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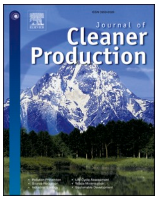

# Are digital servitization-based Circular Economy business models sustainable? A systemic what-if simulation model

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A R T I C L E I N F O

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A B S T R A C T

Manufacturing companies are struggling with the implementation of Circular Economy, especially due to the uncertainty regarding its potential sustainability benefits. In particular, and despite digital servitization is advocated by several studies as a way to achieve environmental gains, circular business models based on digital servitization are not always sustainable due to burden shifting and unexpected consequences which are difficult to assess before implementation. This is particularly relevant for the Electrical and Electronics Equipment industry, which suffers structural weaknesses such as the dependance on critical raw materials and an increasing waste generation. However, literature lacks models and tools able to address the complexity inherent in the systemic micro-macro perspective envisioned by Circular Economy, while studies that quantitatively assess the sustainability impacts and trade-offs of digital servitization-based circular scenarios are limited. This article aims to develop a better understanding of how the sustainability impacts of circular and servitized scenarios can be assessed and quantified at the economic, environmental, and social level, adopting a systemic perspective through the development of a what-if simulation model. The model is implemented in a spreadsheet tool and applied to a digital servitization-based Circular Economy scenario inspired by the case of a company offering long-lasting, high-efficient washing machines as-a-service. Results show that digital servitization can actually lead to a win-win-win situation with net positive effects to the environment, the society, and the economy. This result is based on the joint application of product design for digitalization and life extension, pay-per-use business models, and product reuse. These results are robust within a significant range of key parameters values. Practitioners and policymakers may use the model to support the evaluation of different circular and servitized scenarios before implementation.

## 1. Introduction

Circular Economy (CE) has reached increasing attention among academia and policymakers as a means to promote sustainability (Geissdoerfer et al., 2017). According to the European Circular Economy Action Plan, implementing CE actions has the potential to increase the EU GDP by an additional 0.5% by 2030, to create new jobs, and to augment companies profitability by reducing material costs (European Commission, 2020). Despite such a promising landscape, manufacturing companies are struggling with the implementation of CE at the micro level, and a limited application of the CE concept is observed at the macro level (Circle Economy, 2023). Servitized business models in particular have been indicated as a promising way to achieve environmental sustainability since, by leaving the product ownership to the provider, they enhance the lifetime extension of goods - e.g., through several usage cycles of reuse and refurbishment - and reduce the impacts in the usage phase - e.g. through increased availability and optimization of energy consumption (Tukker, 2015). The potential of servitization to increase sustainability can be further augmented by the adoption of digital technologies through the so-called ‘digital servitization’ (Gebauer et al., 2021; Kohtamäki et al., 2022).

However, one of the main factors hindering the implementation of CE is the uncertainty regarding the sustainability benefits that can be achieved by CE transition in the long run (Bressanelli et al., 2019). CE scenarios and in particular the ones based on digital servitization are not always sustainable, e.g., due to life cycle burden shifting and unexpected consequences which are difficult to assess without taking a systemic perspective (Kjaer et al., 2016; Matschewsky, 2019; Rigamonti and Mancini, 2021). The need to decrease the environmental impact through CE is particularly relevant for Electrical and Electronics Equipment

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(EEE), an industry with structural dependence on critical raw materials and huge Waste (WEEE) generation (Althaf et al., 2019; Baxter et al., 2016; Forti et al., 2020; Pollard et al., 2021). Recent research has dealt with the assessment of the sustainability impacts of CE scenarios in the (W)EEE industry, adopting different perspectives and methodologies (Mathur et al., 2020; Roci et al., 2022; Van Loon et al., 2020; Wasserbaur et al., 2020). Nevertheless, studies that quantitatively assess the impacts and trade-offs of CE scenarios with respect to the triple-bottom-line are limited, and quantitative models and tools capable of representing the systemic micro-macro perspective envisioned by CE are lacking (Howard et al., 2022; Schaubroeck et al., 2021). As well, whether and under which circumstances digital servitization-based CE business models can lead to improved environmental, economic, and social performance has not been thoroughly investigated by the literature.

Stemming from these gaps, the ambition of this paper is to develop a better understanding of how the sustainability impacts of circular and digital servitization scenarios can be assessed and quantified at the economic, environmental, and social level with a systemic perspective, through the development of a what-if simulation model. Two Research Questions are therefore formulated.

RQ1: How to assess the sustainability impacts of CE scenarios in a systemic way?
RQ2: In which conditions can CE business models based on digital servitization lead to win-win-win solutions on the triple bottom line?

The model has been developed and applied to the Washing Machine (WM) manufacturing industry and supply chain, given its high potential for CE implementation (Bracquené et al., 2020; Ellen MacArthur Foundation, 2012). The model has then been implemented in a spreadsheet tool, which has been used to assess the large-scale, industry-wide sustainability impacts of a digital servitization-based CE scenario for the EU27+UK[1] context. The application stem from the case study of a company offering WMs designed for higher efficiency and extended lifecycle through a subscription-based pay-per-use model. This model encourages users to do their laundry responsibly and to return WMs at the end of life for refurbishment.

The remainder of the paper is structured as follows. Section 2 provides the rationale for this study and a review of the literature on CE and on sustainability impact assessment methods employed in the (W)EEE industry. Section 3 outlines the research methodology. Section 4 describes the developed what-if simulation model and the experimentation process. Section 5 presents the results, which are discussed in Section 6. Lastly, conclusions are drafted in Section 7.

## 2. Theoretical background

### 2.1. *Designing and evaluating Circular Economy scenarios: a systemic perspective*

CE is usually described in literature as an ‘umbrella concept’ (Blomsma and Brennan, 2017) that comprises several strategies such as material recovery, energy efficiency, and the implementation of closed-loop cycles of reuse, remanufacturing, and recycling (Figge et al., 2023; Kirchherr et al., 2017). Manufacturing companies wishing to implement CE need to redesign their products, business models and supply chains (Bressanelli et al., 2021). Product life extension and eco-design should be employed to keep products, components and materials at their highest utility and value (Ardente and Mathieux, 2014; Mont, 2008; Pinheiro et al., 2019). The adoption of servitized business models such as leasing, sharing and pay-per-use encourage resource efficiency and product lifetime extension (Kjaer et al., 2019; Tukker, 2015). The integration of reverse logistics into conventional supply chains reduces waste and increases product reuse, remanufacturing, and recycling (Parajuly and Wenzel, 2017). Moreover, several enabling factors may favor the transition towards CE by companies, such as digital technologies (Bressanelli et al., 2018), users’ involvement (Amasawa et al., 2018), regulations and government intervention (Saidani et al., 2018). In particular, the adoption of digital technologies in combination with servitized business models leads to digital servitization (Kohtamäki et al., 2019). Digital servitization can bring substantial benefits on the environmental dimension of sustainability. As an example, IoT and Big Data-enabled functionalities within an ‘as-a-service’ offering may lead to increased resource efficiency, extending the lifespan or closing the loop (Bressanelli et al., 2018), while digital platforms allow offering integrated solutions both to industrial and private customers (Kohtamäki et al., 2022).

System-thinking has been indicated as one of the main requirements for successfully adopting the CE paradigm in manufacturing companies (Lieder and Rashid, 2016). A systemic view encompassing the entire value network, as well as the different elements involved in the system and their relationships is in fact needed (Fraccascia et al., 2019; Hopkinson et al., 2020). Implementing one circular action in isolation and without such systemic perspective may prevent the achievement of the intended sustainability benefits on the triple bottom line (Bressanelli et al., 2021; Lieder et al., 2017). For instance, extending the product life without altering the company business model runs the risk of reducing economic profitability, since product life extension will result in cannibalization and lower sales (Bressanelli et al., 2019). As well, the remanufacturing of products that have not been specifically designed in a modular way might be environmentally and economically challenging, because product dismantling and reassembly may imply greater environmental impacts and more costs compared to the achievable benefits (Mont, 2008). Alternatively, the expected environmental benefits of product reuse may be jeopardized by the absence of a proper and functional reverse logistics system, since more transportation may be required (Krikke, 2011).

Therefore, there is the need to adopt a systemic perspective when designing and evaluating CE scenarios. First, as mentioned above, several actions, levers and enabling factors need to be combined (Bressanelli et al., 2021), to avoid the risk of not achieving the expected benefits. Secondly, all the three pillars of economic, environmental, and social sustainability should be considered when evaluating the implementation of CE scenarios, following the triple bottom line perspective (Joyce and Paquin, 2016), to ensure that scenarios are truly sustainable (Korhonen et al., 2018). Finally, different CE implementation levels, ranging from the micro (single product, single company, single customer) to the meso (supply chain) and macro (regional), should be jointly analyzed (Ghisellini et al., 2016), to ensure that sustainability benefits are achieved at different layers in an integrated or complementary way (Desing et al., 2020).

### 2.2. *Assessing the sustainability impacts of Circular Economy scenarios in the (W)EEE industry*

CE scenarios designed with a systemic perspective may entail sustainability benefits to the environment, the economy, and the society. In the (W)EEE industry, earlier research assessed and quantified the sustainability impacts of CE scenarios, covering different angles. Table 1 illustrates to which extent these studies adopted a systemic approach at the CE actions, benefits assessment, and scope levels, illustrating the emerging gaps.

Several methodologies have been employed for sustainability impact assessment, ranging from static Life Cycle Assessment (LCA) and Costing (LCC) analyses to dynamic modelling and stock and flows simulations. LCA evaluates the environmental impact of a product throughout its entire life cycle, with the aim to identify potential areas for environmental improvement (ISO 14040, 2021). LCC, on the other hand, is a

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[1] The EU27+UK is the political and economic union of 27-member states that are located primarily in Europe plus the United Kingdom after Brexit.

**Table 1**
Previous literature on the sustainability impact assessment of Circular Economy in the (W)EEE industry.

| Article | Aim | Methodology | Perspective | | |
|---|---|---|---|---|---|
| | | | Actions | Benefits | Scope |
| Van Loon et al. (2020) | Investigate manufacturers and users' profitability of leasing and remanufacturing washing machines | Analytical model | Servitized business model and supply chain levers - Product remanufacturing of leasing and buying business models of premium, economy, and budget washing machines | Economic for the supply chain (manufacturer profitability); Economic for the users (consumer costs without consumables) | Micro (washing machines) |
| Klint and Peters (2021) | Examine the potential for shared systems to reduce the environmental impacts of laundry activities | Life Cycle Assessment | Servitized business models and users' active role - Sharing (private vs shared laundry) and the effects of consumers choices during machine operation | Environmental ($CO_2$ emissions) | Micro and macro (washing machines' and tumble dryers' operation in Sweden) |
| Otterbach and Fröhling (2024) | Quantify the environmental benefits of washing-as-a-service business models | Life Cycle Assessment | Servitized business models and product design (leasing, product life extension, pay-per-wash) | Environmental (ReCiPe, 2016 impact assessment method) | Macro (washing machines in Germany) |
| Bressanelli et al. (2022) | Assess the economic and environmental impacts of pay-per use and refurbishment business models, while investigating the degree of users' acceptance and factors influencing it | Analytical evaluation model and logistic regression | Servitized business models and supply chain levers - Pay-per-use and refurbishment business models | Economic for the users (Total Cost of Ownership); Environmental ($CO_2$ emissions) | Micro (washing machines in Italy) |
| Sigüenza et al. (2021) | Assess the material and environmental gains of the long-term and potentially large-scale adoption of leasing and pay-per-use circular business models in the Dutch market | Dynamic Life Cycle Assessment modelling | Servitized Business Model - Leasing and pay-per-use circular business models with lifetime extension | Environmental (material use and climate change) | Macro (washing machines in the Netherlands) |
| Boldoczki et al. (2021) | Investigate under which circumstances increasing the circularity of EEE (by setting reuse targets) lead to environmental benefits | Combination of dynamic material flow analysis and Life Cycle Assessment | Supply chain levers - Product reuse | Environmental (ReCiPe, 2016 impact assessment method and cumulative energy demand) | Macro (washing machines in Germany) |
| Glöser-Chahoud et al. (2021) | Assess the effect of modifications in service lifetimes and use structures of refrigerators and mobile phones on their environmental performance | Dynamic material flow analysis and Life Cycle Assessment | Product design - Lifetime optimization | Environmental ($CO_2$ emissions over the entire product life cycle) | Macro (refrigerators and mobile phones at a European level) |
| Mathur et al. (2020) | Assess the circularity of the photovoltaic panel industry by proposing the notion of Life Cycle symbiosis | Life Cycle Assessment coupled with industrial symbiosis | Supply chain management - End of Life strategy (recycling) | Environmental ($CO_2$ emissions and ecotoxicity impacts) | Macro (photovoltaic panels in North America) |
| Wasserbaur et al. (2020) | Analyze the environmental benefits of a large-scale shift from a washing machines ownership-based model to an access-based household laundry scenario | System Dynamics | Servitized business models - Product sharing with different ownership rates | Environmental ($CO_2$ emissions) | Macro (washing machines operation in Swedish and European contexts) |
| Guzzo et al. (2021) | Provide a System Dynamics model for the quantification of the effects of the implementation of CE strategies on nationwide stocks and flows of EEE to evaluate full decoupling | System Dynamics | Supply chain and product design - Product reuse, remanufacturing, and recycling; product lifespan shortening and extension | Environmental (WEEE stocks and flows) | Macro (flat display panel TVs in the Netherlands) |
| Guzzo et al. (2022) | Evaluate how the implementation of CE interventions focused on collecting products at the end of life helps meeting the Brazilian targets for WEEE collection and treatment | System Dynamics | Supply chain and users' active role (WEEE collection interventions) | Environmental (WEEE stocks and flows) | Macro (smartphones in Brazil) |
| Lieder et al. (2017) | Assess different circular design strategies considering various circular business models | Multi-method simulation approach (Agent-Based and Discrete Event) | Servitized business models and supply chain management - Reuse, remanufacturing, and recycling at component level in a buy-back, leasing, and pay-per-use supply chain setting | Economic for the supply chain (lifecycle costs); Environmental (CO2 emissions) | Micro (washing machine case study) |
| Roci et al. (2022) | Propose a multi-method model architecture for the systemic exploration and quantification of Circular Manufacturing Systems economic and environmental impacts. | Multi-method simulation approach (Agent-Based, Discrete-Event and System Dynamics) | Servitized business models, product design and supply chain management - Service-based business model that includes long-lasting washing machines designed to facilitate multiple lifecycles through reuse | Economic for the supply chain (life cycle revenues and costing); Environmental ($CO_2$ emissions) | Micro (100 washing machines provided in a subscription-based scheme) |
| Roci and Rashid (2023) | Assess the economic and environmental impact of circular business models to investigate the | Multi-method simulation modelling (Agent-Based, Discrete-Event and System | Servitized business models - Service-based business model with different schemes (fixed fee, pay- | Economic for the supply chain (life cycle costing and revenues); | Micro (100 washing machines offered as a service) |

(continued on next page)

Table 1 (*continued*)

| Article | Aim | Methodology | Perspective | | |
|---|---|---|---|---|---|
| | | | Actions | Benefits | Scope |
| | effect of payment schemes and subscription contract duration | Dynamics) with statistical design and analysis of experiments | per-use, hybrid fixed and variable fee) and different contract duration (short, mid- long-term) | Environmental ($CO_2$ emissions) | |

financial analysis technique used to assess the Total Cost of Ownership (TCO) of a product over its entire life cycle, considering not only the initial purchase cost but also the costs associated with installation, operation, maintenance, and disposal (Brusselaers et al., 2020; Saccani et al., 2017). Van Loon et al. (2020) developed an analytical model to estimate the LCC for consumers and the profits for manufacturers generated through the leasing of remanufactured white goods. Klint and Peters (2021) used LCA to assess the environmental potential of sharing WMs in Sweden and the effects of consumers choices during machines operation. Otterbach and Fröhling (2024) adopted LCA to quantify the environmental benefits of product-as-a-service business models for WMs in Germany. Bressanelli et al. (2022) assessed the economic and environmental impacts of pay-per use and refurbishment business models through a users' TCO and a product LCA model. LCA has been often combined with dynamic modelling of materials flows and stocks, to provide the environmental performances over time of large-scale, macro systems. Sigüenza et al. (2021) adopted a dynamic LCA modelling to assess the material and environmental gains of the long-term and large-scale adoption of leasing and pay-per-use models in the Dutch market, using WM as a case study. Boldoczki et al. (2021) combined LCA with dynamic material flow analysis to investigate under which circumstances setting targets for WEEE reuse leads to circular and environmental benefits in Germany. Glöser-Chahoud et al. (2021) merged dynamic material flow analysis with LCA to assess the effect of modifications in service lifetimes of refrigerators and mobile phones on their environmental performance at a European level. Mathur et al. (2020) merged LCA with industrial symbiosis for assessing the circularity of the photovoltaic panel industry. To model complex systems, some authors have resorted to System Dynamics, which is a computer-based modeling approach that help studying the behavior of systems over time and understanding their feedback loops (Forrester, 1961). Guzzo et al. (2021) developed a System Dynamics model for the quantification of the environmental effects (WEEE stock and flows) of the implementation of CE strategies for flat display panel TVs in Netherlands. Guzzo et al. (2022) further refined this System Dynamics model to evaluate the implementation of CE interventions focused on collecting smartphones at the end of life and their effects on the Brazilian targets for WEEE collection and treatment. Wasserbaur et al. (2020) adopted System Dynamics to analyze the environmental benefits (reduction of $CO_2$ emissions) of a large-scale shift from WMs ownership to an access-based household laundry scenario. Lastly, some attempts have been made to combine different dynamic simulation methodologies into multi-method assessments, including System Dynamics, Discrete Event and Agent-Based modelling. Discrete Event is a modeling and simulation technique that is adopted to study systems that change state over time due to the occurrence of discrete events, while Agent-Based is a computational modeling technique used to simulate the behavior and interactions of autonomous individual entities (agents) within a system, where each agent has its own set of rules, behaviors, and decision-making capabilities. Lieder et al. (2017) adopted a multi-method simulation approach to assess the economic and environmental performance of reuse, remanufacturing, and recycling strategies using WM as a case study. Roci et al. (2022) proposed a multi-method model architecture for the quantification of economic and environmental impacts of service-based business models simulating the performance of 100 WMs provided in a subscription-based scheme. Roci and Rashid (2023) improved this multi-method model to investigate the effect of different payment schemes and subscription contract duration on the economic and environmental performance of circular business models for WMs.

While these efforts are commendable, they present limitations. In particular, previous research on the sustainability impact assessment of CE scenarios in the (W)EEE industry lacked a systemic approach in terms of simultaneous consideration of the effects of CE actions, the evaluation of sustainability benefits at the triple bottom line, and combined adoption of a micro-meso-macro scope, as reported in the last three columns in Table 1. Most papers, in fact, have investigated servitized business models, product design or product end-of-life strategies in isolation, this way not unveiling the full potential of a systemic CE transition. Moreover, while almost all the articles analyzed have addressed the quantification of environmental impacts, very few dealt with the economic implications for users and for the supply chain, and none with the social sphere of sustainability. These aspects are however needed to provide a complete sustainability outlook and guide policy and industry decision-makers. Concerning the scope, most articles adopted either a micro (single product, single company, single user) or macro (geographical region) perspective. Therefore, and although several literature reviews in the (W)EEE industry stress the need to simultaneously investigate and quantify the economic, environmental and social impacts of CE scenarios (Bressanelli et al., 2021; Rosa et al., 2019), whether CE can contribute in the long run to sustainability under a win-win-win strategy with respect to the triple-bottom-line still remains an open question. To address this issue, the development of models able to quantitatively assess in a consistent way the micro and macro, industry-wide application of CE business models is still needed (Sigüenza et al., 2021), and therefore is addressed in this research.

## 3. Materials and method

To address the abovementioned gaps, this paper develops and applies a what-if simulation model to a digital servitization scenario. Simulation is an increasingly relevant methodological approach to theory development in business strategy, organization, and operations management (Wayne, 2004). It is a technique that uses computer software to imitate the operation of real-world systems (Davis et al., 2007). To develop novel insights through simulation, literature suggests following several phases, including the definition of research questions and the identification of theories to address them; the selection of a suitable simulation approach; the creation of a simulation model through computational representation; model verification; experimentation; and the validation of simulation results (Davis et al., 2007). As a first step, previous Sections formulated the Research Questions and provided the theoretical frameworks for this research.

The selection of an appropriate simulation approach depends on the model purpose and on the questions it is intended to answer (Roci et al., 2022). In this case, the purpose is to carry out what-if scenario analyses comparing linear and CE business models in a systemic perspective, to evaluate the potential of circular scenarios and assess their long-term sustainability in the steady state. Spreadsheet simulation can be used to address this need (Seila, 2006; Wayne, 2004), and has therefore been chosen as the simulation approach for this research. In addition, spreadsheet simulation is appropriate for dealing with the high level of detail complexity (Grösser, 2017) that is generated by the large number of elements and relations considered when adopting a systemic approach encompassing CE actions, benefits, and scope.

A what-if simulation model has been built to enable the

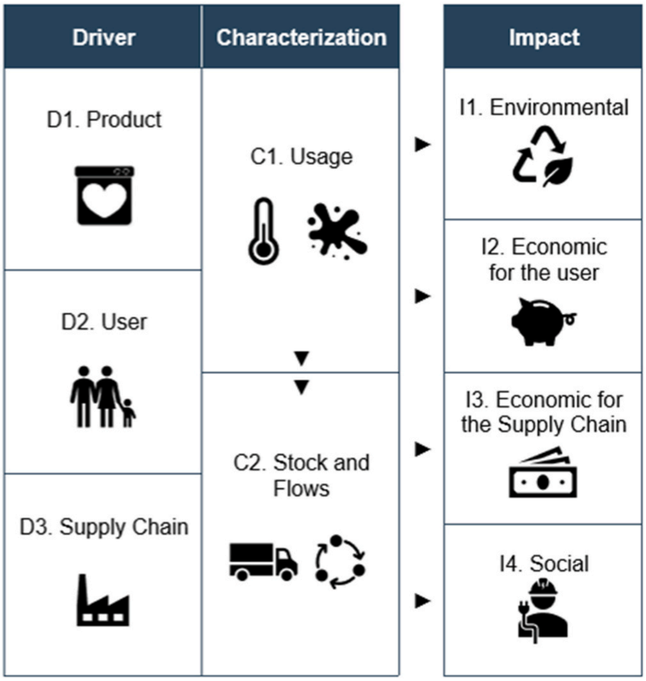


**Fig. 1.** Simulation model blocks: configuration drivers, characterization, impacts.

quantification and comparison of different linear and circular scenarios in steady state. The model has been developed for the WM supply chain to provide a practical example. It links the economic, environmental, and social impacts generated by a CE scenario to a set of configuration drivers (Fig. 1). Four blocks of measurable impacts are modelled and considered for comparing scenarios in a systemic perspective. The *environmental impact* block (I1) assesses the carbon footprint connected to one year of households' clothes washing. The *economic impact for the user* block (I2) covers the user's perspective by evaluating the yearly costs that a single user pays for clothes washing. The *economic impact for the supply chain* (I3) draws an estimation of the overall WM supply chain margin. The *social impact* block (I4) computes an estimation of the overall job opportunities that are potentially generable in each tier of the WM supply chain. To assess these impacts, the *usage phase* of WMs (C1) and the WM *stock and flows* (C2) need to be characterized. These characterization blocks support the quantification of the impacts by quantifying the relevant intermediary parameters and variables needed to carry out the scenarios sustainability assessment. Lastly, characterization blocks are fueled by appropriate configuration drivers, which provide the inputs for the assessment. They have been grouped in three blocks, which define the configuration options of the *product* (D1), of the *user* (D2) and of the *supply chain* (D3).

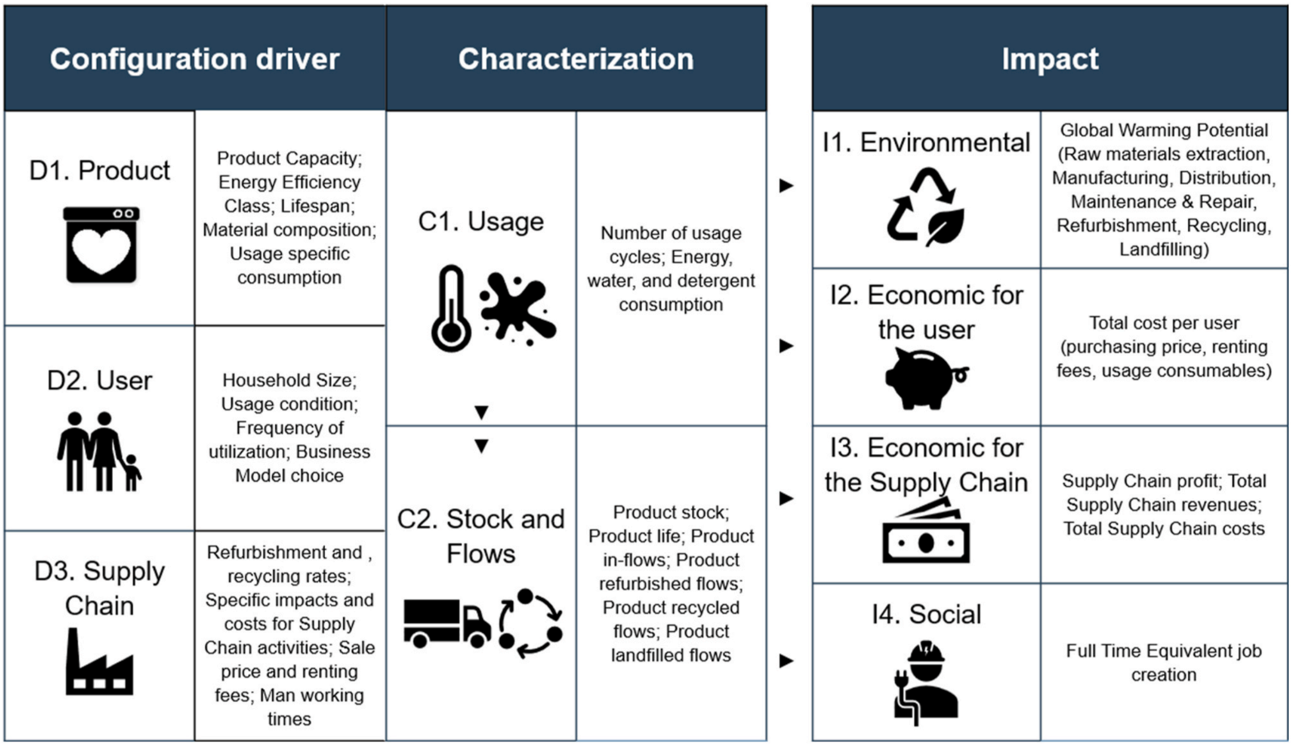
Several capabilities from well-known modelling approaches have been combined and included in the what-if simulation model. To guarantee scenarios comparability, the definition of a functional unit and the setting of consistent system boundaries have been taken from the LCA framework (ISO 14044, 2021; Maliqi et al., 2024). For this analysis, the functional unit has been defined as "*one year of households' clothes washing for a defined population*". System boundaries include all the processes that are needed to deliver the desired function (i.e., clean clothes), including WMs production, distribution, use, maintenance, collection, recovery, and disposal. The formulation of economic indicators has been supported by LCC and TCO methodologies (Lindahl et al., 2014; Saccani et al., 2017). Stock and flows evaluations were inspired by Material Flow Analysis and System Dynamics methodologies. Their principles have been adopted to characterize products and materials flows as well as their accumulation in the system (stock), through the operationalization of the theoretical constructs about WM stock, WM in-flows, WM out-flows, and WM lifespans. The overall model has been implemented through computational algorithms in the spreadsheet tool downloadable from the Supplementary Material. The full formulation and nomenclature used to model the indexes, parameters, and variables is available in the Supplementary Materials.

The model has been then verified to confirm its accuracy, robustness and internal validity (Davis et al., 2007). Simple evaluations by varying one parameter of the model at a time have been checked and replicated with simulation results. Variables (such as stock and flows) have been tracked and visualized at intermediate simulation steps, to check their evolution and evaluate their consistency. Robustness checks have been also carried out by running simulation at extreme parameters values (Wayne, 2004).

Experimentation has been carried out to develop theory and answer RQ2 ('*in which conditions can CE business models based on digital servitization lead to win-win-win solutions on the triple bottom line?*'). A what-if

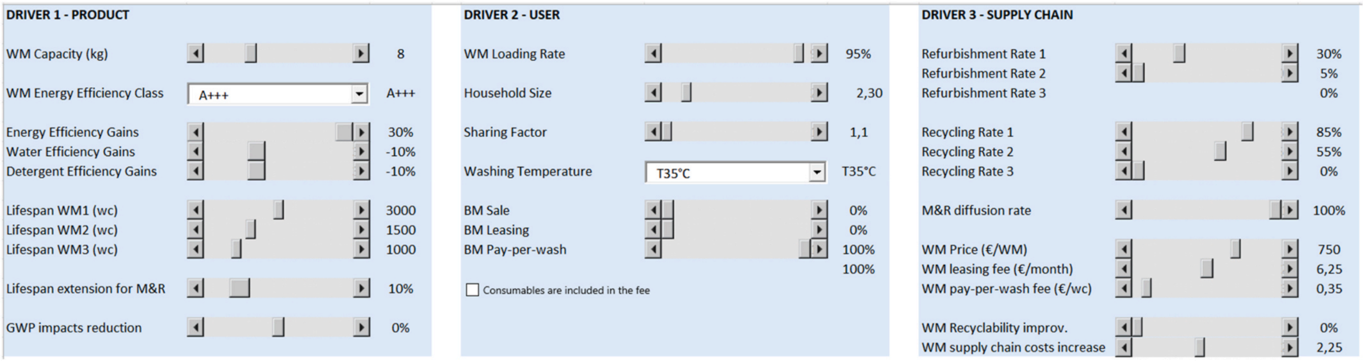
**Table 2**
Validation process and results.

| Dimension | Aspect | Process | Result |
|---|---|---|---|
| Reliability | Completeness | Articles specifically dealing with WMs have been scrutinized to check the completeness of the model (Boyano et al., 2017; Pakula and Stamminger, 2015, 2010; Presutto et al., 2007; Stamminger, 2011; VHK, 2016).<br>Comparison between the parameters included in the model with scientific literature on sustainability impact assessment in the (W) EEE industry (Table 1). | The model includes all the relevant variables and parameters identified in the literature. The completeness is also confirmed by the case study. |
| | Correctness | The formulae used were checked against the reference literature (Boyano et al., 2017; Pakula and Stamminger, 2015, 2010; Presutto et al., 2007; Stamminger, 2011; VHK, 2016).<br>The mathematical model was translated into a spreadsheet simulation tool in MS Excel, and simulations results were double-checked manually.<br>Sensitivity analyses on critical parameters were carried out, to search for errors in the model. | The formulation as well as the computation proved to be correct. No unexpected relationships between inputs and outputs were encountered. |
| | Consistency | Results obtained for similar parameters with similar characteristics were compared. | Similar parameter values lead to similar results. |
| Usefulness | Decision support | Assessment of whether the spreadsheet simulation tool can support informed decision-making. | The results showed that the application provides valuable insights for managers and for policymakers. |
| | Applicability | Evaluation of whether the model can be used in practice. | The simulation tool was used in several case studies in the WM industry and within students' workshops to derive managerial implications. |



| Configuration driver | | Characterization | | Impact | |
|---|---|---|---|---|---|
| D1. Product | Product Capacity; Energy Efficiency Class; Lifespan; Material composition; Usage specific consumption | C1. Usage | Number of usage cycles; Energy, water, and detergent consumption | I1. Environmental | Global Warming Potential (Raw materials extraction, Manufacturing, Distribution, Maintenance & Repair, Refurbishment, Recycling, Landfilling) |
| D2. User | Household Size; Usage condition; Frequency of utilization; Business Model choice | | | I2. Economic for the user | Total cost per user (purchasing price, renting fees, usage consumables) |
| D3. Supply Chain | Refurbishment and , recycling rates; Specific impacts and costs for Supply Chain activities; Sale price and renting fees; Man working times | C2. Stock and Flows | Product stock; Product life; Product in-flows; Product refurbished flows; Product recycled flows; Product landfilled flows | I3. Economic for the Supply Chain | Supply Chain profit; Total Supply Chain revenues; Total Supply Chain costs |
| | | | | I4. Social | Full Time Equivalent job creation |

**Fig. 2.** Model composition.



**DRIVER 1 - PRODUCT**

| | |
|---|---|
| WM Capacity (kg) | 8 |
| WM Energy Efficiency Class | A+++ |
| Energy Efficiency Gains | 30% |
| Water Efficiency Gains | -10% |
| Detergent Efficiency Gains | -10% |
| Lifespan WM1 (wc) | 3000 |
| Lifespan WM2 (wc) | 1500 |
| Lifespan WM3 (wc) | 1000 |
| Lifespan extension for M&R | 10% |
| GWP impacts reduction | 0% |

**DRIVER 2 - USER**

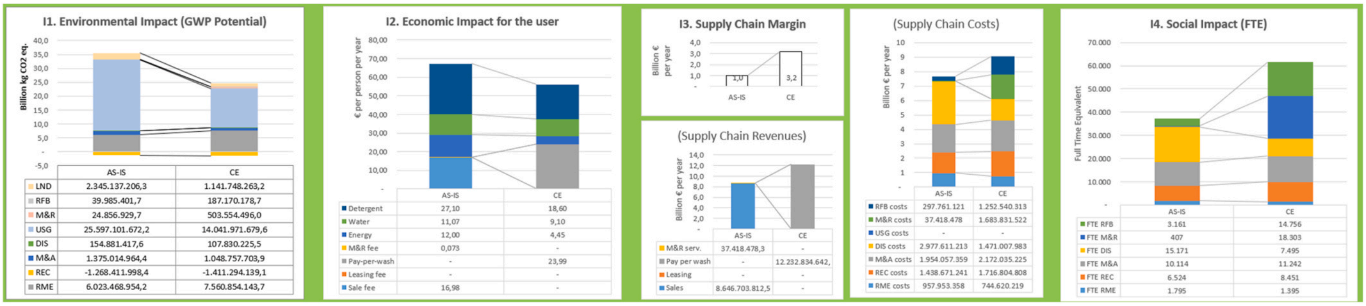
| | |
|---|---|
| WM Loading Rate | 95% |
| Household Size | 2,30 |
| Sharing Factor | 1,1 |
| Washing Temperature | T35°C |
| BM Sale | 0% |
| BM Leasing | 0% |
| BM Pay-per-wash | 100% |
| | 100% |

☐ Consumables are included in the fee

**DRIVER 3 - SUPPLY CHAIN**

| | |
|---|---|
| Refurbishment Rate 1 | 30% |
| Refurbishment Rate 2 | 5% |
| Refurbishment Rate 3 | 0% |
| Recycling Rate 1 | 85% |
| Recycling Rate 2 | 55% |
| Recycling Rate 3 | 0% |
| M&R diffusion rate | 100% |
| WM Price (€/WM) | 750 |
| WM leasing fee (€/month) | 6,25 |
| WM pay-per-wash fee (€/wc) | 0,35 |
| WM Recyclability improv. | 0% |
| WM supply chain costs increase | 2,25 |

**Fig. 3.** Screenshot of the spreadsheet simulation tool: scenario parametrization (drivers).



I1. Environmental Impact (GWP Potential)

| | AS-IS | CE |
|---|---|---|
| LND | 2.345.137.206,3 | 1.141.748.263,2 |
| RFB | 39.985.401,7 | 187.170.178,7 |
| M&R | 24.856.929,7 | 503.554.496,0 |
| USG | 25.597.101.672,2 | 14.041.971.679,6 |
| DIS | 154.881.417,6 | 107.830.225,5 |
| M&A | 1.375.014.964,4 | 1.048.757.703,9 |
| REC | -1.268.411.998,4 | -1.411.294.139,1 |
| RME | 6.023.468.954,2 | 7.560.854.143,7 |

I2. Economic Impact for the user

| | AS-IS | CE |
|---|---|---|
| Detergent | 27,10 | 18,60 |
| Water | 11,07 | 9,10 |
| Energy | 12,00 | 4,45 |
| M&R fee | 0,073 | - |
| Pay-per-wash | - | 23,99 |
| Leasing fee | - | - |
| Sale fee | 16,98 | - |

I3. Supply Chain Margin

(Supply Chain Revenues)

| | AS-IS | CE |
|---|---|---|
| M&R serv. | 37.418.478,3 | - |
| Pay per wash | - | 12.232.834.642, |
| Leasing | - | - |
| Sales | 8.646.703.812,5 | - |

(Supply Chain Costs)

| | AS-IS | CE |
|---|---|---|
| RFB costs | 297.761.121 | 1.252.540.313 |
| M&R costs | 37.418.478 | 1.683.831.522 |
| USG costs | - | - |
| DIS costs | 2.977.611.213 | 1.471.007.983 |
| M&A costs | 1.954.057.359 | 2.172.035.225 |
| REC costs | 1.438.671.241 | 1.716.804.808 |
| RME costs | 957.953.358 | 744.620.219 |

I4. Social Impact (FTE)

| | AS-IS | CE |
|---|---|---|
| FTE RFB | 3.161 | 14.756 |
| FTE M&R | 407 | 18.303 |
| FTE DIS | 15.171 | 7.495 |
| FTE M&A | 10.114 | 11.242 |
| FTE REC | 6.524 | 8.451 |
| FTE RME | 1.795 | 1.395 |

**Fig. 4.** Screenshot of the spreadsheet simulation tool: impacts.

scenario analysis has been carried out through the application of the model to a case inspired by a company offering WMs through a pay-per-use business model. The model was used to assess the sustainability impacts of this CE scenario – scaled-up to the entire European WM industry – against the European current baseline. Primary information was collected from the case study through interviews with the company CEO. Information was then triangulated with secondary sources such as the company website and its internal documentation. The collected information was then used to feed the model. Although some values have been altered to avoid the disclosure of sensitive information, the case

**Table 3**
Scenarios modelling and parametrization.

| Driver | Baseline scenario | Digital servitization-based CE scenario |
|---|---|---|
| D1. Product | $C = 6.5\,kg$<br>$EEC = A+$<br>$WEC = 100\%$<br>$DEC = 100\%$<br>$L_1 = 2,500\,wc$<br>$L_2 = 1,500\,wc$<br>$L_3 = 0\,wc$<br>$\Delta L_{M\&R,1} = 250\,wc$<br>$\Delta L_{M\&R,2} = 150\,wc$<br>$\Delta L_{M\&R,3} = 0\,wc\ q_m = \{\text{Supplementary Material}\}$<br>$rec_m = \{\text{Supplementary Material}\}$ | $C = 8\,kg$<br>$EEC = A+++-30\%$<br>$WEC = 90\%$<br>$DEC = 90\%$<br>$L_1 = 3,000\,wc$<br>$L_2 = 1,500\,wc$<br>$L_3 = 1,000\,wc$<br>$\Delta L_{M\&R,1} = 300\,wc$<br>$\Delta L_{M\&R,2} = 150\,wc$<br>$\Delta L_{M\&R,3} = 100\,wc\ q_m = \{\text{Supplementary Material}\}$<br>$rec_m = \{\text{Supplementary Material}\}$ |
| D2. User | $YLW = 1,200\,kg$<br>$LR = 85\,\%$<br>$PPL = 510\,Mio$<br>$HS = 2.3$<br>$Shr = 1/0.90$<br>$T = 40^{\circ}_{C}$<br>$DDF = 100\%$<br>$SLmax_1 = 20$<br>$SLmax_2 = 10$<br>$SLmax_3 = 5$<br>$BM_{sale} = 100\%$<br>$BM_{ppm} = 0\%$<br>$BM_{ppw} = 0\%$ | $YLW = 1,200\,kg$<br>$LR = 95\,\%$<br>$PPL = 510\,Mio$<br>$HS = 2.3$<br>$Shr = 1/0.90$<br>$T = 35^{\circ}_{C}$<br>$DDF = 85\%)$<br>$SLmax_1 = 20$<br>$SLmax_2 = 10$<br>$SLmax_3 = 5$<br>$BM_{sale} = 0\%$<br>$BM_{ppm} = 0\%$<br>$BM_{ppw} = 100\%$ |
| D3. Supply Chain | $R_{Rfb,1} = 5\,\%$<br>$R_{Rfb,2} = 0\,\%$<br>$R_{Rfb,2} = 0\,\%$<br>$R_{Rec,1} = 65\,\%$<br>$R_{Rec,2} = 55\,\%$<br>$R_{Rec,3} = 0\,\%$<br>$Y_{M\&R} = 5\%\ gwp_{X,m} = \{\text{Supplementary Material}\}$<br>$F_{RevLog} = 1.5$<br>$GWP\_Sav_{Rfb,2} = 70\,\%$<br>$P_{sale} = 450\,€$<br>$D_{Rfb,1} = 0\%$<br>$D_{Rfb,2} = 35\%$<br>$F_{M\&R} = 3.75$<br>$X_{M\&R} = 1$<br>$X_{usg} = 1$<br>$MWT_X = \{\text{Supplementary Material}\}$<br>$CW_X = \{\text{Supplementary Material}\}$<br>$OC_X = \{\text{Supplementary Material}\}\ sav_{Rec,m} = 50\%$<br>$T_{avl} = 1,840\ hours/year$ | $R_{Rfb,1} = 30\,\%$<br>$R_{Rfb,2} = 5\,\%$<br>$R_{Rfb,3} = 0\,\%$<br>$R_{Rec,1} = 85\,\%$<br>$R_{Rec,2} = 55\,\%$<br>$R_{Rec,3} = 0\,\%$<br>$Y_{M\&R} = 100\%\ gwp_{X,m} = \{\text{Supplementary Material}\}$<br>$F_{RevLog} = 1.5$<br>$GWP\_Sav_{Rfb,2} = 70\,\%$<br>$P_{fix} = 0\,€\ per\ month$<br>$P_{ppw} = 0.35\,€\ per\ wash$<br>$D_{Rfb,1} = 0\%$<br>$D_{Rfb,2} = 0\%$<br>$X_{M\&R} = 0$<br>$X_{usg} = 1$<br>$MWT_X = \{\text{Supplementary Material}\}$<br>$CW_X = \{\text{Supplementary Material}\}$<br>$OC_X = \{\text{Supplementary Material}\}\ sav_{Rec,m} = 50\%$<br>$T_{avl} = 1,840\ hours/year$ |

study has been kept representative. Then, sensitivity analyses have been carried out to study the influence of relevant parameters on the results (Kleijnen, 1995).

Lastly, and since a model is a simplified representation of the reality, its validity has been evaluated to confirm the quality of the output and its generalized applicability (Adrion et al., 1982; Karlsson, 2008; Wayne, 2004). The model and its results have been validated for reliability and usefulness through results comparison with similar studies (Boyano et al., 2017; Pakula and Stamminger, 2015, 2010; Presutto et al., 2007; Stamminger, 2011; VHK, 2016) and through the discussion of the results with managers operating in the WM supply chain. The validation process as well as its results are summarized in Table 2. The model and its results were judged complete, correct, consistent and useful in terms of decision support and applicability.

## 4. Model description and experimentation steps

### 4.1. Sub-models composition

The model blocks mentioned above (configuration drivers, characterization, and impacts) are hereafter illustrated in detail, as summarized in Fig. 2.

### 4.1.1. Configuration drivers

The configuration of the product (D1) describes the main product characteristics that are useful to build product homogeneous classes with similar functionalities and characterized by the materials contained in the product Bill of Material as well as by other product technical data that affects the product lifespan (e.g., data associated to failures and maintenance) and consumption during usage. In the case of WMs, they are the product energy efficiency class, the capacity, the expected lifespan, the material used to manufacture the WM as well as the expected specific consumption associated to the usage phase of the product, such as the energy, water, and detergent consumption per each wash cycle. The configuration of the user (D2) aims to describe homogeneous customers' clusters, with similar characteristics such as household size, WM loading rate, and consumption patterns during usage such as the washing temperature used. The configuration of the supply chain (D3) describes the structure and the characteristics of the supply chain, including the options regarding the product end-of-use, the unitary costs incurred by each actor in the supply chain, the unitary environmental impacts related to each activity in the product lifecycle as well as the labor contents and intensity (in terms of man-hours) of each supply chain activity.

### 4.1.2. Usage characterization

The usage block (E1) characterizes the utilization phase of the product, as a combination of the input provided by the product (D1) and by the user (D2). Its main aim is to quantify the relation between usage behavior and the consumption of consumables. First, the number of

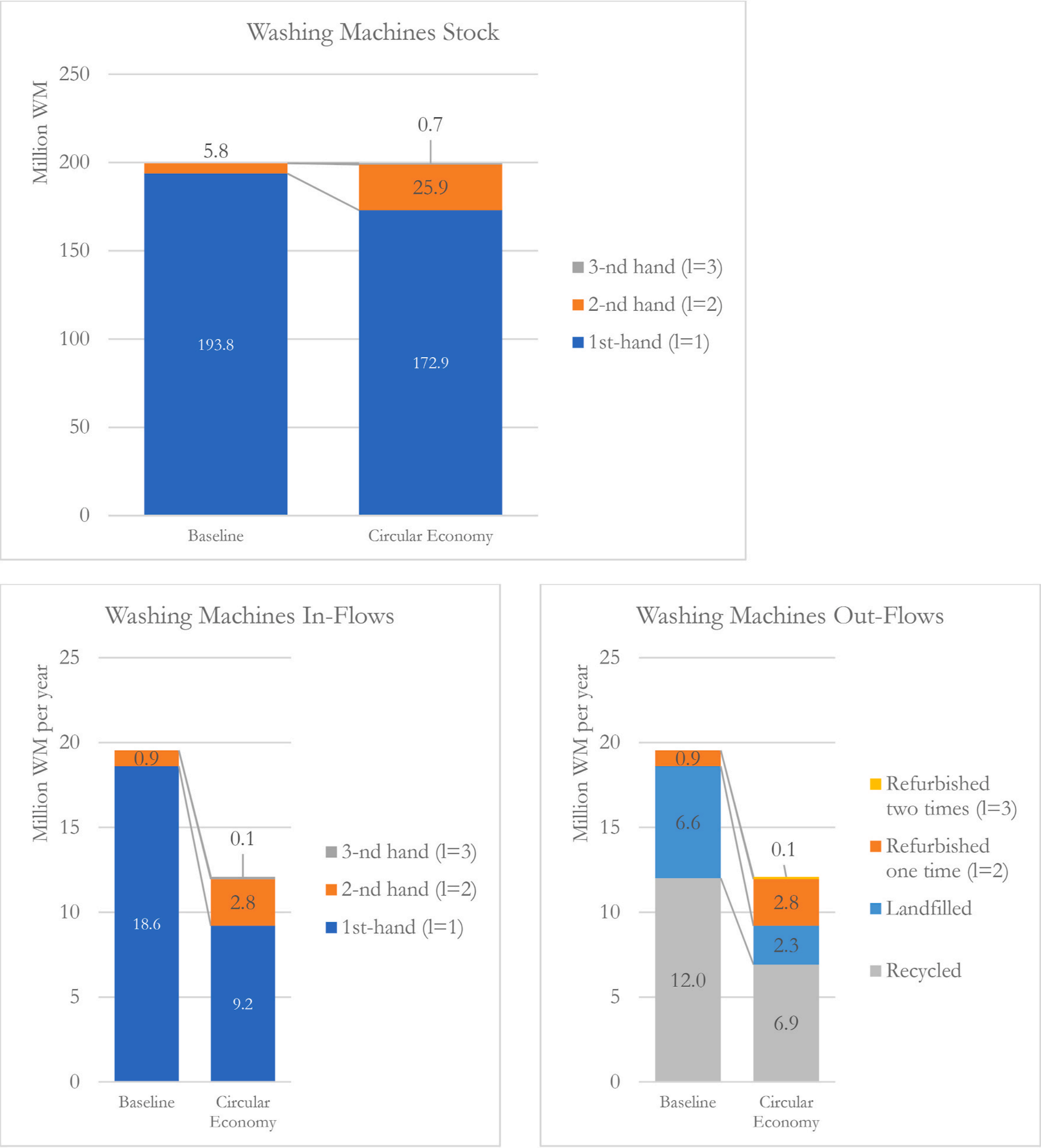


**Fig. 5.** WMs stock and flows in linear and CE scenarios.

washing cycles that a household perform in a year ($N_{wc}$) is computed through Eq. (1), which divides the yearly laundry that a household needs to wash in a year (*YLW*) by the actual laundry washed in a single WM. The latter is defined by multiplying the capacity of the WM (*C*) by the WM loading rate (*LR*), i.e., the ratio between the kg washed and the WM capacity.

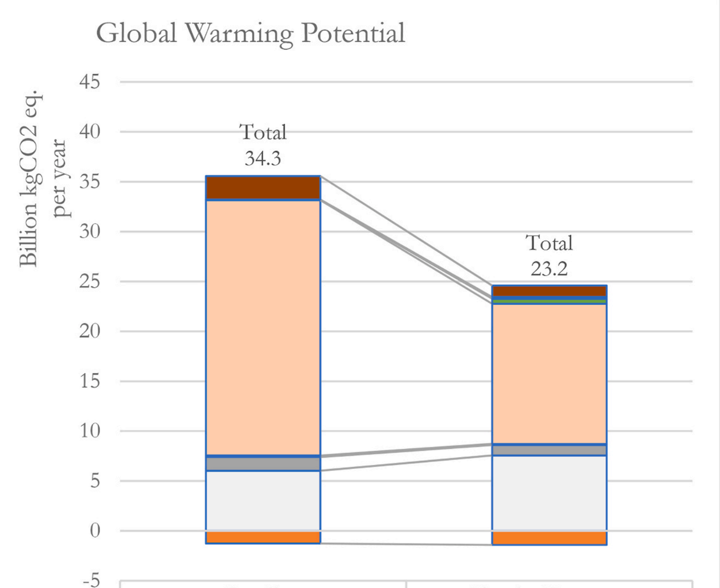
$$N_{wc}\left[\frac{wc}{hh \times year}\right] = \frac{YLW}{C \times LR} \tag{1}$$

Then, the consumption of the main consumables during the usage of the WM is computed. They are the energy (*EC*), water (*WC*) and detergent (*DC*) consumption, computed through Eqs. (2)–(4) as the result of the product between the specific average energy ($E_{wc}$), water ($W_{wc}$) and detergent ($D_{wc}$) consumption of a single washing cycle and the number of washing cycles done by a household in a year, as defined above. $E_{wc}$ is usually defined in literature as a function of the washing temperature (*T*), of the product energy efficiency class (*EEC*) and of the WM capacity (*C*) (Boyano et al., 2017). $W_{wc}$, instead, is usually characterized in literature as a function of the WM capacity (*C*), the WM loading rate (*LR*), and the WM water efficiency (*WEC*) (Lasic and Stamminger, 2015). Lastly, $D_{wc}$ is defined in literature as a function of the actual laundry washed ($C \times LR$), of how detergent-efficient is the WM (*DEC*), and of users' behavior (*DDF*) (Boyano et al., 2017). If specific washing data on energy, water and detergent consumption are available, it is suggested to directly use them. If no data are available, it is possible to estimate them by using regression equations (See Supplementary Materials).

$$EC\left[\frac{kWh}{hh \times year}\right] = N_{wc} \times E_{wc}\{T; EEC; C\} \tag{2}$$

$$WC\left[\frac{Litre}{hh \times year}\right] = N_{wc} \times W_{wc}\{C; LR; WEC\} \tag{3}$$

$$DC\left[\frac{kg}{hh \times year}\right] = N_{wc} \times D_{wc}\{C; LR; DEC; DDF\} \tag{4}$$



| | Baseline | Circular Economy |
|---|---|---|
| 🟫 Landfilling | 2.35E+09 | 1.14E+09 |
| 🟦 Refurbishment (incl. logistics) | 4.00E+07 | 1.87E+08 |
| 🟩 Maintenance and Repair | 2.49E+07 | 5.04E+08 |
| 🟧 Usage | 2.56E+10 | 1.40E+10 |
| 🟨 Distribution | 1.55E+08 | 1.08E+08 |
| ◼ Manufacturing and Assembly | 1.38E+09 | 1.05E+09 |
| 🟧 Credits for Recycling | -1.27E+09 | -1.41E+09 |
| □ Raw Materials Extraction | 6.02E+09 | 7.56E+09 |
| Total | 3.43E+10 | 2.32E+10 |

**Fig. 6.** Environmental impact.

#### 4.1.3. *Stock and flows characterization*

The stock and flows block (E2) characterizes the installed base and the main yearly volumes of the input (products sales) and the output (end-of-life products). Both stock and flows are defined starting from the configuration of the Supply Chain (D3) and from the users' choice in terms of business model adopted (D2). First, the overall WM installed base ($WM_{stock}$) is computed through Eq. (5) by dividing the overall population of the geographical region under study (*PPL*) by the number of people who uses the same WM. The latter is given by the product of the household size (*HS*, i.e., the number of persons living in the same household) with the 'sharing factor' (*Shr*, i.e., number of households who share the same WM, e.g., through laundry facilities or via common rooms for apartments).

$$WM_{stock}[WM] = \frac{PPL}{HS \times Shr} \tag{5}$$

When the overall system under study is in a steady state, i.e., when it does not change over time, the overall stock (i.e., the installed base) of WM is constant over time, since the input flows are equals to the output. This condition is true for the WM industry in Europe, where data from APPliA (2023) confirm a stability of the WM installed base since several years. The following input-output flows are then computed. In a CE, products can have several lives and can be used by different users. As explained in the Supplementary Materials more in detail, when a WM reaches its '*l*' end of use, it can be discarded or refurbished, according to the 'Refurbishment Rate' ($R_{Rfb,l}$). Refurbished WMs start a new use-life with a new user, while discarded WMs can be recycled for material recovery ('Recycling Rate', $R_{Rec,l}$) or be landfilled and leave the system ('Landfill Rate', $R_{Lnd}$). Each year an amount of WMs ($WM_{EoL}$) equals to the ratio between the total WM stock and the WM average life ($WML_{avg}$) leaves the system (i.e. reaches the End of Life), as specified by Eq. (6). Given the steady state of the system, they are replaced by new WMs ($WM_{in,1}$)

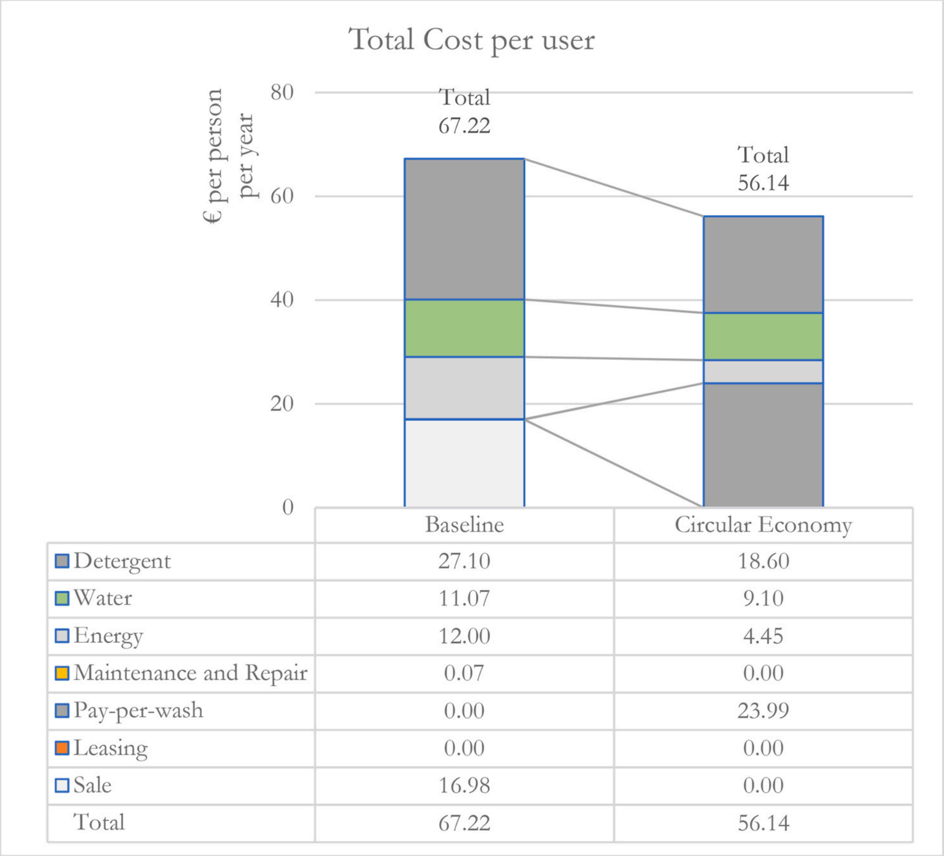
$$WM_{EoL}\left[\frac{WM}{year}\right] = \frac{WM_{stock}}{WML_{avg}} = WM_{in,1}\left[\frac{WM}{year}\right] \tag{6}$$

The WM average life is computed by dividing the technical lifespan of the WM in its l-use ($L_l$) by the number of washing cycles that a household do per year ($N_{wc}$), as defined before in Eq. (1). Maintenance and repair activities, if activated, can bring to WMs lifespan extension. The number of WMs that, each year, gets refurbished, and thus leaves and re-enters the system at the same time, is computed through Equation (7). $WM_{in,2}$ are WMs that have been refurbished one-time and thus start their second use-life ($l = 2$), $WM_{in,3}$ are WMs that have been refurbished two-times, and thus start their third use ($l = 3$), and so forth.

$$WM_{in,l+1}\left[\frac{WM}{year}\right] = WM_{in,1} \times \prod_{l=1}^{l} R_{Rfb,l} \tag{7}$$

#### 4.1.4. *Impacts*

The environmental impact block (I1) assesses the environmental impacts connected to one year of households' clothes washing in the defined geography. It includes all the processes that are needed to deliver the desired function (clean clothes), i.e., WMs production, distribution, use, maintenance, collection, recovery, and disposal. Even though several indicators can be used, only the Global Warming Potential (GWP) indicator is modelled. Equation (8) computes the



| | Baseline | Circular Economy |
|---|---|---|
| ▨ Detergent | 27.10 | 18.60 |
| 🟩 Water | 11.07 | 9.10 |
| ▨ Energy | 12.00 | 4.45 |
| 🟨 Maintenance and Repair | 0.07 | 0.00 |
| ▨ Pay-per-wash | 0.00 | 23.99 |
| 🟧 Leasing | 0.00 | 0.00 |
| ☐ Sale | 16.98 | 0.00 |
| Total | 67.22 | 56.14 |

**Fig. 7.** Economic Impact for the user.

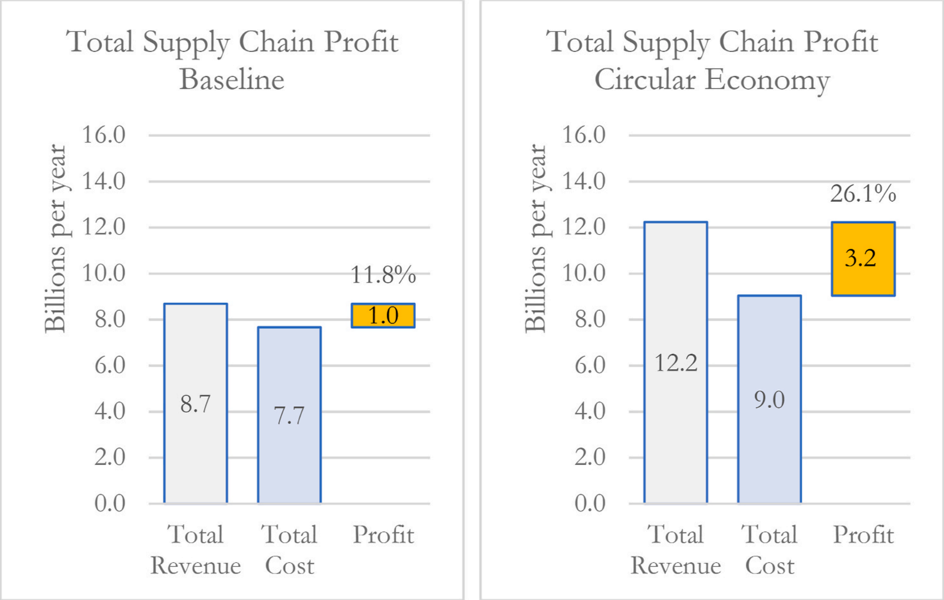


**Fig. 8.** Economic Impact for the supply chain.

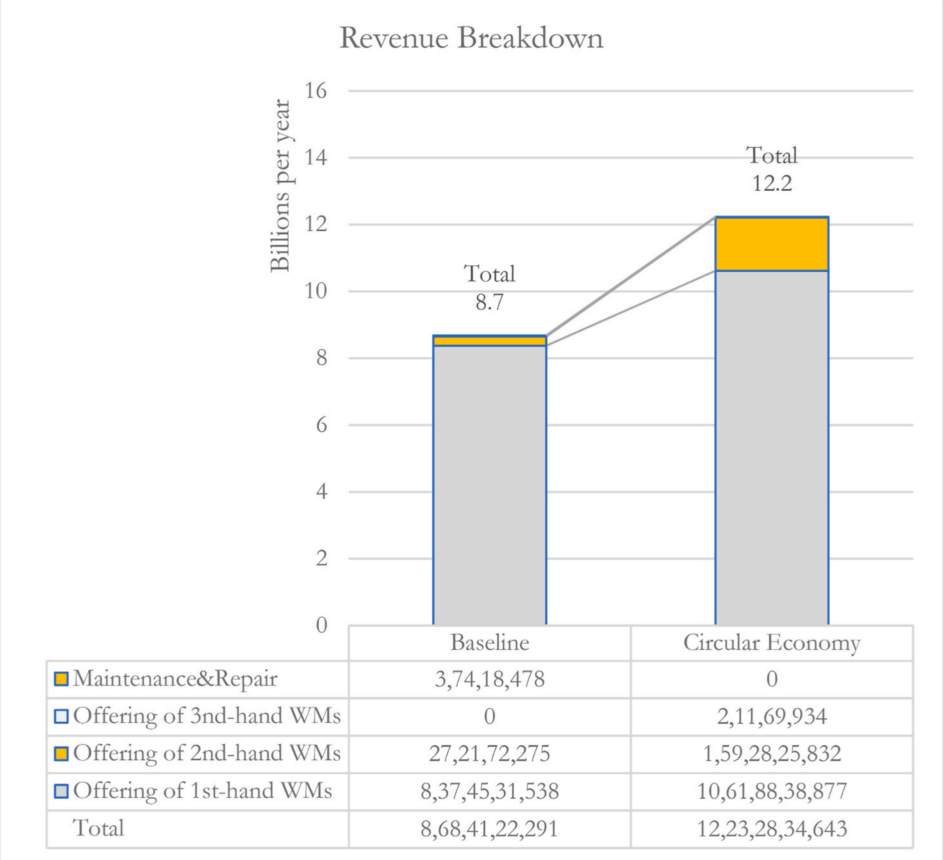
environmental GWP impact of the CE scenario (kg $CO_2$ eq.) adding up the GWP impacts belonging to each WM lifecycle phase, ranging from raw materials extraction to disposal, and multiplying them by the WM flows and stocks interested. In particular, it considers the carbon footprint connected with: the production and distribution of the new WMs that, each year, enter the steady state system; the yearly energy, water and detergent consumption generated during the usage phase of the entire WM stock; the maintenance and repair activities carried out on a portion ($Y_{M\&R}$) of the WM stock; the collection and refurbishment of second-hand, third-hand (and so forth) WMs that, each year, reach the end of use and thus leave but re-enter the system; the recycling or disposal of WMs that, each year, reach the end of life.

$$GWP\left[\frac{kgCO2_{eq}}{year}\right] = GWP_{RME} \times WM_{in,1} - GWP_{Rec} \times WM_{Rec} + GWP_{M\&A} \times WM_{in,1} + GWP_{Dis} \times WM_{in,1} + (gwp_e \times EC + gwp_w \times WC + gwp_d \times DC) \times Shr \times WM_{stock} + (Y_{M\&R} \times GWP_{M\&R}) \times WM_{stock} + \sum_{l=2}^{l_{max}} \left( \left( GWP_{RevLog} + GWP_{in,l} + GWP_{Dis} \right) \times WM_{in,l} \right) + GWP_{Lnd} \times WM_{Lnd} \tag{8}$$

The economic impact for the user block (I2) assesses the yearly costs that a single user pays for clothes washing, as computed in Eq. (9). Households can do laundry in several ways, that range from the traditional buying and owning a WM to the access to laundry services. Each alternative has a different payment scheme, which affects in different ways the total users' cost computed through this block. Three different payment schemes are modelled: traditional sale ($BM_{sale}$), leasing ($BM_{ppm}$) and pay-per-wash ($BM_{ppw}$). In a traditional sale business model, the WM purchasing price ($P_{sale}$) is divided by the WM service life ($SL_l$). In a pay-per-use business model, the fee is multiplied by the number of washing cycles carried out by the household in a year ($N_{wc}$). If households buy or access a refurbished WM, a discount (applied on the purchasing price or on the access fee of the leasing or pay-per-use offering) is applied ($D_{Rfb,l}$). Maintenance, repair, and usage costs (C1) are also included.

$$TC_{hh}\left[\frac{€}{year \times hh}\right] = = \sum\nolimits_l \left( \frac{BM_{sale} \times F_{sale,l}}{Shr} \times \frac{WM_{in,l}}{\sum_{l=1}^{l_{max}} WM_{in,l}} \right) + \sum\nolimits_l \left( \frac{BM_{ppm} \times F_{ppm,l}}{Shr} \times \frac{WM_{stock,l}}{WM_{stock}} \right) + \sum\nolimits_l \left( BM_{ppw} \times F_{ppw,l} \times \frac{WM_{stock,l}}{WM_{stock}} \right) + \left( X_{M\&R} \times \frac{Y_{M\&R} \times F_{M\&R}}{Shr} \right) + \left( X_{usg} \times (c_e \times EC + c_w \times WC + c_d \times DC) \right) \tag{9}$$

The economic impact for the supply chain block (I3) assesses the overall profit that the household WM supply chain can raise, each year, connected to washing activities. This supply chain profit ($PRFT_{SC}$) is computed in Eq. (10), as total revenues ($TR_{SC}$) generated throughout the



| | Baseline | Circular Economy |
|---|---|---|
| 🟧 Maintenance&Repair | 3,74,18,478 | 0 |
| ☐ Offering of 3nd-hand WMs | 0 | 2,11,69,934 |
| 🟧 Offering of 2nd-hand WMs | 27,21,72,275 | 1,59,28,25,832 |
| ☐ Offering of 1st-hand WMs | 8,37,45,31,538 | 10,61,88,38,877 |
| Total | 8,68,41,22,291 | 12,23,28,34,643 |

**Fig. 9.** Breakdown of revenues for the supply chain.

supply chain minus total costs ($TC_{SC}$). Revenues are gained by the supply chain as a whole and are the counterpart of the costs paid by users, which depend by the business model option (traditional sale, leasing, pay-per-wash) adopted (Eq. (11)). Total supply chain costs include the costs for the materials needed to manufacture a WM ($C_{RME}$; $C_{Rec}$); costs for their assembly ($C_{M\&A}$); new WMs ($WM_{in,1}$) distribution costs ($C_{Dis}$); usage costs if not directly billed to users; costs for maintain and repair ($C_{M\&R}$) the stock of installed WMs ($WM_{stock}$); costs for reverse logistics ($C_{RevLog}$), refurbishment ($C_{Rfb,l}$), and re-distribution ($C_{Dis}$) of second and third-hand WMs (Eq. (12)). Each specific supply chain cost item is further modelled in the Supplementary Materials, by splitting and separating human-labor costs from non-labor (e.g., materials, depreciations, overhead, etc.) costs.

$$PRFT_{SC}\left[\frac{€}{year}\right] = TR_{SC} - TC_{SC} \tag{10}$$

$$\begin{aligned} TR_{SC}\left[\frac{€}{year}\right] = & \sum_{l}\left(BM_{sale} \times P_{sale} \times \left(1 - D_{Rfb,l}\right) \times WM_{in,l}\right) \\ & + \sum_{l}\left(BM_{ppm} \times F_{ppm} \times WM_{stock,l}\right) \\ & + \sum_{l}\left(BM_{ppw} \times F_{ppw} \times Shr \times WM_{stock,l}\right) \\ & + \left(Y_{M\&R} \times X_{M\&R} \times F_{M\&R}\right) \times WM_{stock} \end{aligned} \tag{11}$$

$$\begin{aligned} TC_{SC}\left[\frac{€}{year}\right] = & C_{RME} \times WM_{Lnd} + C_{Rec} \times WM_{Rec} + C_{M\&A} \times WM_{in,1} \\ & + C_{Dis} \times WM_{in,1} + \left(1 - X_{usg}\right) \times \left(c_e \times EC + c_w \times WC + c_d \times DC\right) \\ & \times Shr \times WM_{stock} + Y_{M\&R} \times C_{M\&R} \times WM_{stock} \\ & + \sum_{l=2}^{l_{max}}\left(\left(C_{RevLog} + C_{Rfb,l} + C_{Dis}\right) \times WM_{in,l}\right) \end{aligned} \tag{12}$$

The social impact block (I4) assesses the employment potential in terms of Full Time Equivalent (FTE) positions that are needed to deliver the desired function of clean clothes in one year. Equation (13) computes the FTE positions that are needed for each supply chain activity, adopting a lifecycle perspective. For that purpose, the working man hours needed to perform each supply chain activity (i.e., $MWT_x$) are multiplied by the WM flows or stocks related to each activity, and then divided by the time that is available for a full-time worker in a year ($T_{avl}$ = 1840 h per year).

$$\begin{aligned} FTE[FTE] = & \frac{MWT_{RME} \times WM_{Lnd} + MWT_{Rec} \times WM_{Rec}}{T_{avl}} + \frac{MWT_{M\&A} \times WM_{in,1} + MWT_{Dis} \times WM_{in,1}}{T_{avl}} + \frac{Y_{M\&R} \times MWT_{M\&R} \times WM_{stock}}{T_{avl}} \\ & + \frac{\sum_{l=2}^{l_{max}}\left(\left(MWT_{RevLog} + MWT_{Rfb,l} + MWT_{Dis}\right) \times WM_{in,l}\right)}{T_{avl}} \end{aligned} \tag{13}$$

### 4.2. Experimentation steps

The experimentation phase mentioned in section 3 – i.e., the running of simulations through the what-if simulation model described above – has been carried out through the spreadsheet tool following a three-step process.

The first step is the modelling and parametrization of baseline and CE scenarios. A CE scenario is defined through a combination of a subset of CE actions, levers, and enabling factors such as circular product design, servitized business models, supply chain management, government intervention, users' engagement, and digital technologies (Bressanelli et al., 2021). Readers can refer to Bressanelli et al. (2020) for an overview of how CE scenarios for the WM industry can be modelled. Then, configuration drivers need to be defined based on the activated levers and enablers. These are used for configuring products (D1), users (D2) and the supply chain (D3) (Fig. 3). When defining the drivers, it is important to highlight that the overall model can be used to both assess a single user-product-company (micro, individual level) and an overall installed base (macro, industry-wide) perspective. To conduct the assessment in the first case, specific values that describe the specific case characteristics (e.g., WM of 6 kg capacity, washing temperature of 40 °C, etc.) should be used as input. In the second case, instead, average values and distributions reflecting the overall population under study should be used as inputs (e.g., the average WM capacity of the entire installed base is 6 kg, the average washing temperature used by user is 40 °C, etc.).

The second step is the assessment and comparison of the sustainability impacts against the baseline, linear scenario. The configuration of drivers previously defined provides the inputs for the characterization of usage, stock, and flows, according to Equations (5)–(7). Then, the two scenarios are evaluated and compared through the four impacts assessed (Fig. 4).

The third and last step is sensitivity simulation and analysis on the main configuration drivers, to test results robustness and support the investigation of Research Questions.

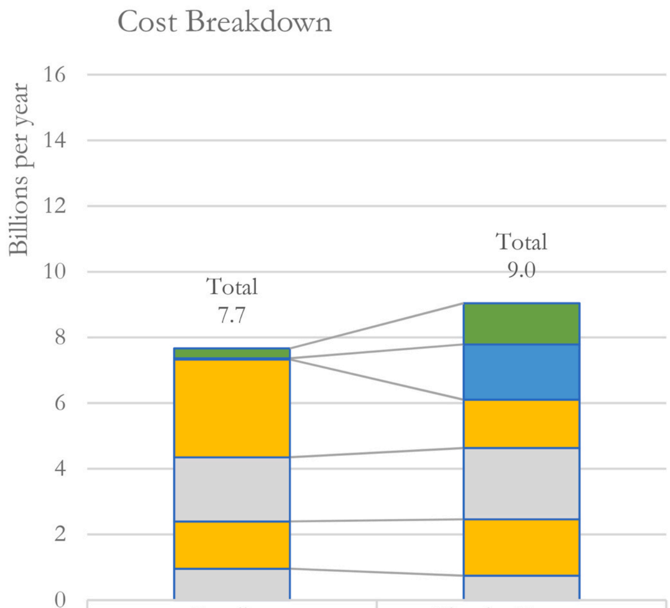
## 5. Results

### 5.1. Scenarios modelling and parametrization

Two scenarios for the European WM industry have been modelled and parametrized (Table 3): a traditional, ownership-based linear economy one (baseline scenario) and a digital servitization-based circular one (CE scenario).

The parametrization of the baseline scenario is based on secondary information (see Supplementary Materials). Since the baseline scenario depicts the current situation, no CE actions or enabling factors are activated or exploited: the current (average) design of WMs, the current linear business model and supply chain structure are considered (Boyano et al., 2017). On average, a new WM runs for 2500 washing cycles ($L_1$), while a second-hand WM can run for additional 1500 washing cycles ($L_2$). To measure the input related to the user (D2), it is assumed that, on average, each household needs to wash about 1200 kg of laundry each year ($YLW$), based on previous studies (Lasic et al., 2015). Moreover, an average Loading Rate of 85% is considered. A European population of 510,000,000 people is considered, with an average household size of about 2.3 people per household, and a WM ownership rate of 90% (Eurostat, 2023). The average washing temperature ($T$) is 40 °C (Boyano et al., 2017). Regarding the input related to the supply chain (D3), new WMs are sold at an average price ($P_{sale}$) of 450 € (Boyano et al., 2017). Currently, it is assumed that only a small share of WMs is refurbished at the end of its first-use ($R_{Rfb,1}$ = 5%), and second-hand WMs are not further refurbished ($R_{Rfb,2}$ = 0%). Only the 65% of first-hand WMs are recycled ($R_{Rec,1}$ = 65%).

The parametrization of the digital servitization CE scenario is inspired by the case of a Product-as-a-Service provider that offers the opportunity to access WMs through pay-per-use subscriptions



| | Baseline | Circular Economy |
|---|---|---|
| 🟩 Refurbishment | 29,77,61,121 | 1,25,25,40,313 |
| 🟦 Maintenance&Repair | 3,74,18,478 | 1,68,38,31,522 |
| 🟨 Distribution | 2,97,76,11,213 | 1,47,10,07,983 |
| ⬜ Manufacturing&Assembly | 1,95,40,57,359 | 2,17,20,35,225 |
| 🟨 Recycling | 1,43,86,71,241 | 1,71,68,04,808 |
| ⬜ Raw Materials | 95,79,53,358 | 74,46,20,219 |
| Total | 7,66,34,72,771 | 9,04,08,40,069 |

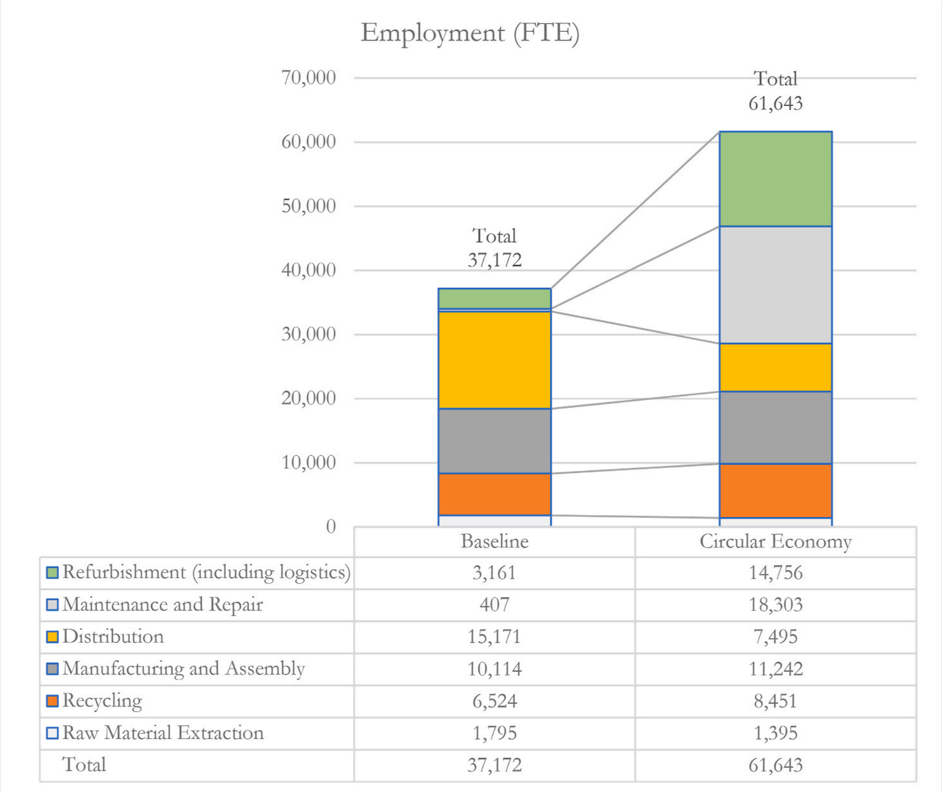
**Fig. 10.** Breakdown of costs for the supply chain.

(Bressanelli et al., 2018). This case provides a suitable arena for what-if analysis since it combines several CE actions (product design, servitized business models, reverse logistics) and enabling factors (users' involvement and digitalization) at the same time. The company, in fact, provides high-efficient WMs designed to last. These WMs have a capacity of 8 kg and a high energy efficiency class. During their first use-life, WMs can run until reaching 3000 washing cycles ($L_1$), while second-hand and third-hand WMs can run for additional 1500 and 1000 washing cycles respectively ($L_2$ and $L_3$). The WM Bill of Material provided in the Supplementary Materials has been taken and used to feed the model ($q_m$). WMs are equipped with an IoT tool that contributes to the provision of personal hints on how to save energy and reduce costs during washing operations. Therefore, 'smart' WMs components have been added to the WM design to include the product digitalization effect that is needed to run this offering. Regarding the input related to the user (D2), a Loading Rate of 95% is considered, since the hints support customers in not using the WM when it is not necessary (leading to fewer washing cycles per household per year compared to the baseline scenario). For the same reason, the washing temperature ($T$) is of 35 °C. Lastly, the company retains the ownership of WMs and collects them when users end the subscription contract. Collected WMs are refurbished and reused in a new subscription cycle with a new user. Regarding the input related to the supply chain (D3), it is assumed that the 30% of WMs are refurbished at the end of their first-use ($R_{Rfb,1} = 30\%$), and a small share of second-hand WMs are further refurbished ($R_{Rfb,2} = 5\%$). Since the end-of-life management is improved, the 85% of first-hand WMs that are not refurbished is recycled ($R_{Rec,1} = 85\%$), and the 55% of second-hand WMs is recycled ($R_{Rec,2} = 55\%$). Since they are included in the overall pay-per-use offering, maintenance and repair services are performed on 100% of the WM stock. A pay-per-use fee of 0.35 € per washing cycle is considered ($P_{ppw} = 0.35$).

### 5.2. *Sustainability impact assessment results*

In the CE scenario, the number of washing cycles that is run each year is reduced from 217 to 158 per household, because of the increase in the WM loading rate and in the WM capacity (Eq. (1)). A total of about 200 million WMs are in operation both in the linear and digital servitization CE scenario (Eq. (5)). However, the WM average lifespan is increased from 10.7 to 21.7 years, due to the combination of (i.) the increase in the technical life of WM by design; (ii.) the reduction of the number of washing cycles per year; (iii.) the 100% diffusion of maintenance and repair activities; and (iv.) the refurbishment of WMs at the end of their first use. The stock and flows in steady state as computed through the model are shown in Fig. 5. Overall, the number of WMs that enters the system each year sharply reduces from 18.6 million to 9.2 million (−50.6%), because of the lifetime extension achieved through the combination of WM design, maintenance and repair services included in the servitized business model and the reduced usage achieved through pay-per-use. At the same time, 9.2 million of WMs leave the system each year: 6.9 million are recycled, and 2.3 million go to landfill. Moreover, the number of WMs refurbished each year increases from about 0.93 to 2.90 million.

The four impacts of the digital servitization CE scenario are then assessed and compared to the baseline. Fig. 6 depicts the overall environmental impact of the digital servitization CE scenario, in terms of billion kg of $CO_2$ eq. and compares it to the baseline. Overall, the GWP is reduced from 34.3 billion kg of $CO_2$ eq. that are currently emitted each



| | Baseline | Circular Economy |
|---|---|---|
| 🟩 Refurbishment (including logistics) | 3,161 | 14,756 |
| ⬜ Maintenance and Repair | 407 | 18,303 |
| 🟨 Distribution | 15,171 | 7,495 |
| ⬛ Manufacturing and Assembly | 10,114 | 11,242 |
| 🟧 Recycling | 6,524 | 8,451 |
| □ Raw Material Extraction | 1,795 | 1,395 |
| Total | 37,172 | 61,643 |

**Fig. 11.** Social impact.

year, to 23.2 billion kg $CO_2$ eq. (−32.4%). This result is mainly obtained thanks to the reduction of the environmental impact connected to the usage phase, due to the combined effect of the reduction in the energy, water, and detergent consumption of each single washing cycle, generated from the adoption of high-efficient WMs, and of the overall reduction in the number of washing cycles due to the increase in the WM capacity and loading rate. Given the overall WM flows reduction, distribution impacts are lower too. This environmental impact reduction offsets the higher specific environmental impact connected to the production and (re)manufacturing of high-efficient, top-quality WMs.

Fig. 7 depicts the total user's cost impact, in terms of euro per year per single person. Overall, the total costs for laundry per single user decreases from 67.22 € to 56.14 € per year per person (−16.5%). This reduction is due to the decrease in the usage costs, generated from the combination of high-efficient WMs with a reduction in the number of washing cycles. In fact, energy costs decrease from 12.00 to 4.45 € per year (−62.9%), water costs from 11.07 to 9.10 € per year (−17.8%), detergent costs from 27.10 to 18.60 € per year (−31.4%).

Fig. 8 depicts the total supply chain profit at a European level, generated from the total revenues and costs incurred in the supply chain in the digital servitization CE scenario and compared to the baseline. Figs. 9 and 10 provide the breakdown of revenues and costs. Overall, the supply chain margin sharply increases from about 1.0 billion € to 3.2 billion € per year (from 11.8% of revenues to 26.1%). In fact, revenues raise from 8.7 billion to 12.2 billion € per year (+40.9%), as a result of the pay-per-use fees related to top-quality, high-efficient first- and second-hand WMs, that include also maintenance and repair services (so 'stand-alone' maintenance and repair services drop to zero). At the same time, costs also increase (from 7.7 to 9.0 billion € per year): unit production and maintenance costs increase since high-efficient WMs require more labor and resources to be produced, maintained, and refurbished. This increase in costs, however, is partially compensated by the reduction in the flows of WMs that, each year, are produced, distributed, and collected at the end of use. Thus, revenue streams increase more than costs, explaining why the overall supply chain profit is higher compared to the baseline.

Lastly, Fig. 11 depicts the total employment impact, i.e., the overall FTE jobs that are created in the supply chain in the digital servitization-based CE scenario. Comparing the results with the baseline, the overall number of FTE increases (+65.8%): about 61,500 FTE are needed, instead of the original 37,170 FTE. More specifically, jobs are created in each supply chain activity (except for raw material extraction and WM distribution), since producing, maintaining, and refurbishing a top-quality, high-efficient WM is more labor intensive than producing, maintaining, and refurbishing a traditional WM. Maintenance and repair services significantly contribute to the achievement of this result: in the CE scenario, these services are spread over the entire WM installed base.

Overall, the digital servitization-based CE scenario scaled-up to the entire European WM industry leads to a win-win-win situation with positive effects on the environment (−32.4% $CO_2$ emissions), to the society (+65.8% increase in FTE positions) and to the economy (the supply chain margin nearly tripled, while users' costs are reduced by 16.5%).

### 5.3. Sensitivity analysis

A sensitivity analysis on three parameters has been carried out. First, the WM lifespans related to each use-life ($L_l$) have been tested in a range from −50% (decreasing lifespans) to +50% (increasing lifespans) of the initial values, using a simulation step of 10%. Fig. 12 shows that the modification in the WM lifespan parameters affects all the four categories of impacts. From an environmental point of view, the GWP function is inversely proportional to the WM lifespan: when the lifespan increases, $CO_2$ emissions decrease. This is explained by the fact that the overall GWP function can be approximated as the sum of two contributions, usage emissions and supply chain emissions. Usage yearly $CO_2$ emissions in steady state do not depend on the WM lifespan, since they are affected only by the number of washing cycles carried out each year

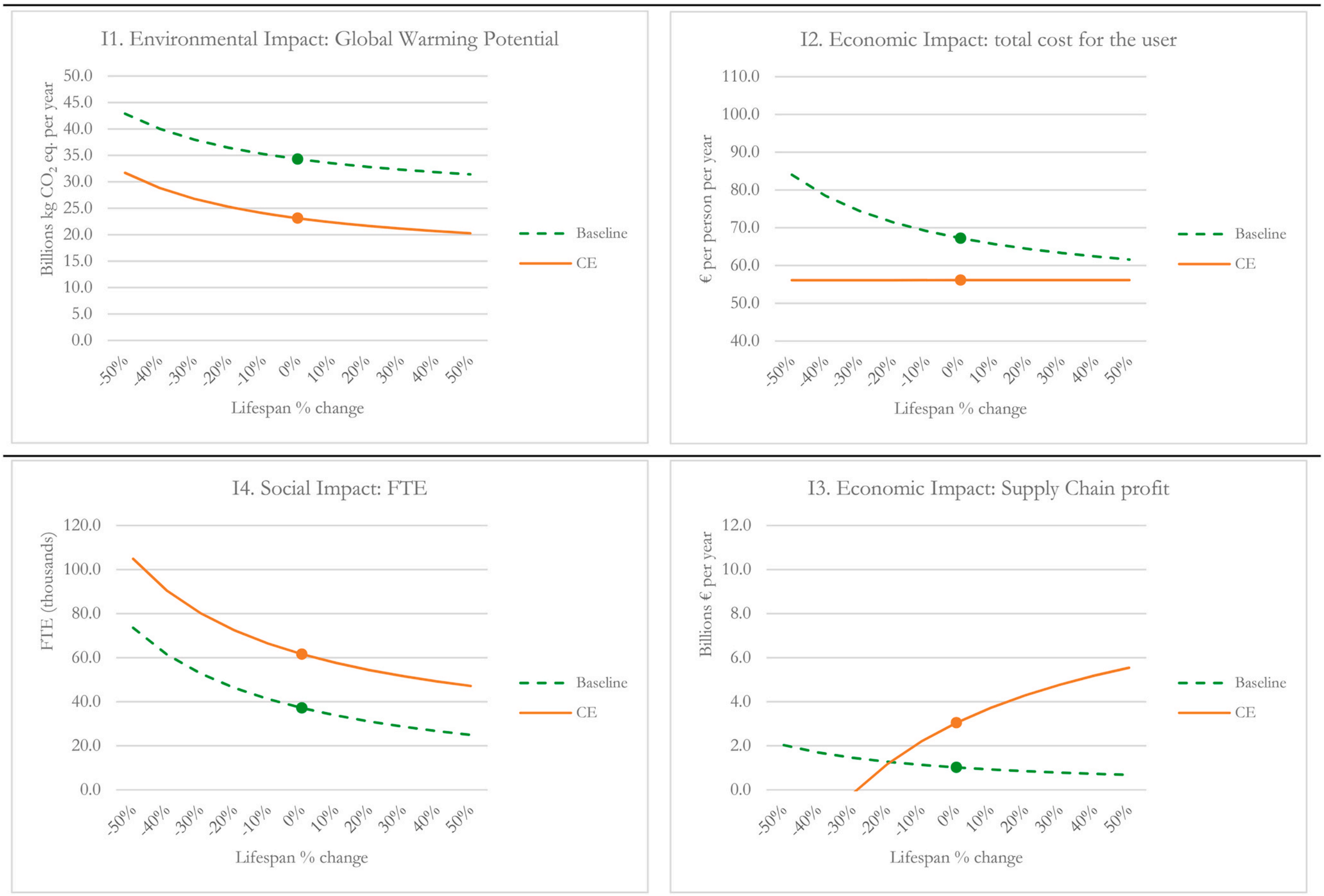


**Fig. 12.** Sensitivity Analysis: WM lifespan.

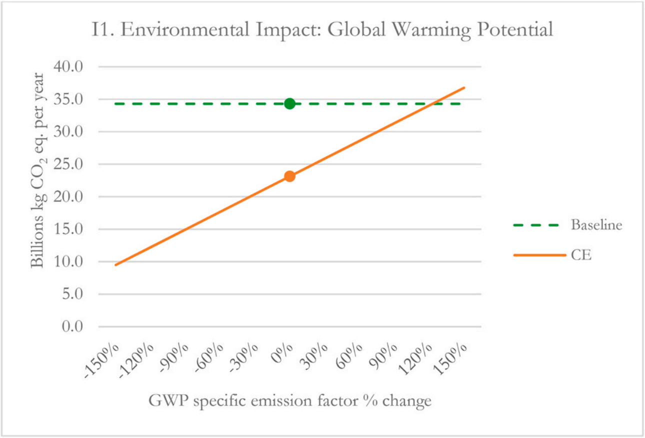


**Fig. 13.** Sensitivity Analysis: GWP production impact of top-quality, high-efficient WMs.

(Eq. (1)) and by the specific energy, water, and detergent consumption (Eqs. (2)–(4)). Supply chain emissions, instead, are generated in the production and transportation phases: their yearly contribution is distributed over the WM lifespan, thus explaining the inversely proportional character. Therefore, increasing WM lifespan leads to lower yearly $CO_2$ emissions. From an users' economic point of view, the sensitivity analysis shows that changing WM lifespan does not modify their laundry costs in the digital servitization-based CE scenario, since users' costs do not depend on the WM lifespan. In the scenario based on traditional sales, instead, users' costs follow an inversely proportional path: when the lifespan increases, users' costs decrease. This is explained by the fact that the impact of the WM price is split over the WM lifespan. From a supply chain economic point of view, the supply chain margin function assumes two different trends. In the traditional sales scenario, the supply chain profit follows an inversely proportional path, since if WM lifespans increase, WM sales decrease. In the digital servitization-based CE scenario, instead, revenues are decoupled from WM sales, and thus the overall profit increases when the lifespan increases too. If the lifespan decreases, solutions based on Servitised BMs perform worse than the linear scenario: in this case more WMs replacement are needed each year, leading to greater production costs, while revenues remain unchanged (because they depend on the WM stock). Consequently, adopting digital servitization-based CE business models is not economically preferable when WMs have short lifespan. This reinforces the need to combine, in a systemic perspective, digital servitization business models with the design of durable products and the prevention of opportunistic users' behavior that could damage products and shorten their life. From a social point of view, the FTE functions are inversely proportional to the WM lifespan: when the lifespan increases, also the FTE needed decreases, since fewer WM replacements occur. An interesting consideration about the slope of the functions arises: the slope is lower in the digital-servitization CE scenario where maintenance and repair services are widespread, because these jobs do not depend on the WM replacements but, instead, are directly proportional to the WM stock.

Second, the GWP specific emission factors related to the production of top-quality, high-efficient WMs in the CE scenario have been tested. They are the specific GWP impacts connected with producing, distributing, maintaining, collecting, refurbishing, and landfilling top-quality, high-efficient WM in the digital servitization-based CE scenario only.

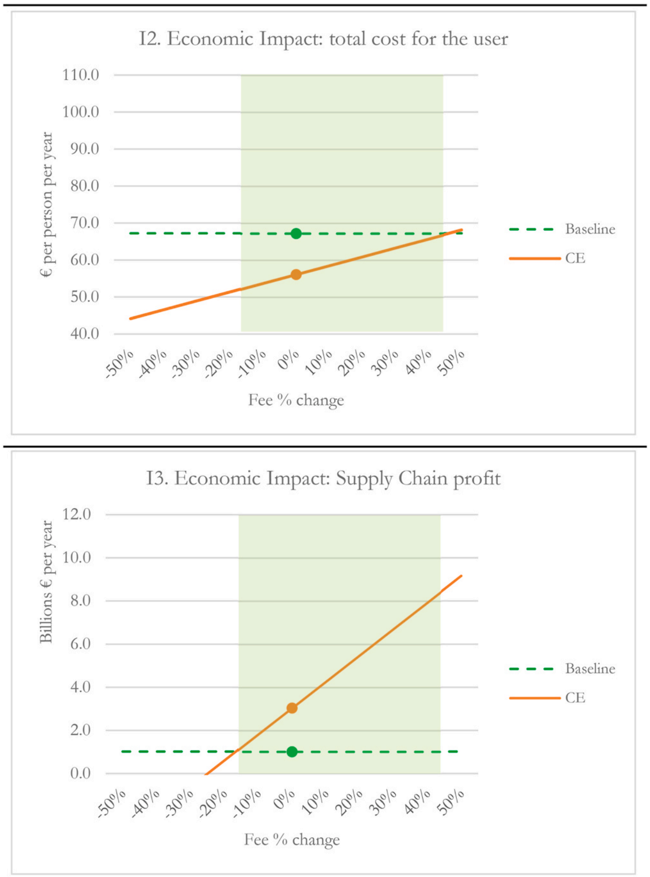


**Fig. 14.** Sensitivity Analysis: Pay-per-wash fee.

These specific emission factors have been modified from −150% (decrease) to +150% (increase) of the initial values (simulation step of 30%), and results have been compared to the (unchanged) baseline scenario. This sensitivity analysis is conducted to test how robust the results of the comparison are, considering the environmental trade-off between the decrease in the usage impacts of high-efficient WMs and the increased impacts for their production, which usually need more material and lead to additional impacts compared to standard products. Fig. 13 shows that there is a linear relation between the total $CO_2$ emissions and the change of GWP specific emission factors. This analysis shows that the digital servitization-based CE scenario environmentally performs better than the baseline, unless the GWP specific impacts for producing and distributing high-end WMs increase more than the 120% of the original values.

Finally, the pay-per-wash fee has been tested by varying it from −50% (decrease) to +50% (increase), using a simulation step of 10%. This sensitivity analysis is conducted to test the robustness of the economic win-win solution. The modification of the pay-per-use fee affects only the economic impact categories (related to the users and to the supply chain). A linear relation between the economic impacts (users' costs or supply chain margin) and the leasing fee is shown in Fig. 14. This analysis shows that an economic win-win situation persists in the range (−10%; +40%). In this range, users can save money compared to the baseline (users' costs in the CE scenario are lower than in the baseline), and the supply chain still achieves a higher margin (the margin in the CE scenario is higher than in the baseline).

## 6. Discussion

### *6.1. RQ1: How to assess the sustainability impacts of Circular Economy scenarios in a systemic way?*

System-thinking is one of the main requirements for adopting the CE paradigm (Lieder and Rashid, 2016) and is essential to achieve a comprehensive assessment of CE actions, addressing issues such as life cycle burden shifting, and preventing unintended consequences (Kjaer et al., 2016; Rigamonti and Mancini, 2021). In this research we have pointed out that such a systemic approach, despite being largely advocated by literature (Desing et al., 2020), struggles in finding implementation in assessment studies, as shown by our review on the (W)EEE industry. This paper provides an answer to RQ1 by developing a model that adopts a systemic perspective through the joint consideration of: (i.) the combined adoption of different CE actions, that may act on different levels such as product design, business models, and supply chain; and are supported by different enabling factors such as digital technologies, users' sustainable behavior and government interventions; (ii.) the evaluation of their impact on the three sustainability pillars (economic, environmental, and social); (iii.) their computation at different aggregation levels (micro and macro). Therefore, the first contribution of this paper is to be found in the systemic conceptualization of the 'building blocks' of a CE model and in the definition of an experimentation process to be followed in the assessment of CE scenarios, as graphically summarized in Fig. 15. This systemic approach overcomes the limitations of current literature on the evaluation of the sustainability impacts of CE scenarios (Howard et al., 2022; Roci and Rashid, 2023; Walzberg et al., 2020), since it provides a complete sustainability outlook and guidance for policy and industry decision makers.

The second contribution stands in the modelling approach adopted. The aim is to conduct what-if analysis to compare linear and CE scenarios in a systemic perspective, to evaluate the potential of circular scenarios and provide their snapshot in the steady state to verify their long-term sustainability. The what-if simulation model allows comparing systemic steady state scenarios, accomodating a high level of detail complexity (Grösser, 2017; Seila, 2006; Wayne, 2004). To achieve this result, different modelling approaches were combined: the LCA method for the definition of the functional unit, product system and system boundaries; the LCA, LCC and TCO methodologies for the mathematical formulation of the impacts at the environmental and economic levels; and the Material Flow Analysis and System Dynamics to inspire the definition of the Stock and Flows and their relations with product lifespan.

The third contribution stands in the development of a spreadsheet tool specific to the WM application case, that is provided in the Supplementary Material to this paper. The tool allows research experimentation and decision-making support for practitioners and policymakers. The tool, based on the definition of a combination of CE levers and enabling factors (scenario modelling), allows setting the relevant parameters (parametrization), and then measuring the impacts at the economic, environmental, and societal levels. A comparison of different scenarios can be carried out, as exemplified by the application in Section 5 to a digital servitization-based CE scenario, to assess its sustainability outcomes. The tool is flexible in accommodating different aggregation strategies to easily measure impacts at different levels. This puts into practice the recommendations of extant literature, which acknowledges different micro-meso-macro approaches and levels of analysis of CE endeavors (Ghisellini et al., 2016; Masi et al., 2017; Murray et al., 2017).

### *6.2. RQ2: In which conditions can Circular Economy business models based on digital servitization lead to win-win-win solutions on the triple bottom line?*

As shown in Section 5, the analyzed digital servitization-based CE

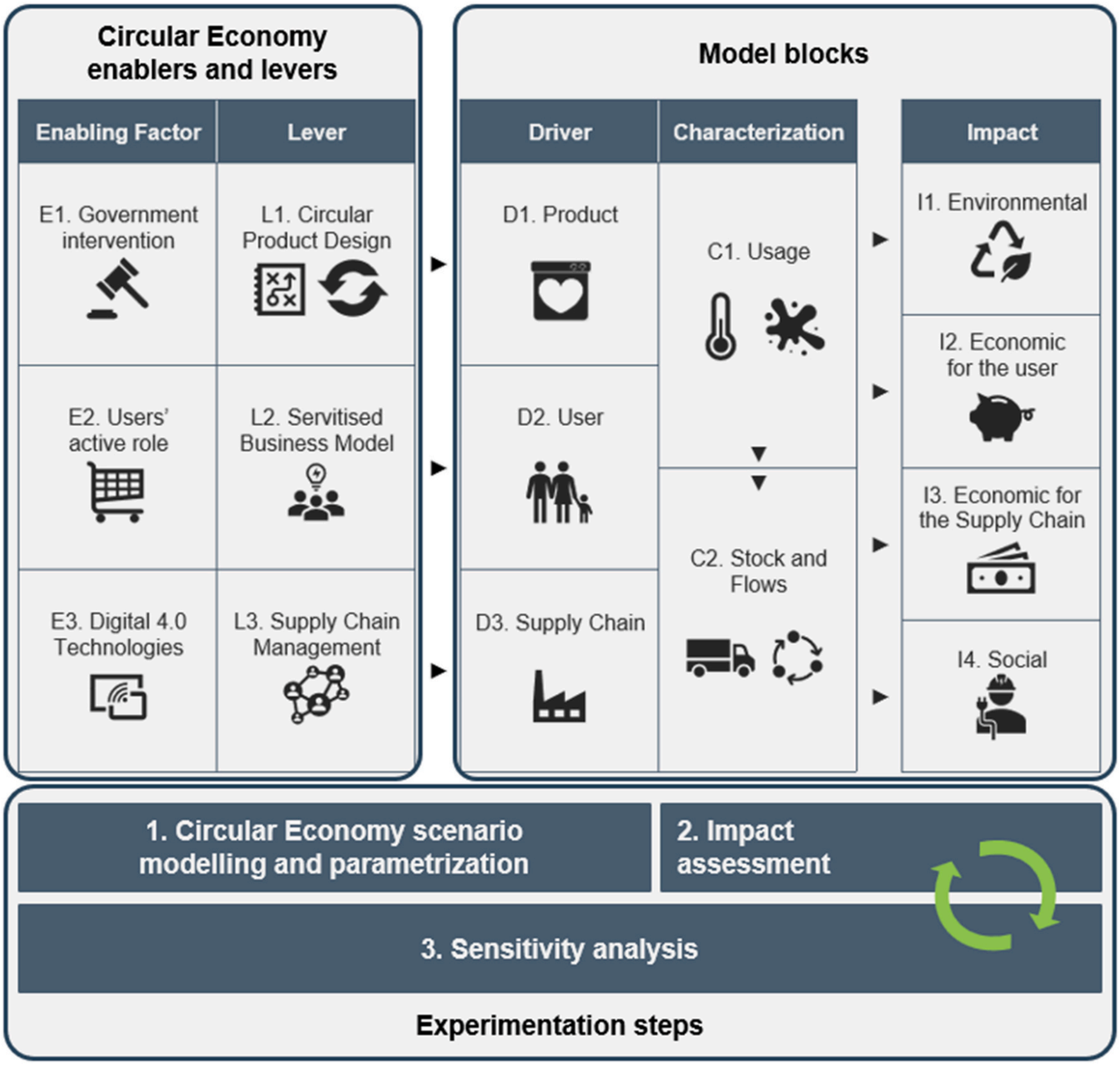


**Fig. 15.** Systemic conceptualization of Circular Economy levers, enablers, model blocks, and experimentation process.

scenario in the WM industry projected at the European level can lead to positive effects on the environment, on the society, and on the economy in the long run. This can be considered as a relevant research contribution of this study. Previous studies, as analyzed in Table 1, supported our findings (Guzzo et al., 2021; Roci et al., 2022). For instance, the environmental sustainability of servitization-based CE solutions compared to traditional offering has been quantitatively confirmed for different geographical contexts: Klint and Peters (2021) showed that shared laundries in Sweden would reduce carbon emissions by approximately 26%; Sigüenza et al. (2021) reported that pay-per-wash business model have 14% less carbon emissions than counterparts in the Netherlands; and Wasserbaur et al. (2020) described how sharing WMs at a European level would reduce carbon emissions by 35%. From a user' perspective, previous literature also showed that pay-per-use business models for WMs can be economically attractive as they lead up to 27% lower operating expenses, although challenging for manufacturers (Roci et al., 2022; Roci and Rashid, 2023). However, these studies lacked a comprehensive and systemic evaluation at different aggregation levels and sustainability dimensions.

The conditions under which these results are achieved are showed in the scenario parametrization and stressed in the sensitivity analysis, which highlights that a convergence among servitization and sustainability outcome is a result of the joint deployment of business models that decouple companies' revenues from products sales, which in turn lead companies to design products that last and to collect them at the end of use for reuse and refurbishment (Ellen MacArthur Foundation, 2012; Tukker, 2015). In this light, the enabling role of digitalization is confirmed as a key driver to achieve the sustainability benefits on the triple bottom line. Besides being an enabler for digital servitization and smart services, digitalization through sensorization and IoT for data collection contributes to product redesign for life extension and energy efficiency (Alcayaga and Hansen, 2019; Bressanelli et al., 2018), to users' engagement and involvement in reducing the consumption of products during usage (Bocken et al., 2018), and to closing the loop through reuse and refurbishment by supporting tracking and tracing for reverse logistics (Boldoczki et al., 2021; Roci and Rashid, 2023). All these concepts have been widely discussed in literature, although in a qualitative way and without taking a systemic perspective. To the best of the authors' knowledge, this is among the first studies that carries out a systemic and quantitative evaluation of the sustainability potential of a digital servitization-based CE business model. The quantitative assessment of the effects (and trade-offs) due to the combined adoption of multiple CE levers and enabling factors in a digital servitization scenario is another relevant contribution of this research, involving both the servitization and CE research domains, that translate into actionable knowledge in a specific industry the general knowledge of the potential benefits of digital servitization.

While this result is specific for the WM industry case analyzed and for the data used to feed the model, the sensitivity analysis supports the idea that business models that limit the manufacturing of new goods (inflows), optimize their resource efficiency along the lifecycle, and promote circularity (reuse and refurbishment) will provide economic, environmental, and social benefits in the long run. This principle can inspire the experimentation of similar digital servitization scenarios in different industries (both through simulation and practical pilot case studies). For instance, through the sensitivity analysis, this study shows that increasing the lifetime of products is only desirable for the supply chain under a servitized business model. This shows how the simultaneous application of different actions represents a very promising hotspot for the CE, leading to win-win-win solutions, and may drive research and practical endeavors to design sustainable business models not based on servitization alone but rather on inserting servitization in a broader set of systemic actions (product redesign, users' engagement, product reuse, remanufacturing, and recycling).

## 7. Conclusions

Companies, institutions, and policymakers need support to carefully assess the sustainability impacts of CE scenarios in a systemic way, to evaluate their potential benefits and associated risks. Recent works have dealt with the assessment of CE impacts. However, there is still a paucity of research that attempts to evaluate the effects of a transition towards CE following a systemic approach on a combination of multiple actions (including digital servitization) at the economic, environmental, and social level, and adopting a joint micro-macro perspective. To provide a first step into closing this gap, this work has developed a what if simulation model, implemented in a spreadsheet tool. The model provides a deeper understanding on how the main economic, environmental, and social impacts of a CE scenario can be identified, assessed, and quantified in a systemic perspective. The systemic conceptualization of CE actions, enabling factors, configuration drivers, characterization blocks, and triple bottom-line impacts proposed in this paper supports the assessment of CE scenarios and their sustainability potential. The model was specifically applied to assess the sustainability impacts of a digital servitization-based CE business model in the WM industry, showing that, by combining digital servitization with actions at the product design and reverse logistics level, benefits on the triple bottom line can be achieved in the long run at the micro and macro levels. This study adds to the current body of knowledge of servitization and CE, shedding light on the sustainability potential of digital servitization-based CE scenarios and on the conditions that allow achieving sustainability win-win-win solutions.

This paper also provides significant managerial and policy implications. Both the systemic conceptualization and the what-if simulation model are meant to assess the results of practical CE scenarios arising from the industrial world. They supported the process of experimentation through scenarios definition, parametrization, and assessment, as exemplified in this paper. Practitioners and policymakers may use the tool to support ex-ante evaluation of different CE scenarios, and to verify ex-post the gained benefits, especially on the environmental and social pillars at the meso and macro levels. Companies in the private sector can be interested in knowing if implementing CE scenarios based on digital servitization are likely to result (or not) in sustainability improvements on the different sustainability dimensions, especially at the micro and meso levels. Results can also support the design of specific CE policies and agendas. For instance, policymakers may use the results about the total environmental savings or the jobs generation opportunities to set supportive legislation and incentives to the adoption of CE and digital servitization strategies.

This research bears also limitations that suggest future research developments. First, the what-if simulation model and the spreadsheet tool have been deployed and tested on a single industry, with therefore limited generalizability. Several applications to other products, industries and supply chains are envisaged, to verify the effectiveness of the systemic conceptualization, model, and tool in other domains. Second, the what-if simulation model has specific limitations. The model does not discount cashflows, it focuses on a limited number of indicators, it is based on the steady state assumption, and it overlooks the effects of indirect jobs. Third, spreadsheet simulation has inherent limitations in dealing with feedbacks, which can lead to self-referenced loops (Seila, 2006). As a result, our spreadsheet tool does not comprehensively capture the mechanisms of several feedbacks such as the 'law of demand' (relation between WM price and sales), product obsolescence (WM efficiency can decrease with wear and increase with the advancement of technology, so their substitution by more efficient products in the future can be environmentally preferable), or other dynamic issues that would require dynamic simulation techniques to properly address them. Each of these limitations provides a promising avenue for future model modifications and refinement.

Lastly, two promising research directions are pointed out. First, this article evaluates the sustainability impacts of a specific CE case study based on digital servitization. Nevertheless, the what-if simulation model has been designed to support a systemic evaluation of different alone and combined CE actions, including product redesign, sharing business models, remanufacturing, and so forth. A promising avenue for future research is to use the model to compare different CE scenarios and evaluate their specific and combined sustainability impacts, in a way to understand which actions have greater potential in terms of sustainability impacts. Second, our results indicate that digital servitization-based CE business models can lead to win-win situations where both users and providers gather economic gains. However, behavioral changes or systemic responses triggered by these transformations may have unintended consequences, such as an increase in consumption and production within other production systems due to how users and providers may spend their saved money (Zink and Geyer, 2017). These unintended consequences, known as rebound effects, may partially or entirely offset the intended environmental, social, and economic benefits (Ackermann and Tunn, 2024; Castro et al., 2022; Metic and Pigosso, 2022). Our research does not effectively capture the complexities associated with direct, indirect, and macro-economic rebound effects (Guzzo et al., 2023), since our simulation model is bounded on the life cycle of a specific product system. How rebound effects can be quantified and incorporated in the model is therefore an intriguing future research avenue.

## CRediT authorship contribution statement

**Gianmarco Bressanelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicola Saccani:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Perona:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142512.

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