & #3 CIRCULAR ECONOMY & WEEE

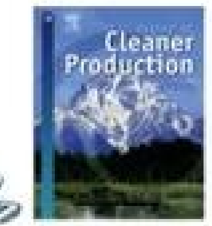


Table 2
Research Gaps and Research Agenda

Aspect	Research Gap	Research Agenda
Objective and Methodology	Research up to now has had mainly explorative and impact evaluation purposes, with little attention put on the design of practical solutions. Research adopted especially quantitative approaches, with static simulation and assessment being the most used one. The survey methodology was used only for explorative purpose to collect data from users: no research has yet used this methodology in the WEEE industry for either collect data from a large set of companies or as a basis for theory testing. Most papers are single method: only 23% of the contributions adopts more than one methodology.	I.) Demonstrate how CE can be applied to the WEEE industry to solve practical problems, through empirical theory-testing and validation research. II.) Investigate CE in the WEEE industry by combining quantitative and qualitative approaches (such as survey and case studies) focused on companies and supply chains.
Geography and Approach	CE in the WEEE industry has been addressed mainly in Europe and Asia. Lack of research comparing CE practices in different geographical areas. Top-down approaches dominated overall and especially on 'sustainability' papers. However, CE is seen as a strategy that companies are willing to implement even without regulatory pressures, given its assumed ability to generate economic advantages besides environmental and social ones.	III.) Explore how geography-related factors may contribute or hinder the adoption of CE in the WEEE industry, across different regions (e.g. Europe, Asia and Africa) IV.) Investigate, quantify and validate the mechanisms for how CE changes companies' behaviour from top-down to bottom-up.

LITERATURE REVIEW #2 & #3
CIRCULAR ECONOMY & WEEE

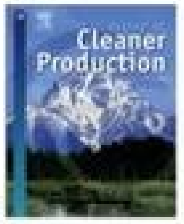


Table 2
Research Gaps and Research Agenda

Aspect	Research Gap	Research Agenda
Actor and life cycle phase	Research has paid little attention to retailers and service providers. Research has paid little attention to the manufacturing and design phases, where users have been rarely taken into account. Overall, CE research in the WEEE industry lacks a systemic and holistic perspective (joint consideration of several supply chain actors and life cycle phases).	V.) Explore the role and the CE implications for retailers and service providers in the WEEE industry. VI.) Study the role and the CE implications for EEE design (especially taking into account users' habits and behaviour) and manufacturing. VII.) Consider all WEEE ecosystem's actors and all life cycle phases simultaneously, to avoid burden shifting and to ensure a systemic implementation (especially in terms of collaboration for achieving CE)
CE 4R scheme	CE in the WEEE industry mainly addressed the Reduce and the Recycle strategies, while limited attention has been paid to Reuse and Remanufacture.	VIII.) Target more Reuse and Remanufacture strategies for WEEE, in order to ensure a higher potential for decoupling value creation from resource consumption.
	The cascading hierarchy among the 'R' strategies as well as the systemic and holistic perspectives of the CE '4R' scheme have generally not been adopted by the literature.	IX.) Address all the CE '4R' strategies jointly (including their cascading potential) in order to extend the lifetime of EEE to the highest possible level.
	CE in the WEEE industry has been mainly investigated as a way to bring economic advantages for the supply chain through Recycle, and as a way to provide economic savings to users through Reduce.	X.) Explore how Reuse, Remanufacture and Recycle can create value to end-users, establish the right incentives for take-back systems and define the links among each 'R' strategy to the achievable social benefits

LITERATURE REVIEW #2 & #3
CIRCULAR ECONOMY & WEEE

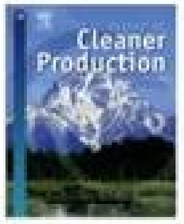
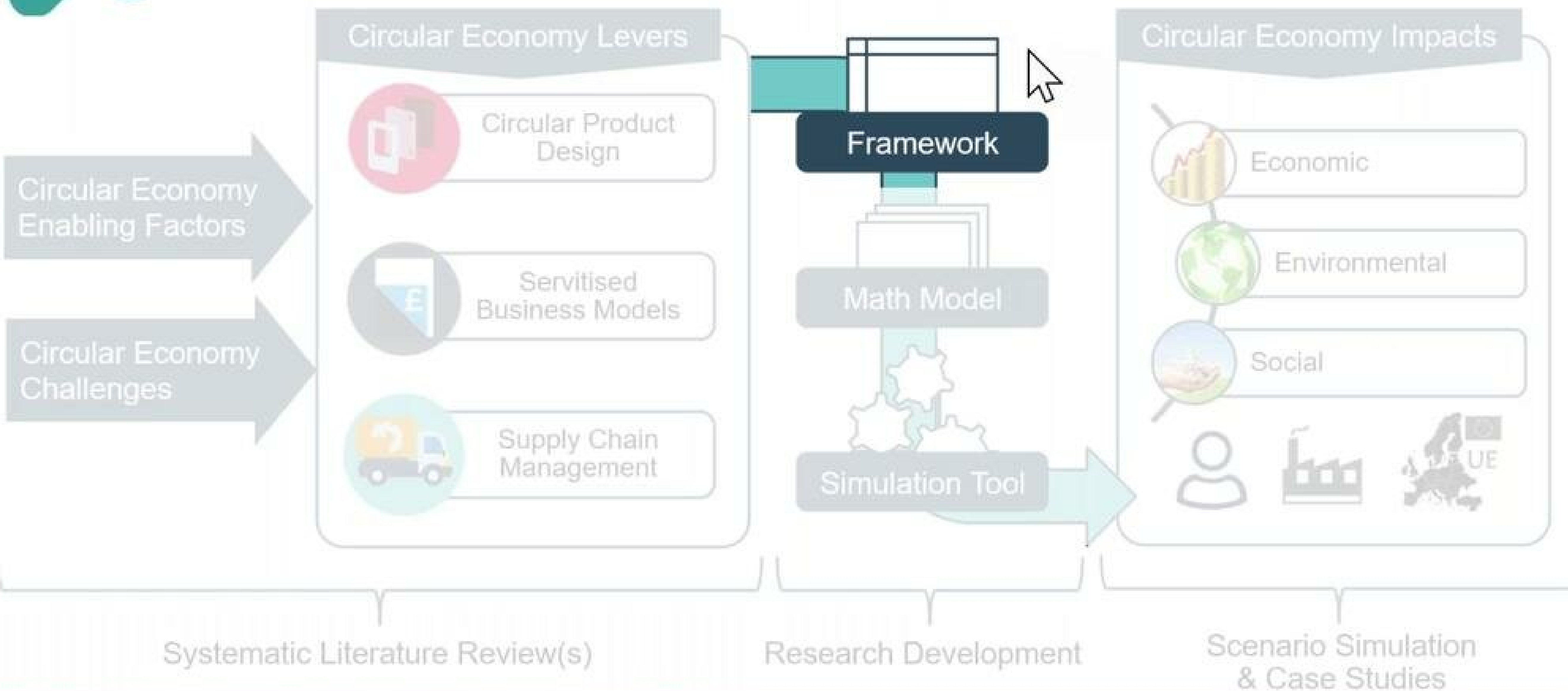


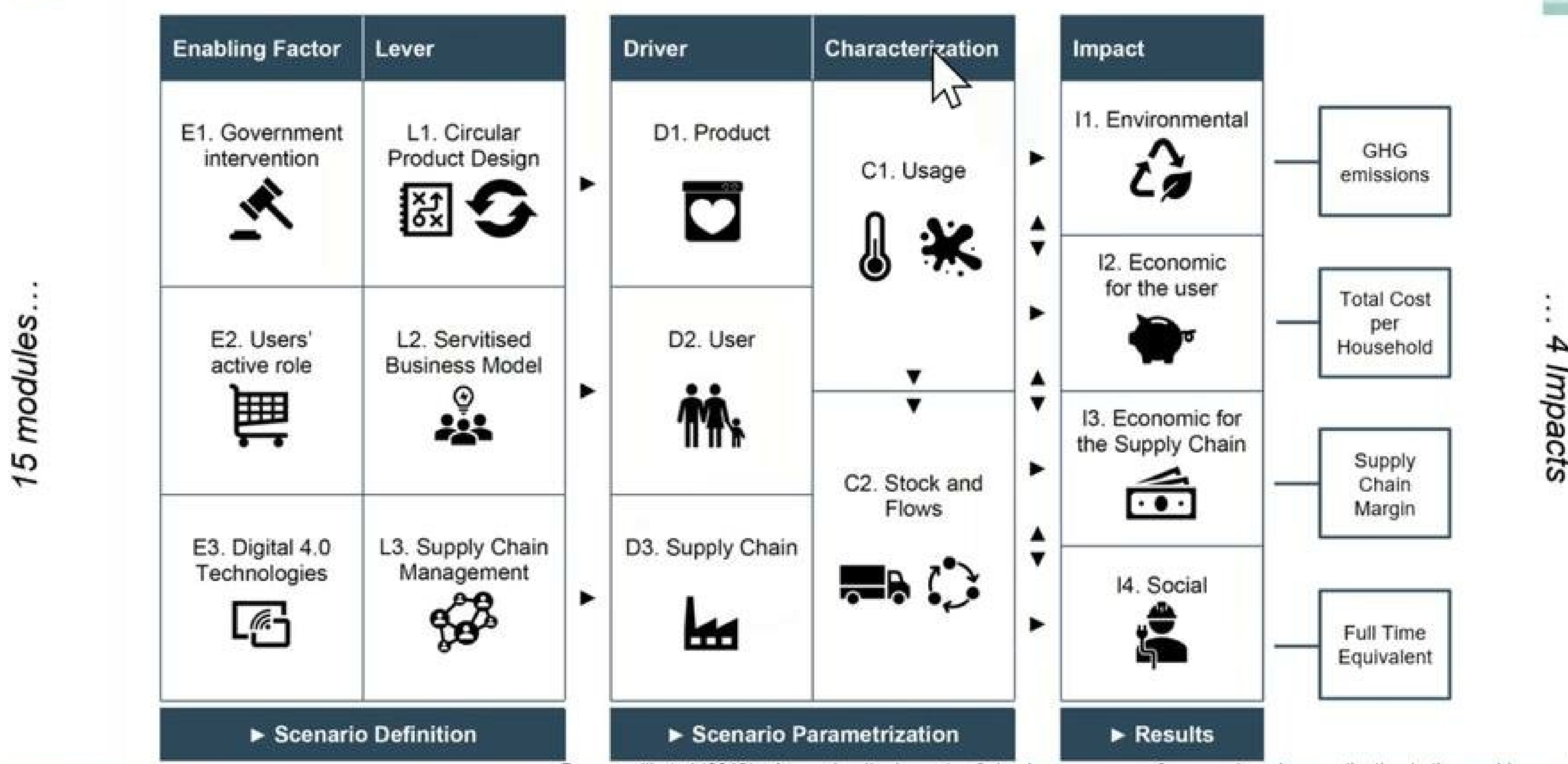
Table 2
Research agenda.

Layer	Findings	Research Agenda
Enablers	Government interventions and users' active role in enabling CE have been well addressed in the past. On the other hand, the enabling role of digitalization has been overlooked: few articles addressed IoT, Big Data and cloud technologies, while no study addressed augmented and virtual reality, blockchain or 3D Printing in the EEE supply chai	1 - Investigate the role of digitalization in enabling CE in the EEE supply chain, especially regarding the enabling potential of blockchain, 3D Printing, augmented and virtual reality
	Lack of a systemic perspective over the CE enablers. Digital technologies are rarely investigated together. The combination of government measures is very seldom addressed. The combined role of users' during purchase, usage and EoL has been rarely investigated	2 - At a higher level: investigate digitalization, government intervention and users' active role simultaneously. At a more detailed level: combine many technologies when researching on digitalization; combine more measures when researching on government intervention; combine all the lifecycle stages when researching on the users' active role
Levers	Research has devoted limited attention to 'reduce' design strategies (durability, standardization, upgradability, attachment and trust)	3 - Investigate design strategies focused on 'reduce' (durability, standardization, upgradability, attachment and trust)
	Research has devoted limited attention to sharing and to result-oriented SBM	4 - Investigate SBM based on result-oriented offering
	Research has devoted limited attention to collaboration among supply chain actors and stakeholders	5 - Investigate the potential and the implications of collaboration in the EEE supply chain for the CE
	CE levers have not been sufficiently investigated in a systemic and holistic perspective: circular design strategies are seldom investigated together; servitised strategies are seldom investigated together; the integration of forward logistics, collaboration and reverse logistics has been rarely addressed	6 - At a higher level, investigate circular product design, SBM and SCM simultaneously. At a more detailed level: combine more design practices if researching on circular design; combine different SBM types if researching on servitisation; combine collaboration, forward and reverse logistics if researching on SCM
Benefits	The application of CE to the EEE supply chain has been mainly focused on environmental impacts and on economic benefits for the supply chain, while few articles covered the social dimension of CE or the economic benefits for the users.	7 - Investigate how CE in general and digitalization in particular can bring social and economic benefits for the users
	Benefits have not been investigated and quantified in a systemic and holistic perspective yet. Whether CE in the EEE industry can (or cannot) contribute to sustainability under a win-win-win strategy still remains an open question	8 - Simultaneously investigate and quantify economic, environmental and social benefits of CE implementation in the EEE supply chain

OVERALL RESEARCH PROCESS AND METHODOLOGY

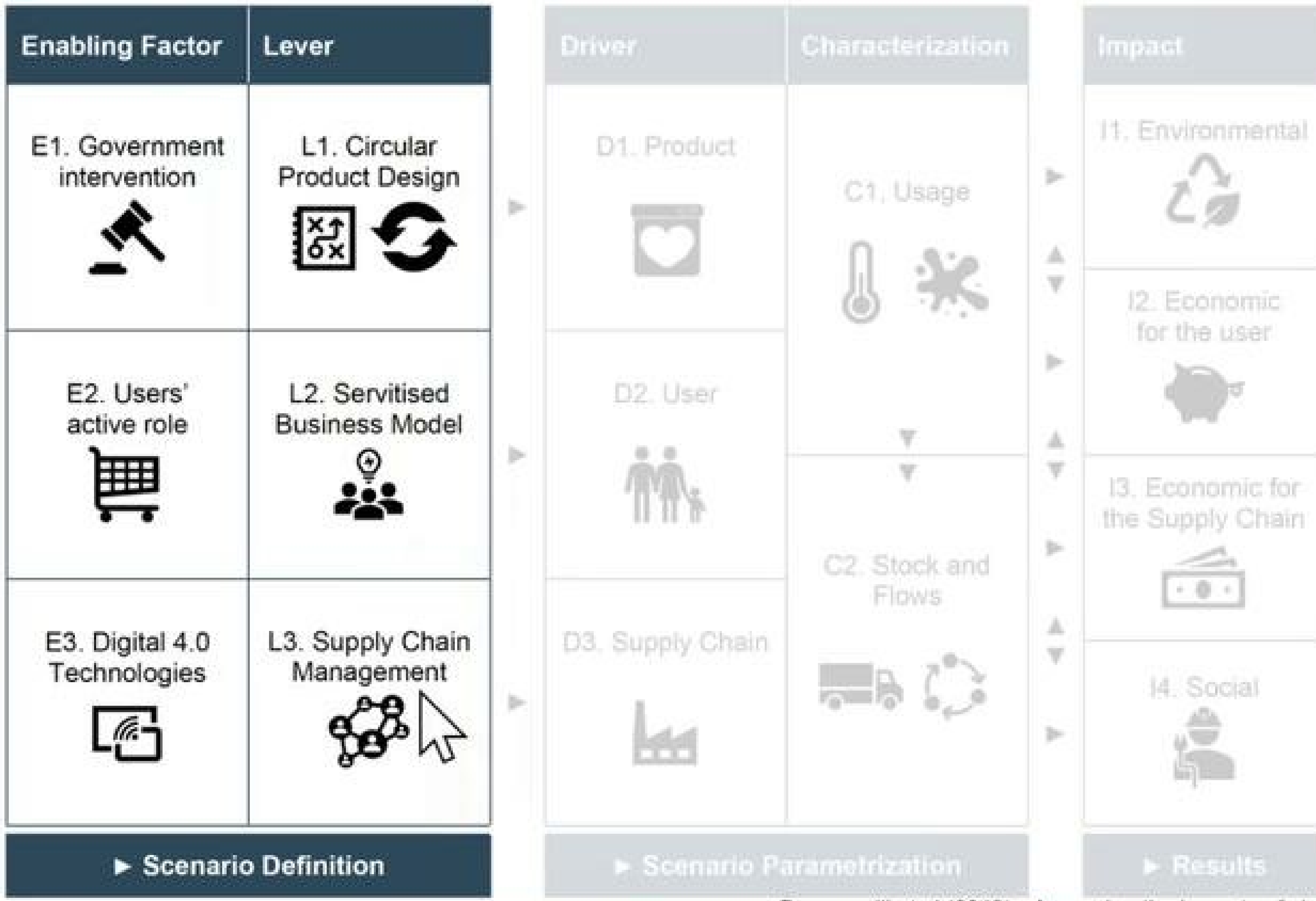


CIRCULAR ECONOMY FRAMEWORK TO ASSESS THE IMPACTS

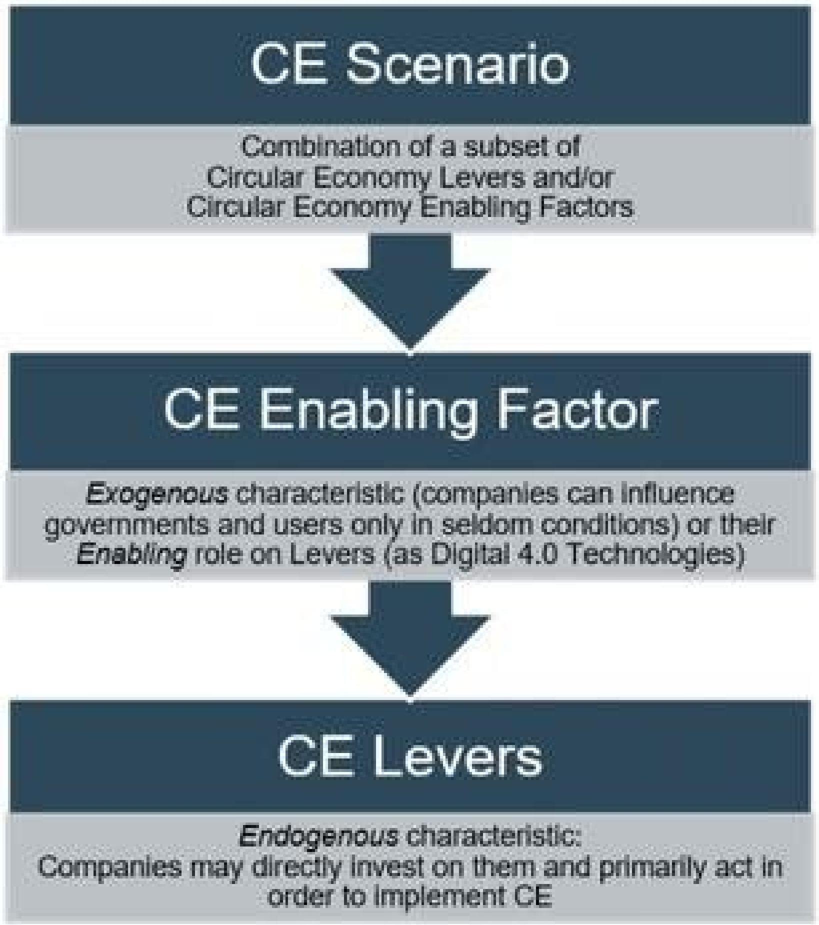


Bressanelli et al (2019) - Assessing the impacts of circular economy: a framework and an application to the washing machine industry

CIRCULAR ECONOMY FRAMEWORK TO ASSESS THE IMPACTS



STEP 1



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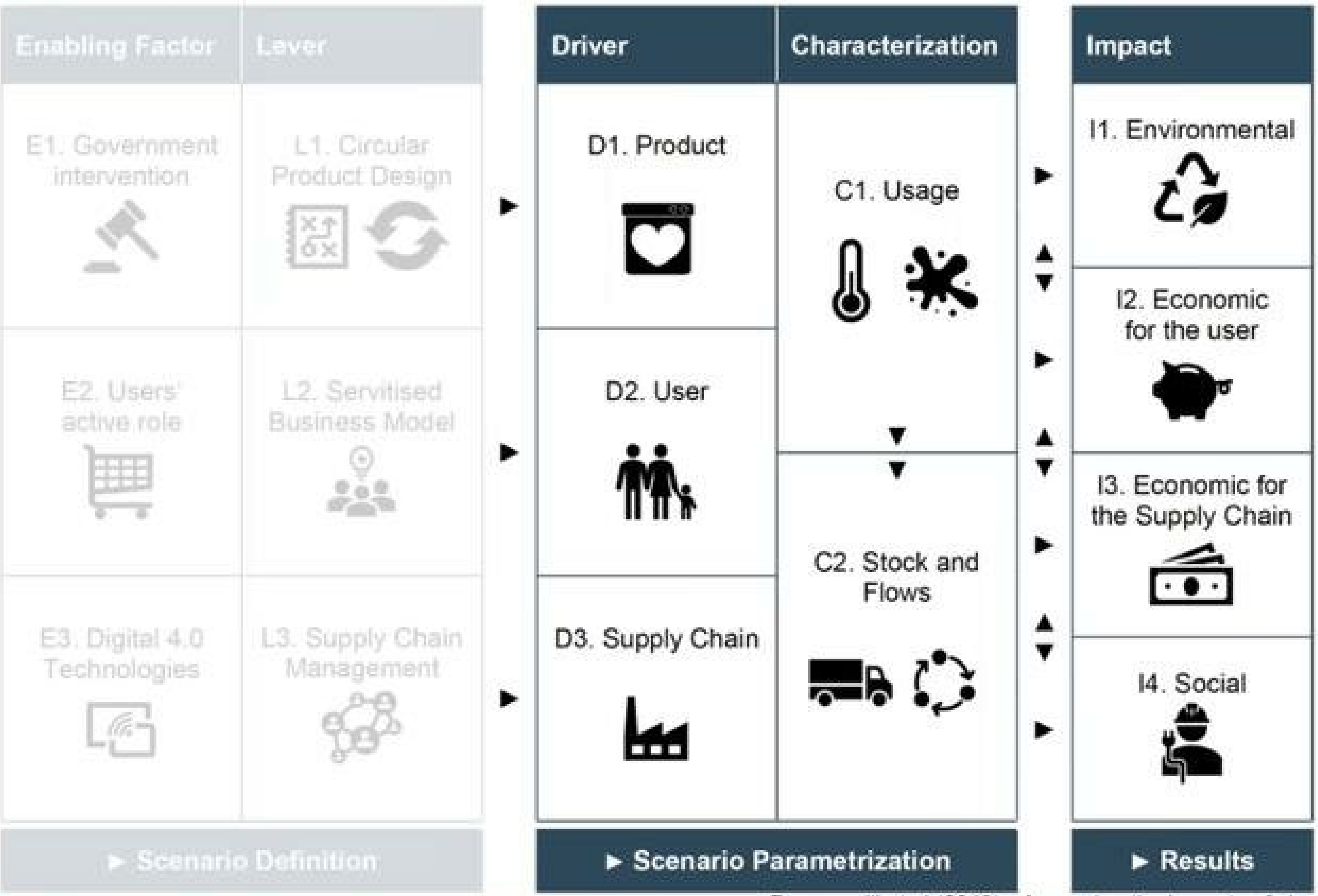
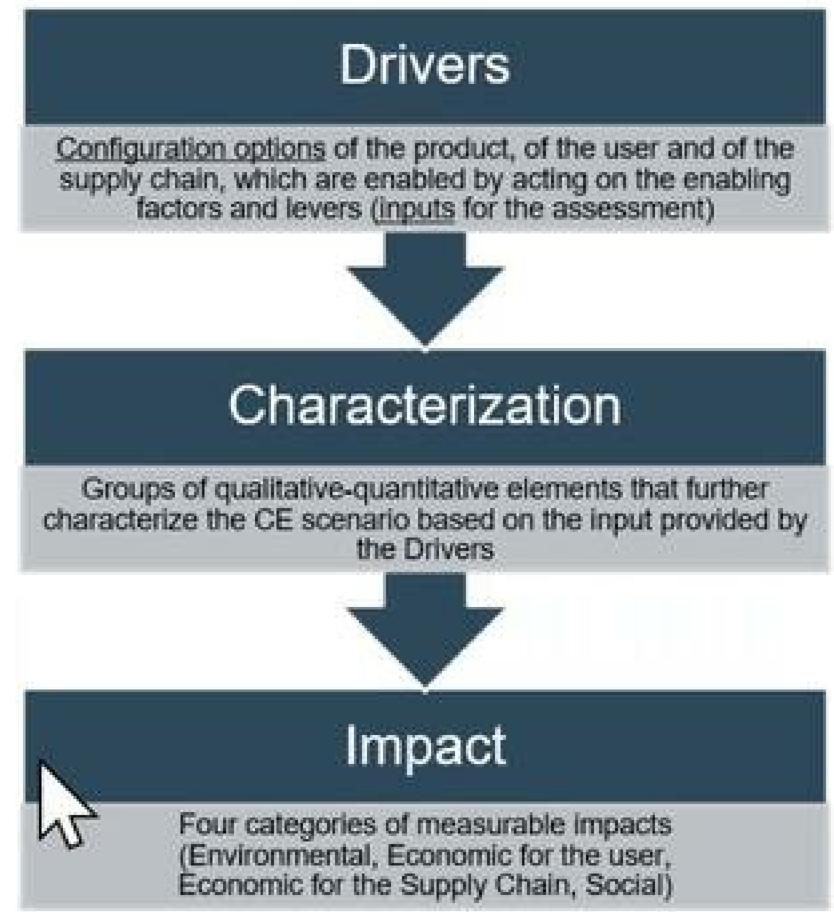
CIRCULAR ECONOMY FRAMEWORK TO ASSESS THE IMPACTS



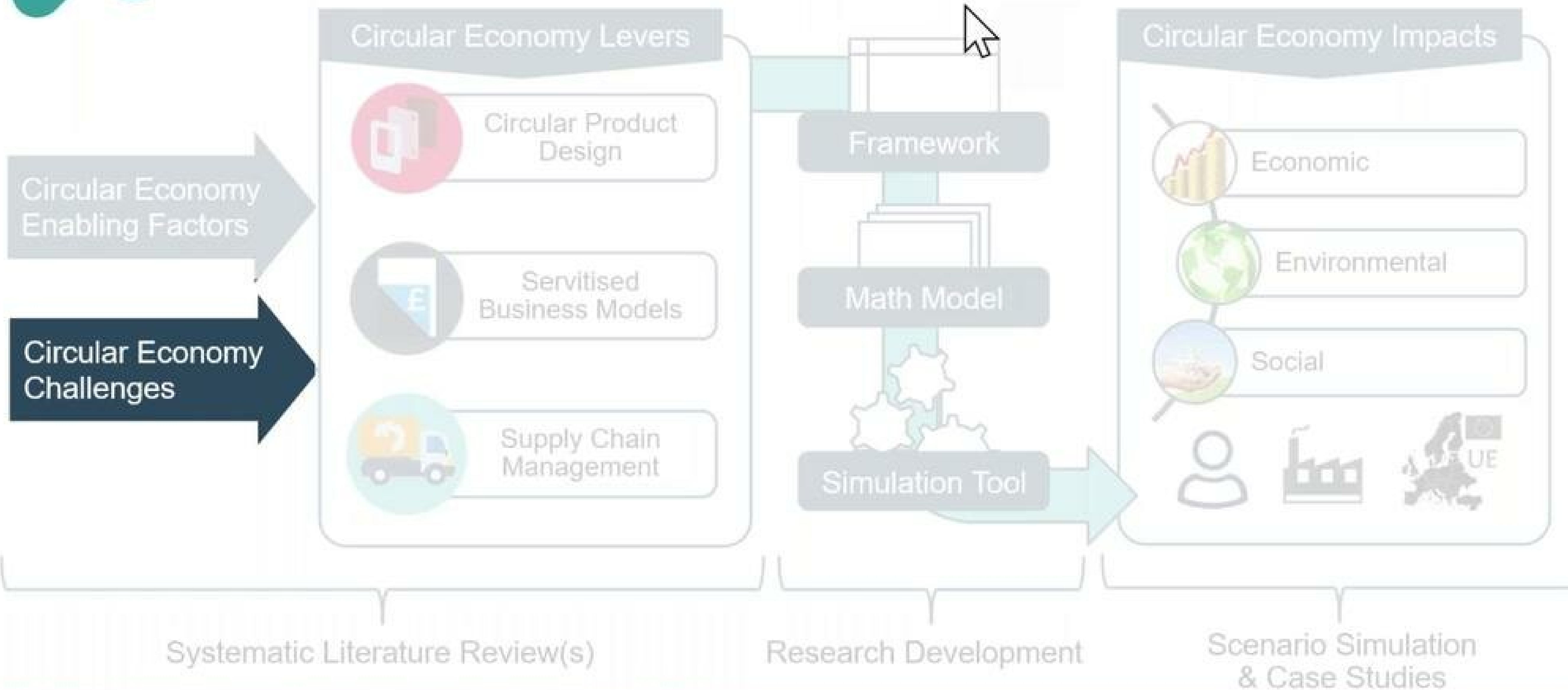
STEP 2



Bressanelli et al (2019) - Assessing the impacts of circular economy: a framework and an application to the washing machine industry

(COFFE) BREAK (?)

OVERALL RESEARCH PROCESS AND METHODOLOGY



(COFFE) BREAK (?)

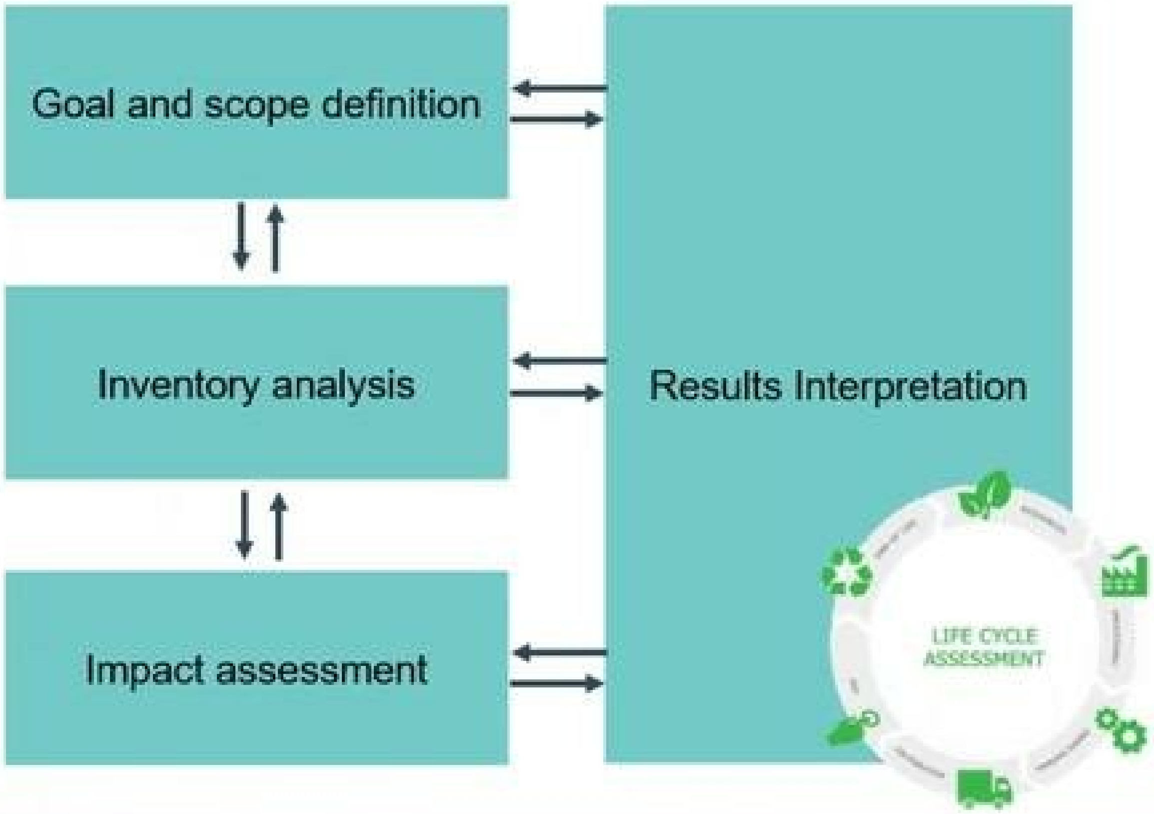
AGENDA

1. Circular Economy and Circular Supply Chains: an introduction
2. Assessing the impacts of Circular Economy scenarios: the Framework
3. The mathematical model and the simulation tool for the washing machine industry
4. Discussion of results, implications and key takeaways

LIFE CYCLE ASSESSMENT

ENVIRONMENTAL IMPACTS

- Life Cycle Assessment (LCA) ISO 14040



ECONOMIC IMPACTS

- Life Cycle Costing (LCC)
- Total Cost of Ownership (TCO)

SOCIAL IMPACTS

- (social) Life Cycle Assessment (sLCA)

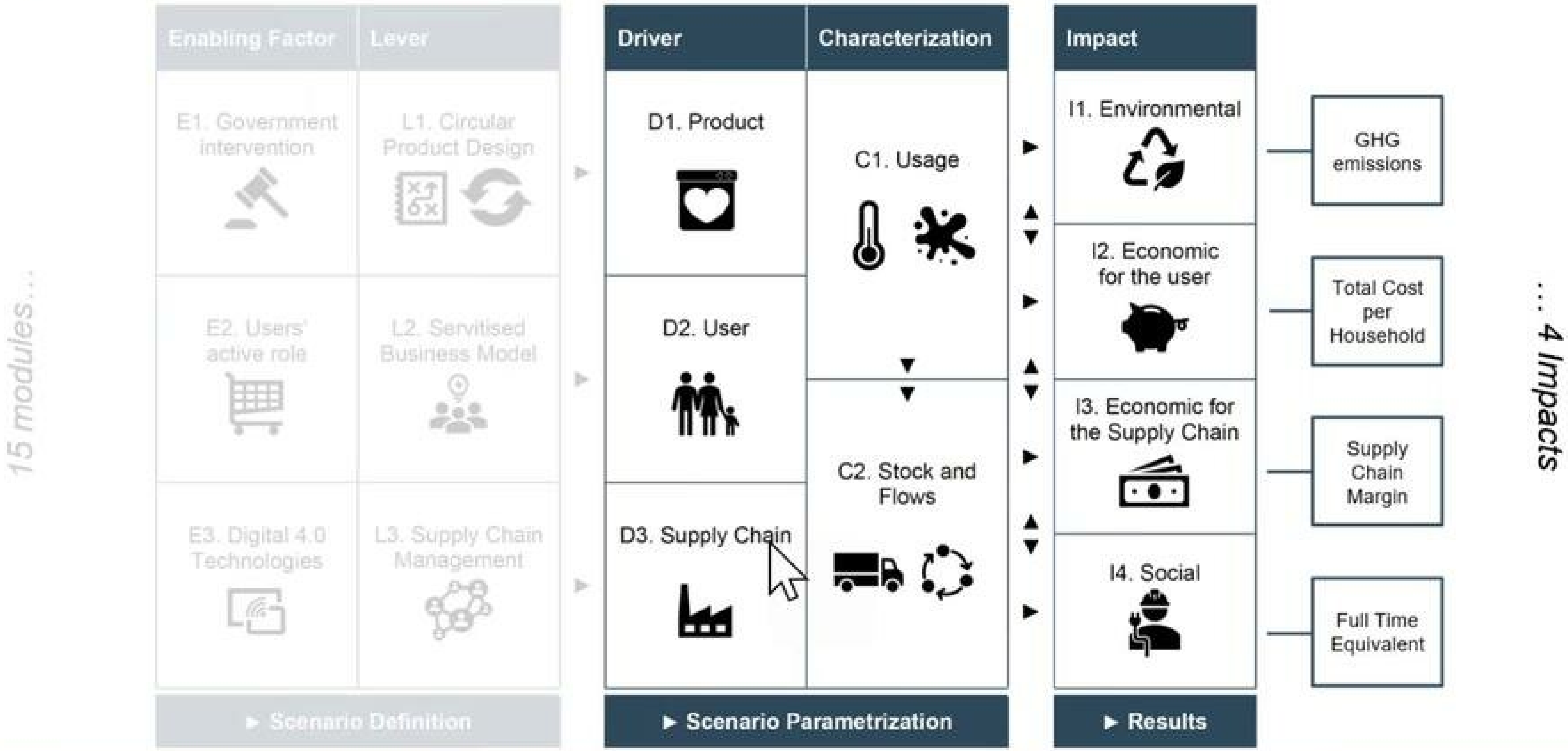
LIFE CYCLE ASSESSMENT

LCA limitations

- It provides a "static" analysis
- It is expensive in terms of time (LCA analysis takes months!) and resources
- It requires specific software, especially for accessing the database (eg. SimaPRO, GABI, ...)
- It is difficult to model the reuse of products, components and resources (but not impossible)
- It should be coupled with LCC, TCO and sLCA methodologies to determine economic and social impacts
- ...

➔ let's try to build a simulation model to quantify the impacts

CIRCULAR ECONOMY FRAMEWORK TO ASSESS THE IMPACTS



DRIVERS

D1. Product (washing machine)

- *C* Washing Machine Capacity (kg)
- *EEC* Energy Efficiency Class
- L_l technical life of the washing machine during its life l, in number of washing cycles

D2. User

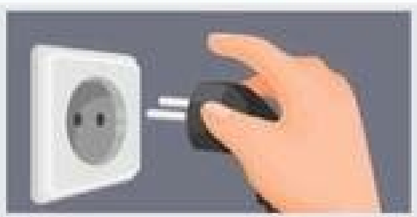
- *HS* Family size (n ° of members)
- *Shr* number of families sharing the same washing machine
- *T* Washing temperature
- *LR* Washing machine capacity saturation rate

D3. Supply Chain

- *Rrfb,l* Refurbishment rate, i.e.% of washing machines that are refurbished at the end of their life
- *Rrec,l* Recycling rate, i.e.% of washing machines that are recycled at the end of their life

C1. USAGE

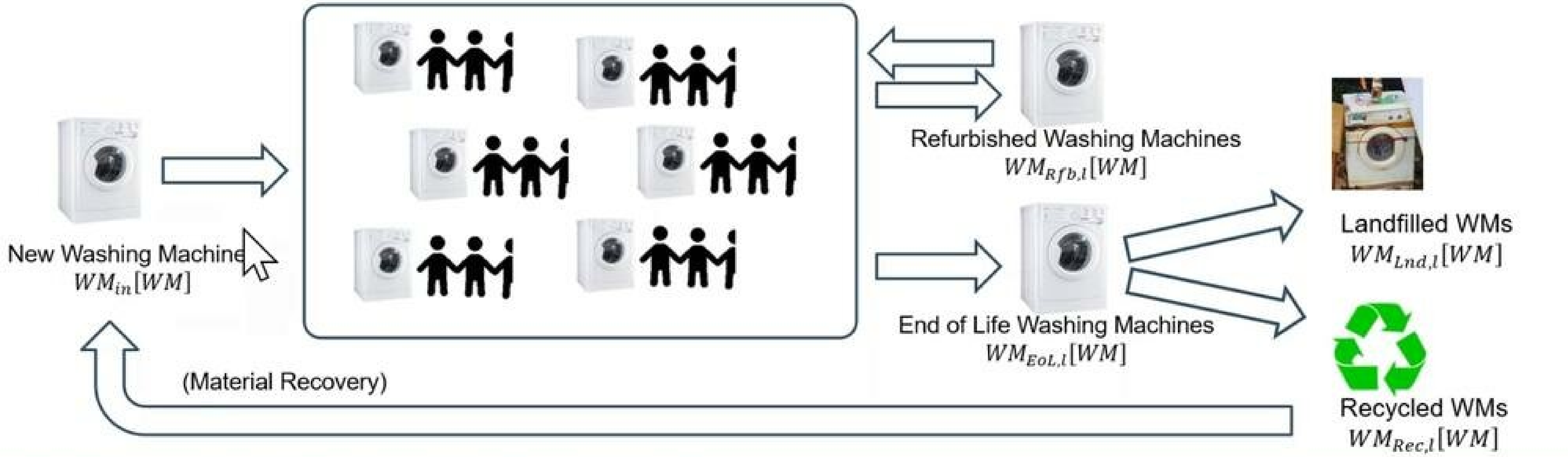
Quantify the consumption of the main resources during the use phase (energy, water, detergent)

RESOURCE / IMPACT		SPECIFIC CONSUMPTION (per each washing cycle)	INTENSITY OF USE (No. of washing cycles per family per year)
Energy		$E_{wc}\left[\frac{kWh}{wc}\right] = f\{T; EEC; C\}$	
Water		$W_{wc}\left[\frac{Litre}{wc}\right] = f\{C; LR; WEC\}$	$N_{wc}\left[\frac{wc}{hh \times year}\right] = \frac{YLW}{C \times LR}$
Detergent		$D_{wc}\left[\frac{kg}{wc}\right] = f\{C; LR; DEC; DDF\}$	

C2. STOCK AND FLOWS

Quantify the installed base of washing machines of the system in question, as a function of the population, the size of the household and the number of families sharing the same washing machine

Washing Machine installed base $WM_{stock}[WM] = \frac{PPL}{HS \times Shr}$



I1. ENVIRONMENTAL IMPACT

Rely on LCA studyes. For simplicity, only one impact indicator (GWP) was considered

Life Cycle Phase	Environmental Impact
Raw materials (credits for money laundering)	$GWP_{RME} \times WM_{in,1} - GWP_{Rec} \times WM_{Rec}$
Production and Distribution	$+ GWP_{M\&A} \times WM_{in,1} + GWP_{Dis} \times WM_{in,1}$
Usage	$+ (gwp_e \times EC + gwp_w \times WC + gwp_d \times DC) \times Shr \times WM_{stock}$
Maintenanc	$(GWP_{M\&R} \times Y_{M\&R}) \times WM_{stock}$
Refurbishment	$+ \sum_{l=2}^{l_{max}} \left((GWP_{RevLog} + GWP_{in,l} + GWP_{Dis}) \times WM_{in,l} \right)$
Landfill	$+ GWP_{Lnd} \times WM_{Lnd}$

I2. Economic for the user

I2. ECONOMIC IMPACT FOR THE USER

Three different payment methods are possible (sale, leasing, pay-per-wash).
There is also a discount for reconditioned washing machines (second hand, third hand, ...)

Traditional sale	Leasing scheme	Pay-per-wash
Sale price (amortized over the life of the washing machine)	Fixed monthly leasine fee	Rate dependent on the number of washing cycles

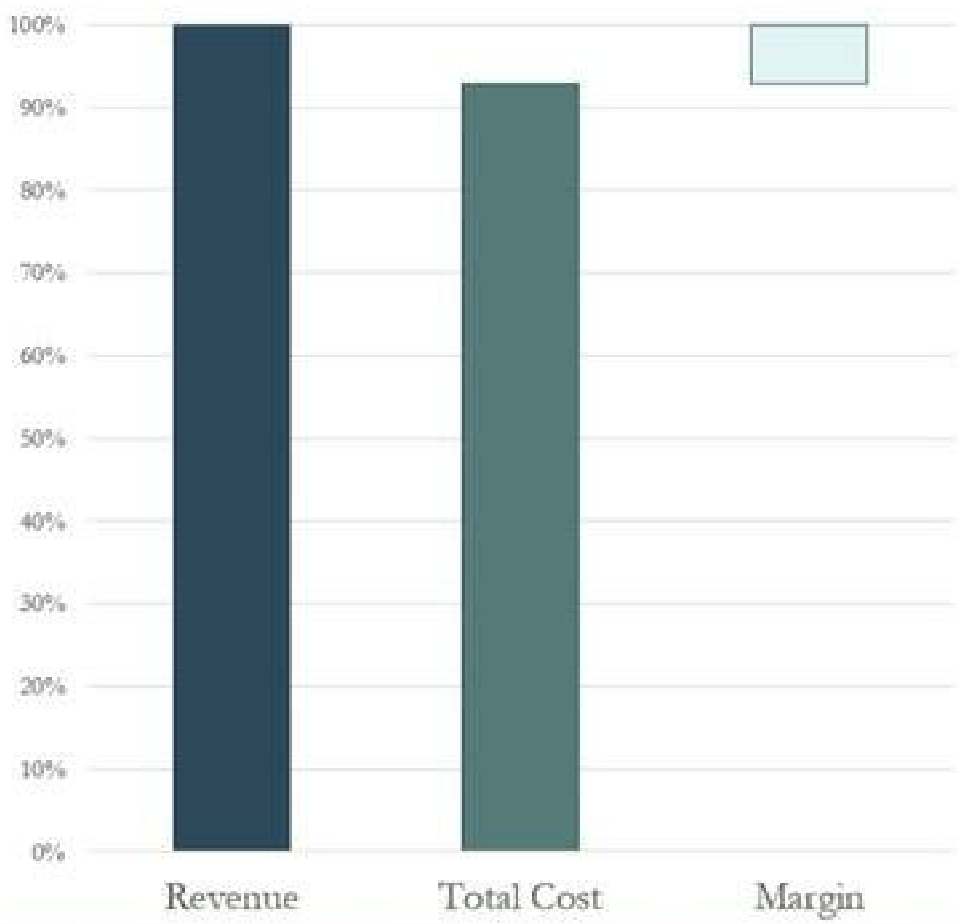
Maintenance and Repair

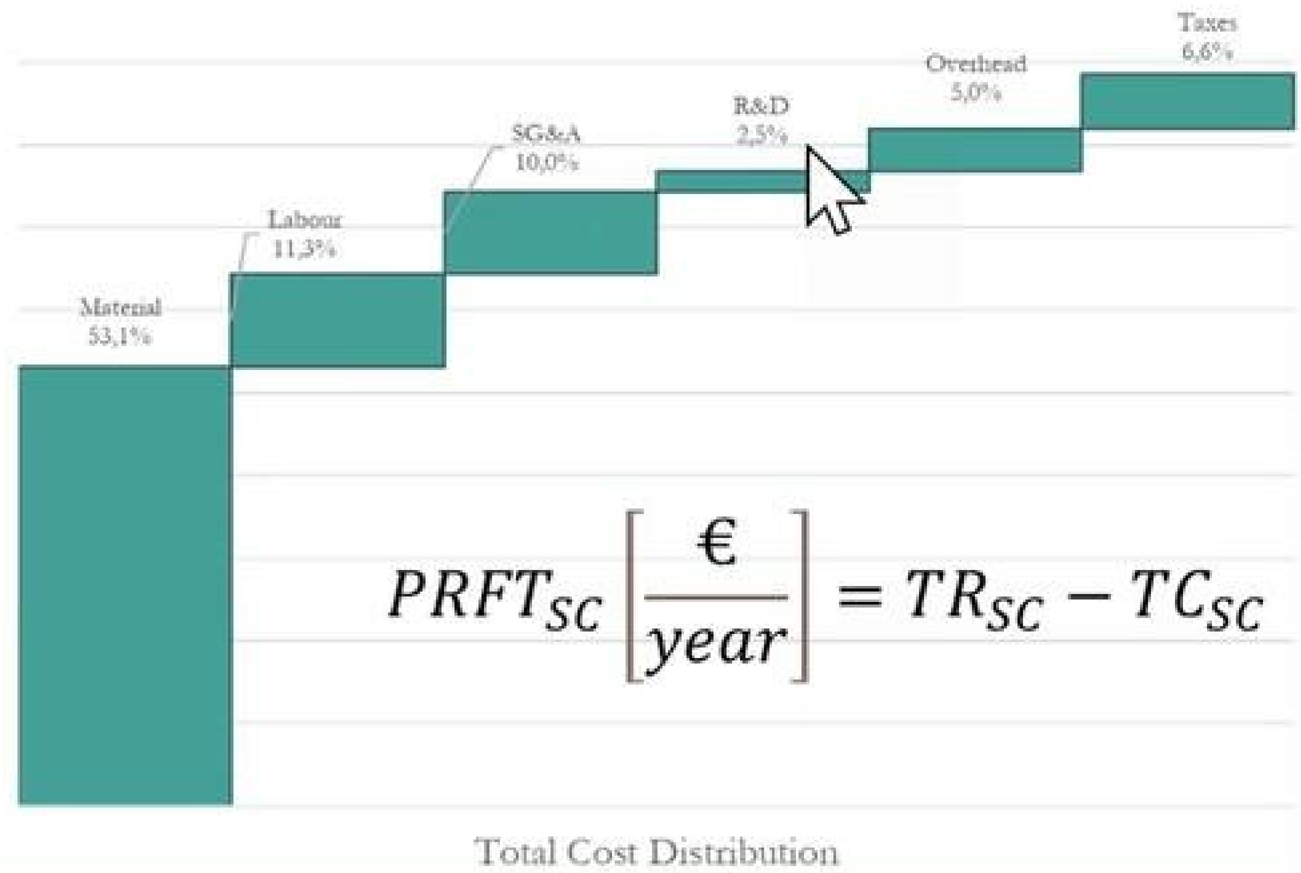
Usage Cost (Energy, water, detergents)

I3. ECONOMIC IMPACT FOR THE SUPPLY CHAIN

I3. Economic for the Supply Chain

Margin for the supply chain: Total Revenues (TR) net of Total Costs (TC)





$$PRFT_{SC}\left[\frac{€}{year}\right] = TR_{SC} - TC_{SC}$$

OVERALL: MATHEMATICAL MODEL (FORMULATION)

$$EC\left[\frac{kWh}{hh \times year}\right] = N_{wc} \times E_{wc}$$

$$WC\left[\frac{Litre}{hh \times year}\right] = N_{wc} \times W_{wc}$$

$$DC\left[\frac{kg}{hh \times year}\right] = N_{wc} \times D_{wc}$$

C1. Usage characterization

To characterize the WM utilisation phase

$$WM_{Rec}\left[\frac{WM}{year}\right] = WM_{in,1} \times \sum_{i=1}^{i_{max}}\left(R_{EoL,i} \times R_{Rec,i} \times \prod_{l=1}^{i-1} R_{Rfb,l}\right)$$

$$WM_{Lnd}\left[\frac{WM}{year}\right] = WM_{in,1} \times \sum_{i=1}^{i_{max}}\left(R_{EoL,i} \times R_{Lnd,i} \times \prod_{l=1}^{i-1} R_{Rfb,l}\right)$$

C2. Stock and Flows

To characterize the Stock and Flows generated by the CE scenario (sales, refurbished, recycled and landfilled WMs)

$$\ldots] = GWP_{RME} \times WM_{in,1} - GWP_{Rec} \times WM_{Rec} + GWP_{M\&R} \times WM_{in,1} + GWP_{Dis} \times \ldots$$
$$+ (gwp_e \times EC + gwp_w \times WC + gwp_d \times DC) \times Shr \times WM_{stock}$$
$$+ (Y_{M\&R} \times GWP_{M\&R}) \times WM_{stock}$$
$$+ \sum_{i=2}^{i_{max}}\left((GWP_{Revlog} + GWP_{in,i} + GWP_{Dis}) \times WM_{in,i}\right) + GWP_{Lnd} \times WM_{Lnd}$$

I1. Environmental Impact

$$\left(\frac{BM_{sale} \times F_{sale,1}}{Shr} \times \frac{WM_{in,1}}{\sum_{i=1}^{i_{max}} WM_{in,i}}\right)$$
$$\left(\frac{BM_{ppu} \times F_{ppu,1}}{Shr} \times \frac{WM_{stock,1}}{WM_{stock}}\right) + \sum_i \left(BM_{ppu} \times F_{ppu,i} \times \frac{WM_{stock,i}}{WM_{stock}}\right)$$
$$\ldots \times \frac{Y_{M\&R} \times F_{M\&R}}{Shr}\Big) + \left(X_{neg} \times (c_e \times EC + c_w \times WC + c_d \times DC)\right)$$

I2. Economic Impact for the user

I3. Economic Impact for the Supply Chain

I4. Social Impact (Employment)

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SCENARIO DECISION VARIABLES

CIRCULAR ECONOMY LEVERS

Circular Product Design

1. Attachment and trust
2. Durability
3. Standardization
4. Maintenance / repair
5. Upgradability
6. Material Selection
7. Sustainable Behaviour
8. Disassembly and Recycling

Servitized Biz. Models

1. Product-oriented (maintenance, repair)
2. Use-oriented - Leasing
3. Use-oriented - Sharing
4. Result-oriented (pay-per-wash)

Supply Chain Management

1. Forward Logistics
2. Collaboration, partnership
3. Reverse Logistics

CIRCULAR ECONOMY ENABLING FACTORS

Digital 4.0 Technologies

1. IoT
2. Big Data & Analytics
3. Cloud
4. 3D Printing
5. Blockchain
6. AR and VR

Government Intervention

1. Legislation
2. Financial incentives
3. Green Public Procurement
4. Standards
5. Education
6. Metrics

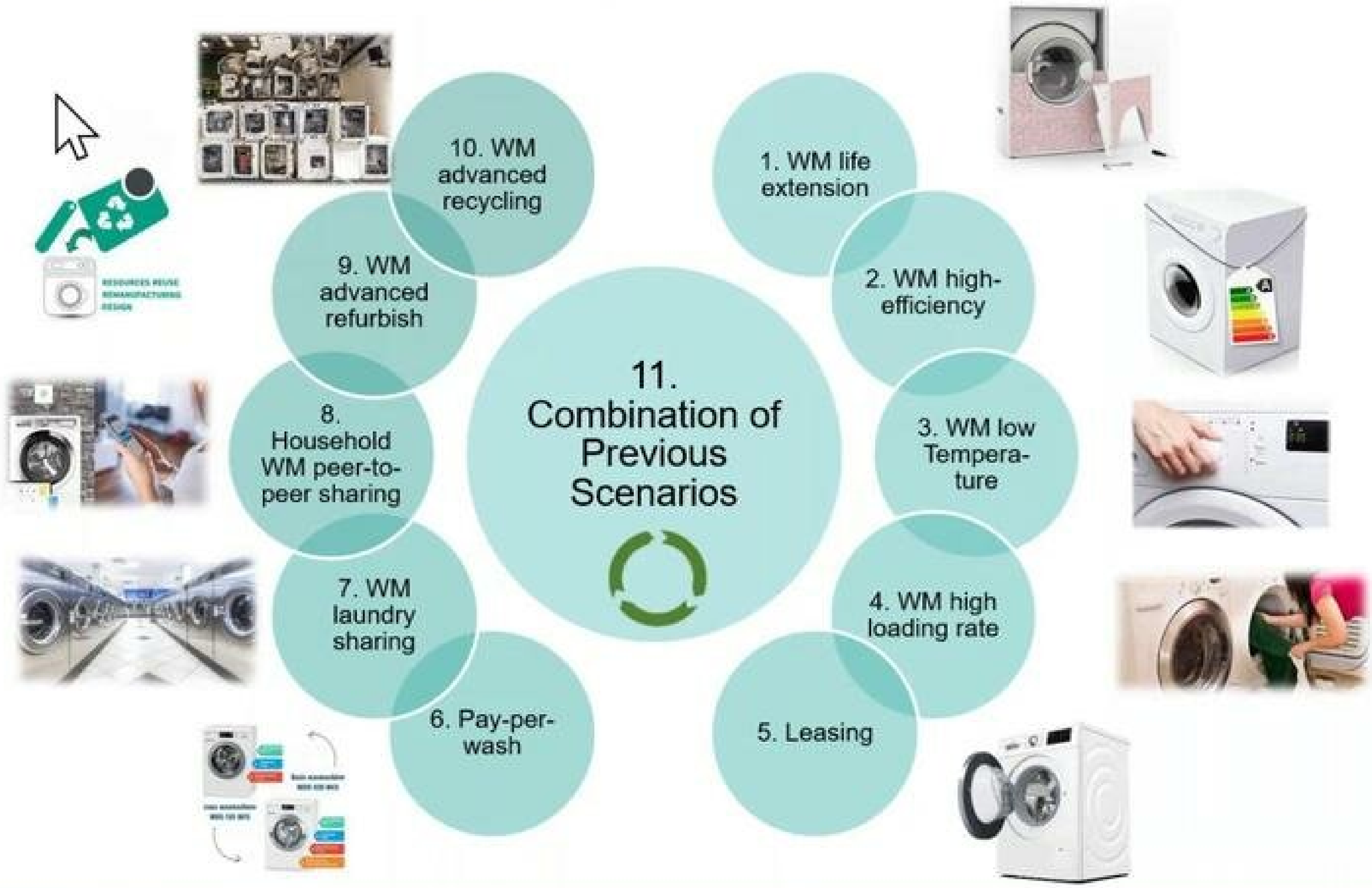
Users' active role

1. Green purchasing choice
2. Sustainable behaviour
3. EoL disposal

CIRCULAR ECONOMY SCENARIOS

10 + 1
Circular Economy Scenarios modelled and analysed compared to the ASI-IS

Assessment at the European Level (EU28)
Population of 510 million inhabitants



CIRCULAR ECONOMY SCENARIOS

		CIRCULAR ECONOMY Enabling Factors			CIRCULAR ECONOMY Levers		
ID	Scenario	Digital 4.0 Technology	Government Intervention	Users' Active Role	Product Design	Servitised Biz Model	Supply Chain Mgmt
1	Extend WM Lifespan			Extending WM lifespan	Durability	Maintenance and repair	
2	Replacing MWs with energy efficient ones		Legislation, Labelling	Purchasing A+++ WMs			
3	Sustainable beaviour (low wash temperature)			Users' behaviour	Sustainable behaviour		
4	Sustainable beaviour (adjusting capacity)			Users' behaviour	Sustainable behaviour		
5	Leasing WMs			Users' role in chose leasing		Leasing (use-oriented)	
6	Pay-per-wash	IoT and Big Data		Users' role in chose pay-per-wash		Pay-per-wash (result-oriented)	
7	Laundry facility (sharing)			Users' role in chose laundry		Sharing to reduce the WMs number	Collaboration with OEM
8	Sharing WMs peer to peer	IoT and Cloud		Users' role in chose sharing		Sharing to reduce the WMs number	
9	Refurbishment			Users' role in chose used WM			Reverse Logistics
10	Improved Recycling content	IoT to track products for collection	Forcing Legislation		Material Selection		Reverse Logistics
11	**Combination of previous scenarios**	**IoT, Big Data, Cloud**	**Driving legislation**	**Users' active role**	**Durability; Material; behaviour**	**Sharing to reduce the WMs number**	**Reverse Logistics**

EXAMPLE: PAY-PER-WASH SCENARIO
Scenario definition and parametrization

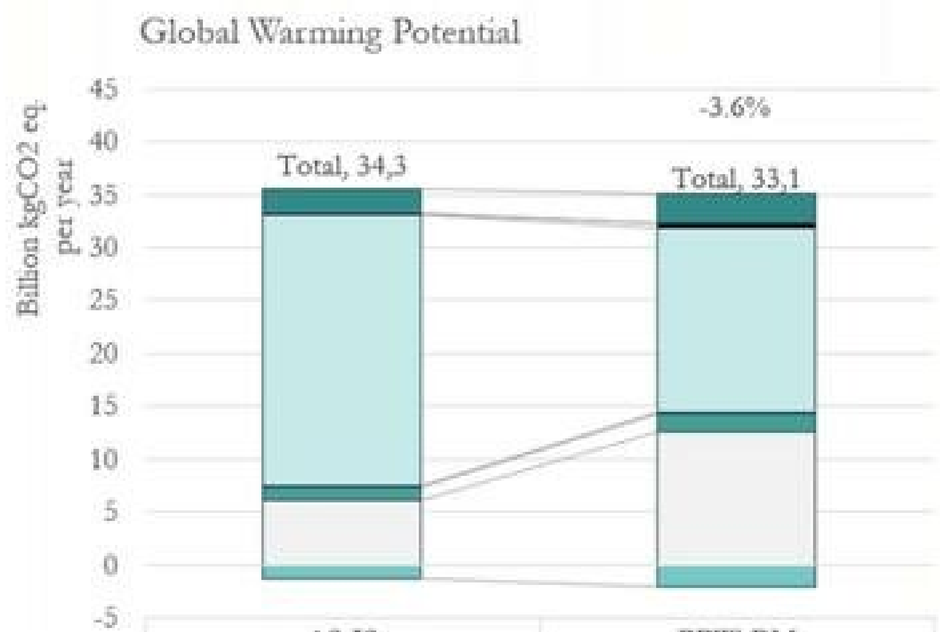
PAY PER WASH

In this scenario, users no longer buy and own a WM, but instead pays a variable fee to gain the rights to use a WM. The fee depends on the washing results achieved (pay-per-wash). Usually, top-quality and high-efficient WMs are offered through this business model.

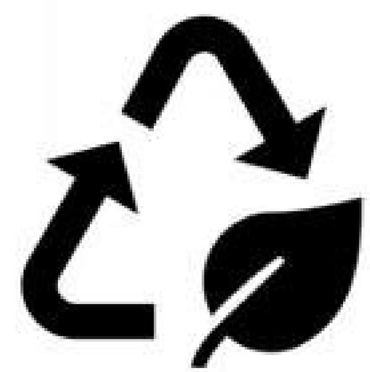
Assessment and comparison of the results to the EU28 AS-IS (Linear Economy)

Enabling Factor	Lever		Driver	
E1. Government intervention	L1. Circular Product Design	►	D1. Product	$C = 6.5\ kg$ $\boldsymbol{EEC = A++ \pm 30\%}$ $\boldsymbol{WEC = 90\%\ (from\ 100\%)}$ $\boldsymbol{DEC = 90\%\ (from\ 100\%)}$ $L_1 = 2.500\ wc$ $L_2 = 1.500\ wc$ $\Delta L_{M\&R,1} = 250\ wc$ $\Delta L_{M\&R,2} = 150\ wc$ $\boldsymbol{q_m = \{WM_{III}\}\ 'smart'}$ rec_m: see table (Table 8.2)
E2. Users' active role **Users' active role in choosing pay-per-wash**	**L2. Servitised Business Model** **Pay-per-wash Business Model**	►	D2. User	$YLW = 1{,}200\ kg$ $\boldsymbol{LR = 95\ \%\ (from\ 85\%)}$ $PPL = 510\ Mio$ $HS = 2.3$ $Shr = 1/0.90$ $T = 40\ °C$ $DDF = 100\%$ $SLmax_1 = 20$ $SLmax_2 = 10$ $\boldsymbol{BM_{sale} = 0\%}$ $BM_{ppm} = 0\%$ $\boldsymbol{BM_{ppw} = 100\%}$
E3. Digital 4.0 Technologies **IoT and Big Data & Analytics**	L3. Supply Chain Management	►	D3. Supply Chain	$R_{Rfb,1} = 5\ \%$ $R_{Rfb,2} = 0\ \%$ $R_{Rec,1} = 65\ \%$ $R_{Rec,2} = 55\ \%$ $\boldsymbol{Y_{M\&R} = 100\%\ (from\ 5\%)}$ $gwp_{x,m}$: see table (Table 8.2) $F_{RevLog} = 1.5$ $GWP\_Sav_{Rfb,2} = 70\ \%$ $\boldsymbol{P_{ppw} = 0.35\ €/wash}$

EXAMPLE: PAY-PER-WASH SCENARIO
I1. ENVIRONMENTAL IMPACT

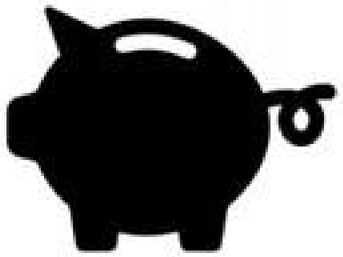


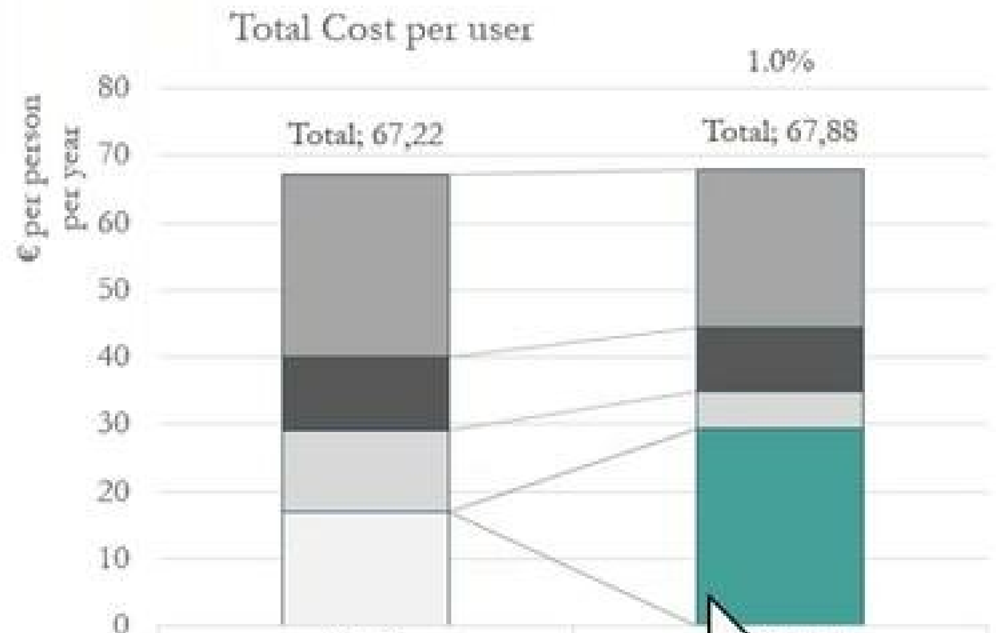
	AS-IS	PPW-BM
Landfilling	2.345.137.206	2.701.662.622
Refurbishment (incl. logistics)	40.739.759	42.473.744
Maintenance and Repair	24.856.930	503.554.496
Usage	25.597.101.672	17.435.603.679
Distribution	160.916.279	131.543.283
Manufacturing and Assembly	1.375.014.964	1.735.388.930
Credits for Recycling	-1.268.411.998	-2.003.666.673
Raw Materials Extraction	6.023.468.954	12.511.014.254
Total	34.298.823.766	33.057.574.336



- **Total GHG emissions reduced by the 3.6%**
- Impacts from use phase decrease (high-efficient washing machines)
- Raw materials extraction impact increases (high-quality washing machines)

EXAMPLE: PAY-PER-WASH SCENARIO
I2. ECONOMIC IMPACT FOR THE USER

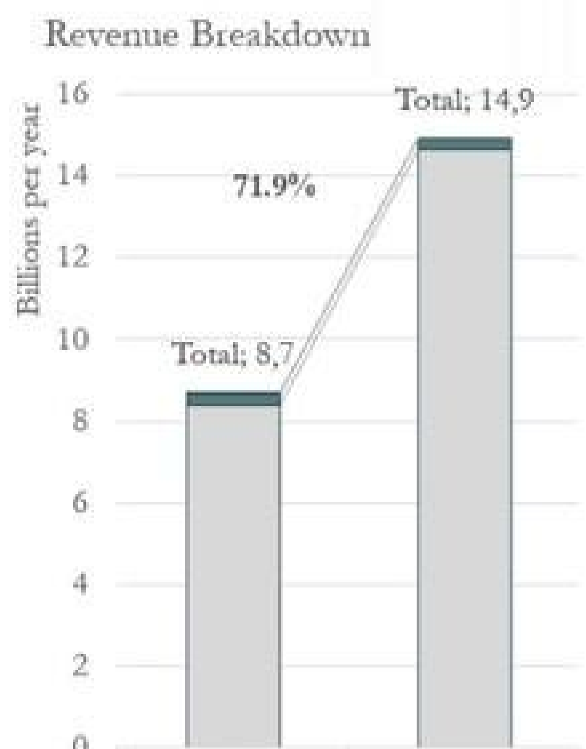




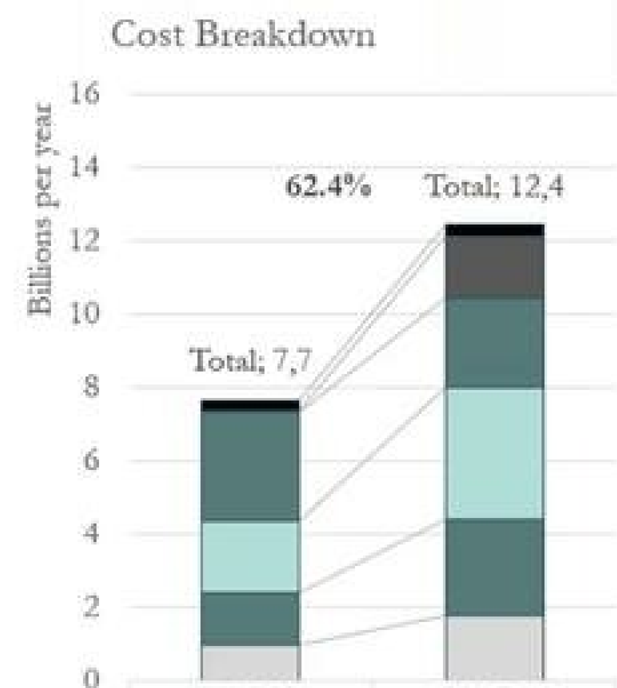
	AS-IS	W-BM
Detergent	27,10	23,43
Water	11,07	9,51
Energy	12,00	5,67
Maintenance and Repair	0,07	0,00
Pay-per-wash	0,00	29,27
Leasing	0,00	0,00
Sale	16,98	0,00
Total	67,22	67,88

- **The cost for users is (more or less) the same (67 €/year)**
- Change in the cost structure (from one-shot price to time-payments)

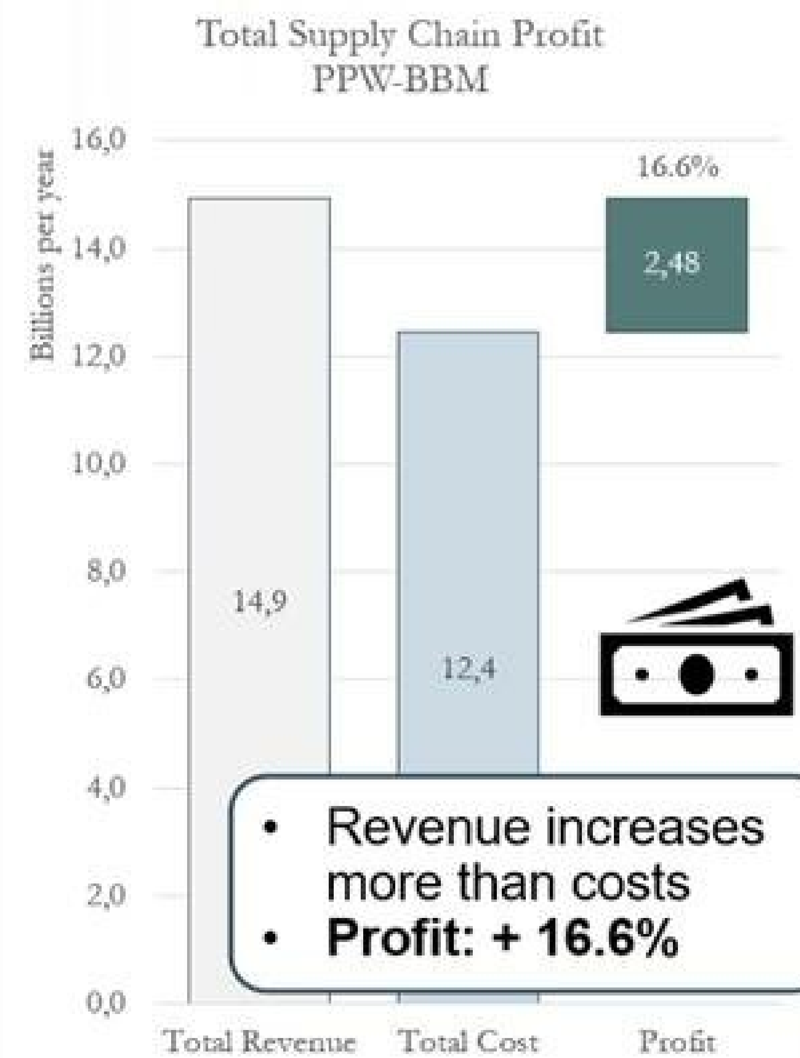
EXAMPLE: PAY-PER-WASH SCENARIO
I3. ECONOMIC IMPACT FOR THE SUPPLY CHAIN



	AS-IS	PPW-BM
M&R	37.418.478	0
Offering of 2nd-hand	272.172.275	285.530.204
Offering of 1st-hand	8.374.[illegible]1.538	14.642.574.550
Total	8.684.1[illegible]2.291	14.928.104.754

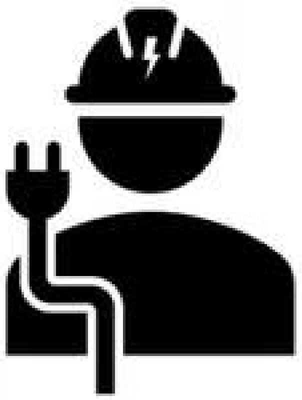


	AS-IS	PPW-BM
Refurbishment	297.761.121	328.982.519
M&R	37.418.478	1.683.831.522
Distribution	2.977.611.213	2.434.090.315
M&A	1.954.057.359	3.594.086.480
Recycling	1.438.671.241	2.646.139.754
Raw Materials	957.953.358	1.761.958.110
Total	7.663.472.771	12.449.088.701

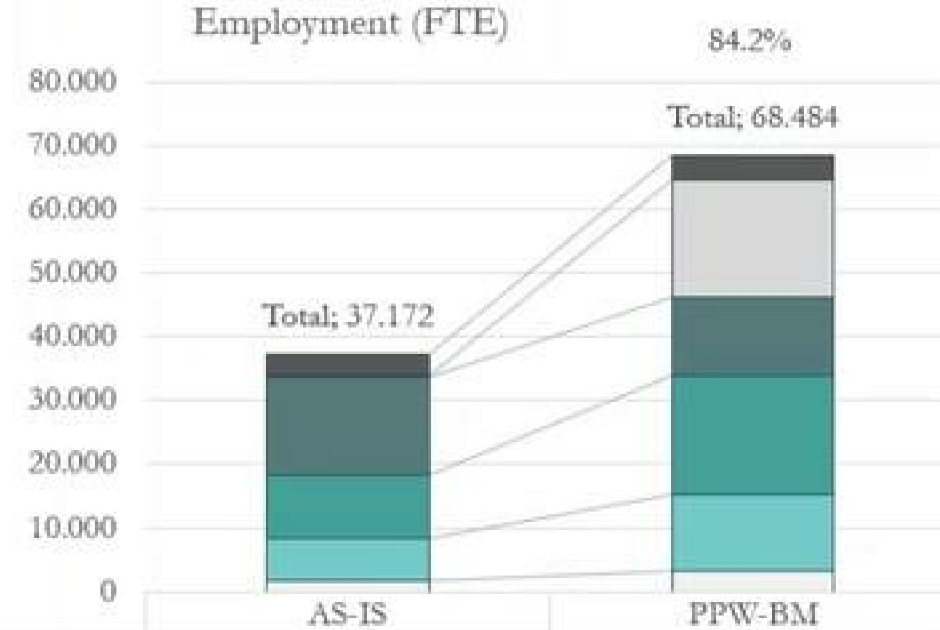


- Revenue increases more than costs
- **Profit: + 16.6%**

EXAMPLE: PAY-PER-WASH SCENARIO
I4. SOCIAL IMPACT

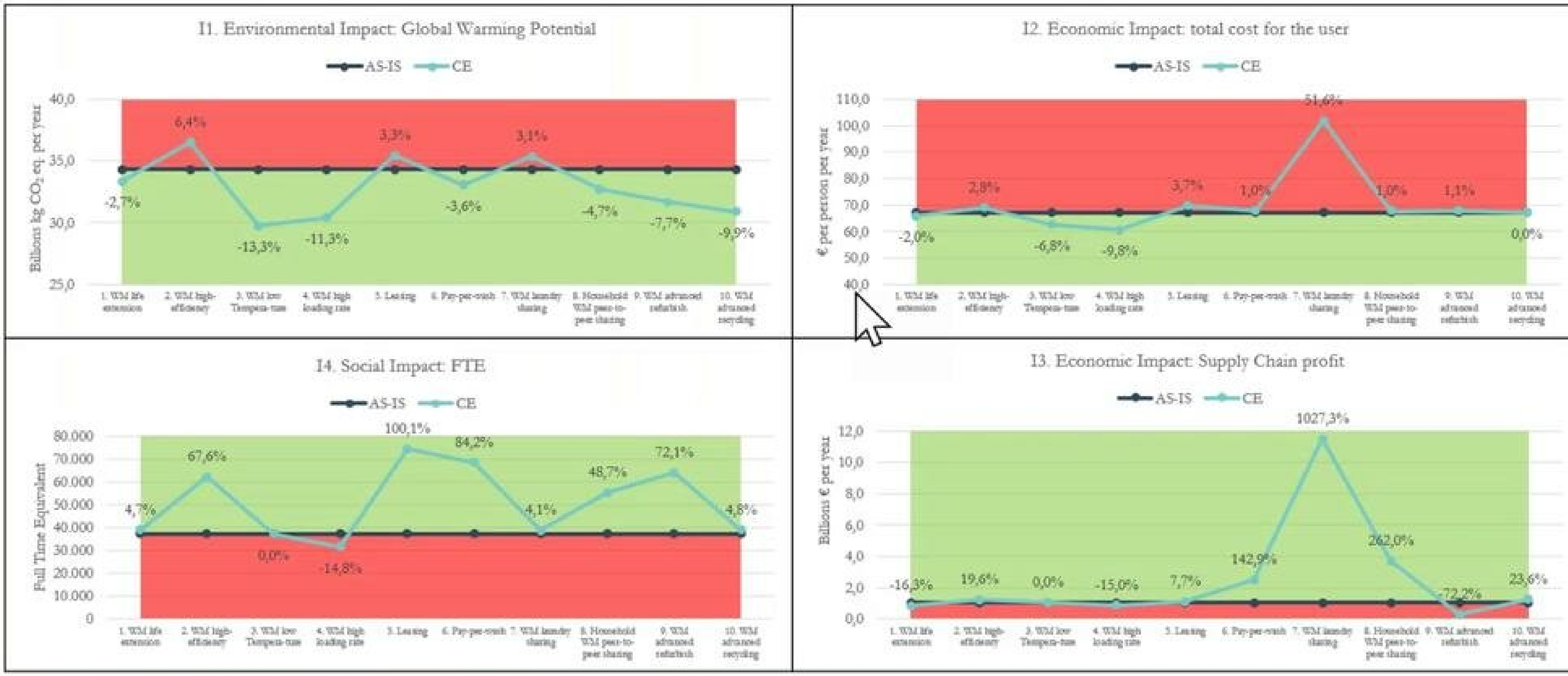


- **Employment opportunities increase by the 84.2%**
- Jobs are created especially in Maintenance and Repair (and production)

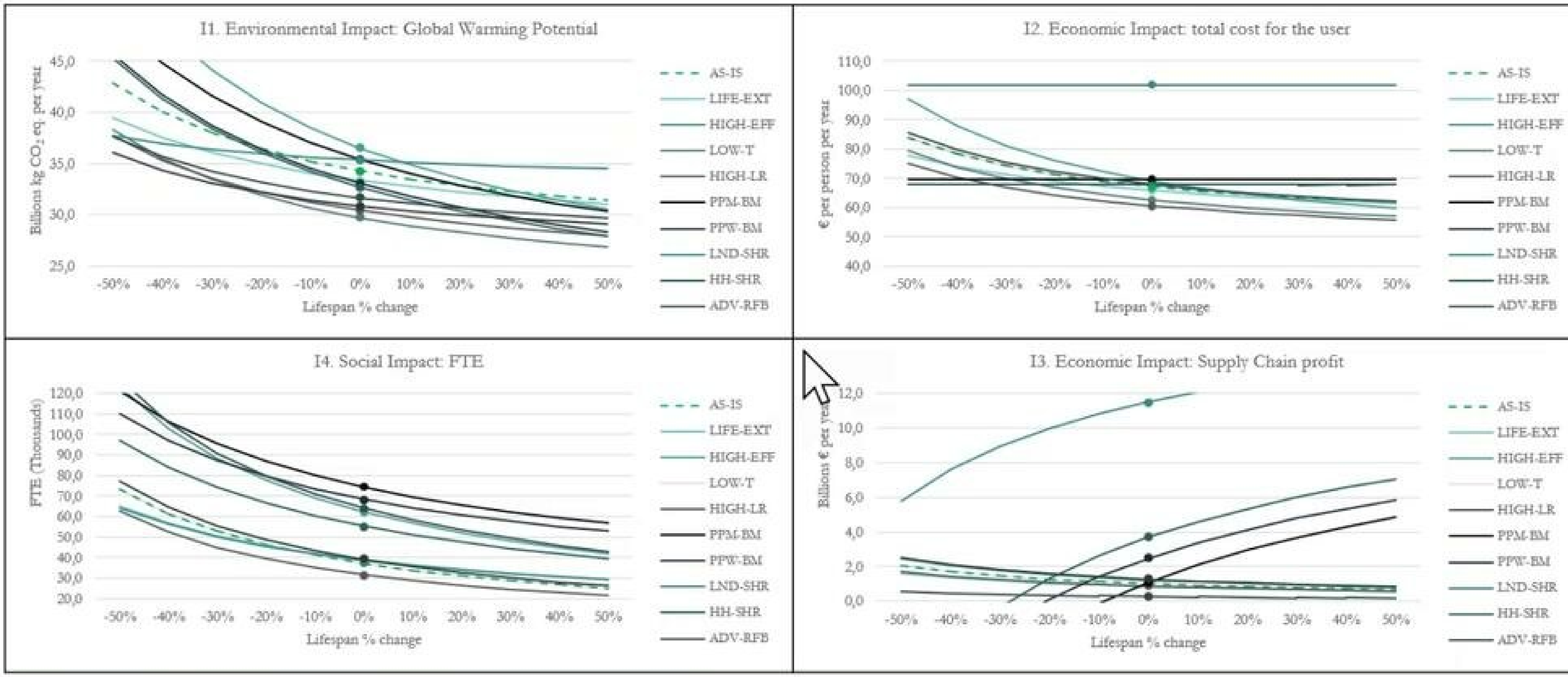


	AS-IS	PPW-BM
Refurbishment (including logistics)	3.161	3.876
Maintenance and Repair	407	18.303
Distribution	15.171	12.402
Manufacturing and Assembly	10.114	18.603
Recycling	6.524	11.999
Raw Material Extraction	1.795	3.302
Total	37.172	68.484

ELABORATION: SCENARIO COMPARISON



ELABORATION: SENSITIVITY ANALYSIS



ELABORATION: CASE STUDIES TESTING

	LAVA PIU LA LAVANDERIA SELF-SERVICE Miele	RI-GENERATION® ELETTRODOMESTICI CHE FANNO BENE
Retailer (pay-per-wash service provision)	Retailer (Laundry facility owner)	EoL actor (Refurbishment and Spare parts provision)
Distribution and service (ppw) →	Distribution and service (sharing) →	EoL refurbishment

CONCLUSION

RQ1

How the potential effects of a Circular Economy transition can be estimated ex-ante or evaluated ex-post?

- **Framework** to support the assessment of CE impacts (i.e. the '*Circular Economy Framework to Assess the Impacts*') by linking the economic, environmental and social impacts generated by a CE scenario to a set of Levers and Enabling Factor
- The framework supported the **Mathematical Formulation** needed to conduct the assessment in a systemic and holistic perspective
- The Mathematical Model has been implemented in a **Simulation Tool**

RQ2

Which are the most promising CE Levers and Enabling Factors and what are the potential benefits achievable?

- **Several CE scenarios for the WM industry were assessed**, using the simulation tool in which the mathematical model was implemented
- **Sensitivity analyses** on critical parameters as well as **three case studies** in the WM supply chain were carried out
- **Identification of promising hotspots in terms of CE scenarios that lead to 4-win impacts**

(MANY) NEXT STEPs

- More robust results
- Montecarlo simulation (to assess uncertainties)
- Dynamic simulation (e.g., system dynamics (?), agent-based (?))
- Extension to other products (electronics, cars, …)
- …

THANK YOU FOR THE ATTENTION
QUESTIONS?

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CONCLUSION

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