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# Circular supply chains theoretical gaps and practical barriers: A model to support approaching firms in the era of industry 4.0

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ABSTRACT

Unlike linear supply chains, Circular Supply Chains (CSCs) require return flows able to capture additional value and involving different stakeholders. The successful interaction of Circular Economy and Industry 4.0 (I4.0) towards a circular, efficient, and competitive transition of current supply chains is unveiled by both current state of theory and practice. Notwithstanding literature's multiple attempts to flank supply chains in this complex shift, the several theoretical frameworks proposed by academics are still not fully capable of bridging linear supply chains to their transitions towards circularity due to a lack of systemic, company-specific, and practical approaches. In addition, practical impediments, risks and treats hindering CSCs development are still under-investigated and, therefore, further research is required in this domain. To address these gaps, this paper aims to develop and propose a model able to support companies in approaching the transition towards CSCs, also embedding guidelines and recommendations in the different steps of this path. The model has been conceptualized based on five I4.0-driven CSCs categories recently proposed through a systematization of the knowledge extant in literature (I4.0 enabling technologies, performance tools and indicators, challenges and barriers, business models and strategies, best practices) and on a gap analysis performed in literature to unveil theoretical gaps and practical barriers in the CSC domain. Finally, the model has been refined and validated by ten selected academic experts through an online asynchronous survey, leading to the detection of seven recurrent practical barriers (lack of tax policies and incentives, weak environmental laws and regulations, limited financial resources and support, high investments and implementation costs, lack of coordination and collaboration among the SC members, lack of technological resources and infrastructures, lack of compatibility and integration of technical platforms) as the most critical in the CSC transition. The model, structured in four main phases (conceptualization, design, implementation and measurement) and grounded on the five categories derived from the literature, addresses each of the steps of the CSC transition according to circular strategies and optimal digital technologies. Managerial implications emerge from the systematization and categorization of methods, approaches and warnings operated in the model proposed. The model turns to be capable of enhancing the realization of the entire CSC process in a digital context, acting against the CSC theoretical gaps and practical barriers detected in the gap analysis conducted in this research.

## 1. Introduction

Circular Economy (CE) and Industry 4.0 (I4.0) are the two main paradigms moving the transition of current Supply Chains (SCs) towards higher efficiency and competitiveness (Rajput & Singh, 2019; Rosa et al., 2020). Several frameworks (Garrido-Hidalgo et al., 2020; Ivascu, 2020; Y. Kazancoglu et al., 2018), models (Hoffa-Dabrowska & Grzybowska, 2020; Safiullin et al., 2020; Tripathi & Gupta, 2020), methodologies (Fernández-Caramés et al., 2019; González Rodríguez et al., 2020; Hussain & Malik, 2020; Tiwari, 2020) and KPIs (Ante et al., 2018; Morella et al., 2020; Singh et al., 2019; Wei et al., 2014) presented in literature demonstrated the interaction among CE, I4.0 and SCs towards a circular shift.

Unlike linear SCs, Circular Supply Chains (CSCs) involve return flows able to capture additional value, also leveraging on multiple waste management strategies and process treatments (Colangelo et al., 2023). Different terms like closed-loop (CLSC), open-loop (OLSC), reverse and green SC have been used in literature to refer to CSCs. CLSCs involve Original Equipment Manufacturers (OEMs) with the aim of reusing

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**Nomenclature**

*Acronyms:*

| | |
|---|---|
| CE | Circular Economy |
| SC | Supply Chain |
| SCM | Supply Chain Management |
| CSC | Circular Supply Chain |
| CSCM | Circular Supply Chain Management |
| CLSC | Closed-loop Supply Chain |
| OLSC | Open-loop Supply Chain |
| SSC | Sustainable Supply Chain |
| SSCM | Sustainable Supply Chain Management |
| BM | Business Model |
| CBM | Circular Business Model |
| 3Rs | Reuse-Recycle-Remanufacturing |
| LC | Life Cycle |
| EoL | End of Life |
| TBL | Triple Bottom Line |
| I4.0 | Industry 4.0 |
| UWB | Ultra-Wide Band technology |
| EVB | Electrical Vehicle batteries |
| IoT | Internet of Things |
| BDA | Big Data Analytics |
| AM | Advanced Manufacturing |
| CPS | Cyber Physical System |
| CSF | Critical Success Factor |
| LCA | Life Cycle Assessment |
| RFID | Radio Frequency Identification |
| WM | Waste Management |
| M&EE | Material and Energy Efficiency |
| OEM | Original Equipment Manufacturer |
| DSS | Decision Support System |
| IS | Industrial Symbiosis |
| SME | Small and Medium Enterprise |
| CD | Circular Design |
| A Rob | Autonomous Robots |
| IoT | Internet of Things |
| UAV | Unmanned Aerial Vehicle |
| IP | Internet Protocol |

recovered materials. On the other hand, OLSCs consider even broader interactions with third parties (Hussain & Malik, 2020). Green SCs encourage cooperation mechanisms (e.g., product design, suppliers' selection and distribution chains) to reach more sustainable economic and environmental performances (Y. Kazancoglu et al., 2018; Masi et al., 2017). Reverse SCs include activities (e.g., product design, operations and End of Life (EoL) management) trying to maximize the value creation and retention for the entire product lifecycle (Genovese et al., 2017).

Despite the various theoretical classifications and applications, there is still a gap related to the identification of the current issues acting against the development of CSCs. Like already evidenced by a recent systematic literature review by Taddei et al. (2022), there is a lack of attention about practical impediments towards a CSC transition, suggesting a further assessment about the difficulties encountered by the approaching organizations. This gap can be due to both CE and I4.0 reasons. From one side, Circular Business Models (CBMs) and industrial strategies suitable to this new context are still under either development or implementation (Rosa et al., 2019). On the other hand, several contributions highlighted the necessity of I4.0 technologies, like Narwane et al. (2021), stating that the adoption of sustainable I4.0 is a key aspect in manufacturing industries to combat global competition, or Dąbrowska et al. (2022) and Floyd et al. (2024), discussing the disruptive effect of digital technology. However, a lack of content is still present in the CSC domain due to the fact that few contributions were able to identify how I4.0 technologies can be practically applied and when they should be implemented to support the CSC implementation and to enhance organizations' circular maturity level (and to overcome the practical barriers occurring during their adoption). To fill this gap, new artifacts (frameworks, models, and methods) supporting the CSC transition of companies through I4.0 technologies are needed. Therefore, the main objective and novelty of this paper is to propose a model able to support companies in approaching the transition from linear to CSCs and to provide them with guidelines and recommendations (in terms of suitable approaches and methods, circular manufacturing strategies, and I4.0 technologies) useful to understand how to cope with the multiple issues that could occur in the different steps of this transition.

The model, during its conception, has been grounded on the 5 categories detected in the recent systematic literature review by Taddei et al. (2022) which was conducted to systematize the theory related to the threefold domain of CE, I4.0 and CSC: CSC I4.0 enabling technologies (focusing on the role of I4.0 technologies in the CSC adoption), CSC performance tools and indicators (concentrating on guidelines and practical tools supporting the measurement of CSC performances), CSC challenges and barriers (discussing about challenging issues acting against the development of CSCs), CSC business models and strategies (presenting managerial and organizational models related with CSCs) and CSC best practices (clustering successful case studies in terms of CSCs). In addition, the model has been conceived based on the results of an analysis of the literature performed to detect the main theoretical gaps and practical barriers hindering the transition of SC from linear to circular. Indeed, the novelty of the proposed model resides in its aim of providing practical support, useful insights, and warnings embedded on it to guide practitioners along the different steps of the transition process from linear to CSC and against the barriers and gaps detected.

Based on this objective, this research addresses the following questions:

- RQ1: Which are the major theoretical gaps and practical barriers hindering the implementation of a CSC?
- RQ2: How to foster the transition of companies from a linear to a CSC exploiting the most suitable I4.0 technologies while copying with the typical impediments of this shift?

The paper is structured as follows. Section 2 describes the research context. Section 3 displays the adopted research methodology. Section 4 provides the main findings. Section 5 discusses the validation and implications of the work. Section 6 argues conclusive considerations while debating limitations and future research trends.

## 2. Research context

To better ground the development of the model proposed in this research, a detailed analysis of the extant frameworks and models related to CSCs (selected from the sample of articles selected by the systematic literature review performed by Taddei et al. (2022)) has been implemented. In particular, two main contributions have been detected (González-Sánchez et al., 2020; Jain et al., 2018) respectively belonging to the CSC business models and strategies and CSC performance tools and indicators categories. Indeed, given that the two papers are particularly in line with the aim of the model proposed in this research, they have been used as a guide for its conception. González-Sánchez et al. (2020) proposed a conceptual model to support the CSC design and implementation based on the 4 main dimensions (relation structure, adaptation of logistics and organizational, disruptive and smart technologies, functioning environment). Successful circularization requires integrated synergic actions by all actors and sectors involved, supported by improved flows of knowledge. In addition, the company needs to adapt both logistically and organizationally. Reverse logistics encourage the return of material, Industrial Symbiosis (IS) favours the exchange of waste between industrial partners, while CBMs model the dynamic management of the resource loops. The main role of information and communication technologies is the application of innovative and efficient methods to optimize the economic processes of production, consumption, and circulation. As a final point, the company can capture value through long-term agreements, the establishment of reward systems, and the achievement of financial and legal commitments.

On the other hand, Jain et al. (2018) proposed a 3-dimensional strategy for CSCs incorporating innovative Business Models (BMs) (strategic level), product design or eco-design (tactical level) and effective Supply Chain Management (SCM) (operational level) decision making. A successful transition to a CSC, indeed, requires multi-dimensional changes such as: product redesigning, reducing SC complexity, adopting innovative BMs and continual measurement of progress towards circularity. In this sense, the paper provided some general multi-dimensional indicators for CSCs, in opposition to the traditional ones.

The two contributions have shown the importance of holistic frameworks in helping companies to ensure an environmental consciousness and in providing a roadmap in terms of environmental, economic, logistical, operational, and organizational activities to adopt CSC models effectively. However, besides the systematicity, the two works share a generic approach focusing on boundary conditions of CSCs rather than proposing proper specific characteristics, expectations, and practical insights. Vice versa, this paper aims at addressing the CSC transition through the perspective of an approaching company.

Hereunder, Table 1 highlights the main characteristics and missing features of the two models.

## 3. Research methodology

The research method adopted in this work is composed by three main subsequent phases: conceptualization, development, and validation (Fig. 1). Based on the method grounded on Design research Methodology (DRM) (Blessing & Chakrabarti, 2009), developed by (Sassanelli et al., 2019) according to inductive reasoning and subsequently adopted in the development of multiple artifacts (e.g., (Lamperti et al., 2023; Sassanelli & Pacheco, 2024; Urbinati et al., 2023)), these steps allow to structure the analysis and the groundwork for the creation of a CSC model able to guide and support interested practitioners in the CSC transition.

The research was triggered by a very recent systematic literature review on the same topic of this research (i.e., CSC in the I4.0 domain), providing a clear systematization of the extant related knowledge. Therefore, starting from the systematic literature review performed by Taddei et al. (2022), its findings (i.e., analysis and gathering of the CSC literature in 5 categories) have been taken as a reference to guide the analysis and the model implementation.

Based on these categories, a further analysis of the sample of literature previously detected by Taddei et al. (2022) has been performed to conduct a gap analysis consisting in listing and categorizing theoretical (open points needing further investigations) and practical gaps (actual barriers regarding the implementation and the adoption of the CSC approach) of the twofold CSC-I4.0 research domain. Thanks to the insights collected from the literature in performing the gap analysis, the CSC model was built in the development phase.

The methodology for the implementation of the model, deeply described in Section 4.2, follows the necessity to address each phase of the CSC transition to support approaching firms in every single step (conceptualization, design, implementation, measurement). Each step of the model provides companies with a set of approaches, guidelines and practices to follow, and warnings to be aware of during the CSC transition. Finally, to have a proof and a confirmation of the model effectiveness and accuracy, its findings have been validated by interviewing experts of the field. In the following sub-sections, the three main phases conducted to perform this research are described in detail.

**Table 1**
Valuable and missing features of the models extant in literature.

| Valuable characteristics | Missing features |
|---|---|
| 360° degrees vision | Company-specific approaches |
| Theoretical methods | Practical insights |
| Different sectors considered | Real impediments |
| Evaluations interest | Actual performance indicators |

### 3.1. *Model conceptualization: CSC gaps analysis*

The decision of analysing both the theoretical and the practical gaps lies in the willingness to ensure a solid investigation base to further enhance the development of the CSC model. Firstly, the theoretical gaps identified in literature have been detected to unveil to researchers which are the open points needing further investigations in the CSC domain. Secondly, the analysis concentrated on the practical gaps, namely the actual barriers unveiled in literature by researchers through the analysis of specific cases dealing with the actual transition, implementation and adoption of CSCs.

The in-depth analysis of the sample of contributions of 198 papers, previously detected by Taddei et al. (2022), led to select the 107 papers that were actually reporting at least one relevant theoretical gap. From the theoretical gap analysis, it turned out that the main barriers were *Practical Gaps* (G1) and *Systemic/integration gaps* (G2), suggesting deepening the investigation of the practical barriers occurring when adopting a circular approach in SCs. To further investigate and detect these practical impediments from the literature, the analysis has been shrunk from the 107 to 52 articles composing the *CSC challenges and barriers* category (defined by Taddei et al. (2022)). Among them, selecting the articles presenting a critical and systematized discussion about relevant barriers in the context of CSC, 13 documents have been taken as a reference for the final practical barriers' selection.

### 3.2. *Model development*

To build the model, based on the results coming from the previous step (i.e., Model Conceptualization), the phases of the model were defined and each of them were linked and described according to the five CSC categories (CSC I4.0 enabling technologies, CSC performance tools and indicators, CSC challenges and barriers, CSC business models and strategies and CSC best practices). Then, based on the analysis of the literature performed, the phases of the model were further characterized according to the following set of features (previously used also in the Taddei et al. (2022) paper): proposition type (framework, approach, guidelines, model, methodology, tool), Triple Bottom Line (TBL) (economic, environmental, social) (WCED, 1987), CE strategies (Cleaner Production (CP), CBMs, Waste Management (WM), Disassembly, Remanufacturing, Reuse, Recycle (3Rs), Servitization, Industrial Symbiosis (IS) and eco-industrial parks, Material and Energy Efficiency (M&EE) and Circular Design Practices (CDPs)) (Acerbi & Taisch, 2020) and I4.0 technologies (Big data and analytics (BDA), Autonomous robots (A Rob), Additive manufacturing (AM), Simulation, Augmented reality (AR), Horizontal and vertical system integration (H&VSI), the Internet of Things (IoT), Cloud and Cyber-security) (Rüßmann et al., 2015). In this way, for each phase of the model, specific characterizations (in terms of CE strategy and I4.0 technologies involved), and successful recurrent practices and approaches have been listed. Finally, the encountered practical barriers have been analysed and assigned to each

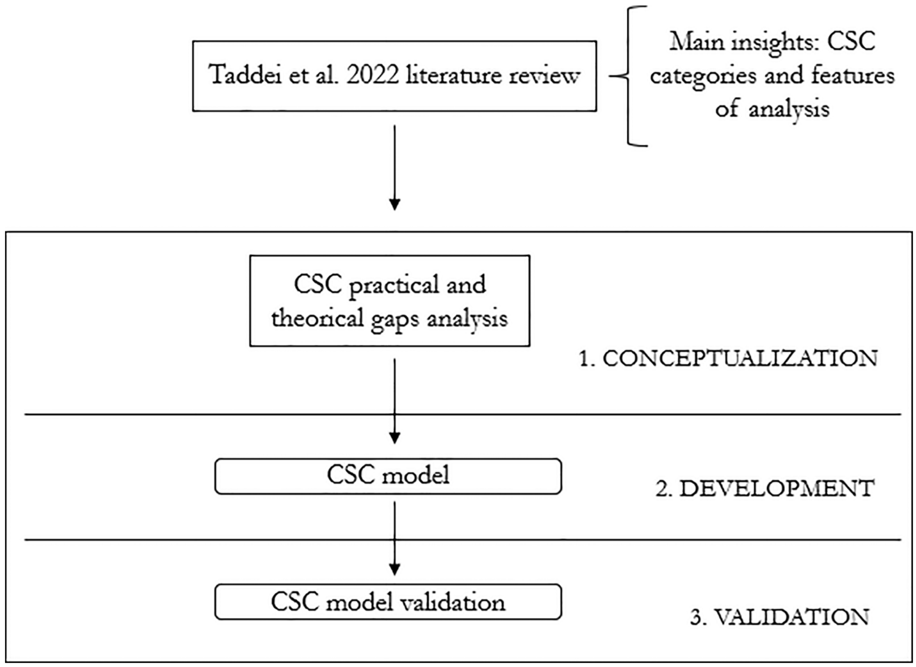


**Fig. 1.** Research methodology adapted by Sassanelli et al. (2019).

of the three phases of the model to provide warnings and support the realization of the transition.

### 3.3. Model validation

This third step of the research methodology consists in the scientific validation of the proposed model. The aim was to verify and validate the reliability and relevance of the model through field experts to guarantee its applicability in the industrial context. To do so, the results obtained from the analysis of the practical barriers and the phase 2 of the model (i.e., Model Development) have been used as the input to construct an interview protocol. The protocol (containing 23 questions) has been structured to allow an online asynchronous survey. The 3 following paragraphs describe in detail the methodology adopted to validate the model.

#### 3.3.1. Protocol design

The protocol used to validate the model has been designed to understand its value. The questions were aimed at investigating the correctness, completeness, and coherence of the model, of each of its single phases, and of the technologies, methods, and practices linked to each of them.

The 23 questions have been structured as follows:

- Questions from 1 to 5 were less specific and aimed to present the main outcomes of the analysis and to acquire feedback about both the results obtained and the model structure. Respondents were asked for their opinions about the 5 CSC categories of analysis and their overall comprehensiveness within the research field. Then, experts were asked to rank the practical barriers categories (financial/economic, technical, legislative/political, organizational and social) and select the respective 5 most important ones among the 17 proposed, according to their experience and knowledge. The last two questions concerned the CSC model. The first one was related to the articulation of the 5 CSC categories in the 3 phases of the model (conceptualization, design, measurement) while the second questioned the relevance of the 17 practical barriers related to the 3 phases.
- Questions from 6 to 23 were dealing with the specific outputs of the model, according to its division in the 3 main phases and their characterization based on practical gaps, proposed practices, I4.0 technologies, and CE strategies. In detail, for each of the 3 phases, respondents were asked to:
- identify the most relevant practical barriers characterising each specific phase, among those emerged from the literature,
- suggest any further practice or approach,
- identify the most important I4.0 technologies among those emerged from the literature as characterising the specific phase, and eventually suggest others,
- identify the most important circular strategies characterising each specific phase among those emerged from the literature, and eventually suggest others.

For the entire survey, the intention was firstly to ask respondents questions related to their experience and knowledge about the CSC domain and then to present the model proposed in this research to avoid biased answers. The complete list of questions is available in the Additional Materials section.

*3.3.1.1. Experts' selection.* Experts have been selected based on their expertise in the twofold CE-SC research domain. Therefore, the contacted academics were experts in CSC, called to verify the value of the model proposed, in terms of phases, relationships, technologies involved, and related practices.

The experts were selected and chosen through Scopus among those who had published at least an article with the words CE and SC in the title and, therefore, characterized by experience about the CSC and sustainable supply chain management. Another requirement was the years of experience, for which the minimum value of 10 years was chosen (always through Scopus).

Thirty experts were selected and invited by the authors to participate to the survey through multiple emails (three reminders have been sent in one month, every two weeks, from 15th of December 2022 up to 15th of January 2023). Hereunder (Fig. 2) a graph reporting invited experts' nationality is displayed.

*3.3.1.2. Conduction of the interviews.* The content of the invitation email

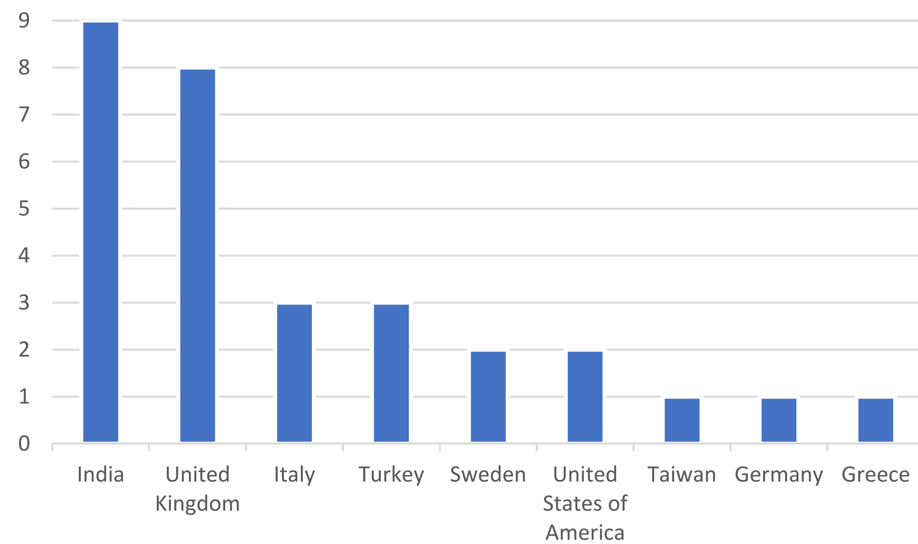


**Fig. 2.** Experts' affiliation nationality and diffusion.

was constituted by the presentation of the research team, the aim of the study, the paper (Taddei et al., 2022) attached as main reference, and the link to the online survey built with Microsoft Forms (an online survey creator, part of Office 365). It was also specified that the survey was intended to verify the value of a new model proposed to support the transition towards CSCs.

The first 10 received answers were taken in consideration to validate the CSC model validation. An answer rate of 33 % of the invited experts was reached in one month, with an approximate completing time of less than 15 min.

*3.3.1.3. Feedback analysis.* Subsequent to the responses collection, three researchers have independently analysed the answers to grasp the main feedback from the survey. The collected answers proved the comprehensiveness of the analysis performed throughout the five categories and the coherence of the model built upon them.

The feedback regarding the proposed seventeen practical barriers confirmed the literature trend, highlighting peculiarities encountered in day-to-day practices (as further discussed in Section 5). As a result of the question asking to indicate the five most important practical gaps, only ten were listed as relevant by at least one expert. Then, of these ten, seven were considered as ultimately relevant since more experts have appointed them in first/second position. Therefore, the final output of Phase 3 (Model Validation) provided the improved and validated CSC model (flanked by prioritized barriers aiming to support companies willing to approach the CSC transition.

## 4. Main findings

The main results of this research consist in the theoretical gaps and practical barriers unveiled with the CSC gaps analysis during the conceptualization phase (presented in sub-section 4.1), and the finalized CSC model obtained after its validation (shown in sub-section 4.2).

### *4.1. Theoretical gaps and practical barriers*

#### *4.1.1. CSC theoretical gaps*

The theoretical gaps in the CSC domain coming from the literature have been gathered in 10 categories, ordered according to the decreasing diffusion rate.

- Practical gaps (G1): deficiency of solutions, implementations, techniques, initiatives, and solutions to practically enhance the CSC adoption;
- Systemic/integration gaps (G2): lack of a systemic approach able to comprehend and integrate all the 3 topics of the research context (I4.0, CE, CSC);
- Theoretical/general gaps (G3): lack of research, studies, evolution of science, knowledge and theoretical understanding about general concepts related to CSCs;
- Gaps about barriers/risks/treats (G4): not detected barriers, risks and treats in the CSC domain;
- Gaps about potentialities/benefits (G5): not defined the benefits that could be achieved adopting a CSC;
- Gaps about perspectives (G6): various perspectives not analysed in detail, for instance the social related one;
- Strategical/business-based gaps (G7): lack of strategical approaches, managerial discussion, systemic management, and strategic plan;
- Measurable gaps (G8): metrics, indicators, evaluations, and measurable effects missing in the context of CSC;
- Gaps about enablers (G9): the main enablers, such as technologies, not fully explored;
- Formal gaps (G10): lack of formal identifications, definitions, classifications, and standardization.

Besides this categorization, many contributions stressed more than one theoretical gap simultaneously. Table 2 presents the diffusion and characterization of the identified 10 gaps in relation to the 5 CSC categories.

By analysing the diffusion of the 10 gaps among the 5 CSC categories, it turns out that the identified gaps are perfectly in line with the content developed in each of the 5 categories by Taddei et al. (2022).

The *CSC I4.0 enabling technologies* category collected, among the 5 categories analysed, the highest number (6) of Gaps about *Enablers* (G9), highlighting the importance of I4.0 technologies to foster the adoption of the circular approach. *Practical Gaps* and *Systemic/Integration Gaps* (G1 and G2) are the most relevant in this specific category. This result remarks the importance of studying the practical implications of technological advancements with a systemic aim.

As could be expected, for the CSC performance tools and indicators category, the most impactful gap (with an occurrence of 10) was *Measurable Gaps* (G8). The research domain, indeed, is deficient of measurable indicators to track the performances.

A combination of G1 (14), G2 (13) and G4 (12) characterizes the CSC challenges and barriers category. This consideration stresses the need of

**Table 2**
CSC theoretical gaps literature analysis.

| CSC CAT. | AUTHORSS | G1 | G2 | G3 | G4 | G5 | G6 | g7 | G8 | G9 | G10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CSC I4.0 enabling technologies | (Chiappetta Jabbour et al., 2020) | | | x | | | | | | x | |
| | (Cwiklicki & Wojnarowska, 2020) | x | x | | | | | | | x | |
| | (Borregan-Alvarado et al., 2020) | | x | x | | | | | | | |
| | (González Rodríguez et al., 2020) | x | x | | | | | | | | |
| | (Zeng et al., 2017) | x | x | | | | | | | | |
| | (Franco et al., 2020) | x | | | x | x | | | | | |
| | (Núñez-Merino et al., 2020) | | x | x | | | | | | | |
| | (Ramirez-Peña et al., 2020) | | x | | | | x | | | | |
| | (**J.** Sharma et al., 2020) | | | x | | | | | | | |
| | (Danjou et al., 2020) | x | | | | | | | | | |
| | (Raut et al., 2020) | x | | | | | | | | x | |
| | (Patrucco et al., 2020) | | | | | | | x | | | |
| | (Abdirad & Krishnan, 2020) | | | x | | | | | | | |
| | (Zekhnini et al., 2020) | | x | | x | | | | | | |
| | (Tiwari, 2020) | x | x | | | | | | | | |
| | (Moldabekova et al., 2020) | x | | | | | | | | | x |
| | (De Vass et al., 2020) | x | | | | x | | | | | |
| | (Chauhan & Singh, 2019) | | | x | | | | | | | x |
| | (Oncioiu et al., 2019) | | | x | | | | | | | |
| | (Ardito et al., 2019) | | x | | | | | | | x | |
| | (Ben-Daya et al., 2019) | | x | | | x | | | | | |
| | (Jermsittiparsert & Boonratanakittiphumi, 2019b) | | | x | | | | | | x | |
| | (Barata et al., 2018) | | | | x | | x | | | | |
| | (Ciccullo et al., 2021) | x | | | | | | | | | |
| | (Del Giudice et al., 2020) | | x | | | | x | | | x | |
| | **TOTAL PER CATEGORY** | **10** | **11** | **8** | **3** | **3** | **3** | **1** | **0** | **6** | **2** |
| CSC PERFORMANCE TOOLS AND INDICATORS | (Morella et al., 2020) | | | x | | | | | x | x | x |
| | (Ivascu, 2020) | x | | | | | | | | x | |
| | (Gružauskas et al., 2018) | x | | | | | x | | | | |
| | (Xie et al., 2020) | | | | | | | | x | | |
| | (De Giovanni & Cariola, 2020) | | x | | | | | | x | x | |
| | (Ehie & Ferreira, 2019) | | | | | | | | | x | |
| | (Singh et al., 2019) | | | | | | | | x | | |
| | (Walker et al., 2021) | x | x | | | | x | | x | | |
| | (Luo et al., 2021) | x | | | | x | | | x | | |
| | (Alkhuzaim et al., 2021) | | | | | | | | x | | |
| | (Doni et al., 2019) | | | | x | x | | | x | | |
| | (Jain et al., 2018) | | | x | | | | | x | | |
| | (**Y.** Kazancoglu et al., 2018) | | x | | | | x | | x | | |
| | (Genovese et al., 2017) | | | x | | | | | | | |
| | (Halstenberg et al., 2017) | x | | | | | | | | | x |
| | **TOTAL PER CATEGORY** | **5** | **3** | **3** | **1** | **2** | **3** | **0** | **10** | **4** | **2** |
| CSC challenges and barriers | (Kumar et al., 2021) | | x | | x | | | | | | |
| | (Ozkan-Ozen et al., 2020) | | x | | x | | | | | | |
| | (**G.** Yadav et al., 2020) | x | | | x | x | | | | | |
| | (**M.** Sharma et al., 2020) | | | | | | x | | | | |
| | (Bag et al., 2020) | x | | | | | | | | | |
| | (Princes, 2020) | x | x | | | | | | | | |
| | (Luthra et al., 2020) | | x | x | | | | | | | |
| | (Pandey et al., 2020) | | | | x | | x | | | | |
| | (Veile et al., 2020) | x | x | | | | | x | | | |
| | (**S.** Yadav et al., 2020) | x | x | | x | | | | | | |
| | (Ogbuke et al., 2020) | x | | | | | | | | | |
| | (Horváth & Szabó, 2019) | | | | x | x | | | | | |
| | (Krykavskyy et al., 2019) | | | | x | x | | | | | |
| | (Kaczmarek, 2019) | | | | x | x | | | x | | |
| | (Liboni et al., 2019) | | x | | | | x | | | | |
| | (Jermsittiparsert & Boonratanakittiphumi, 2019a) | | x | x | | | | | | | |
| | (Bienhaus & Haddud, 2018) | | | | x | x | | | | x | |
| | (**J. M.** Müller & Voigt, 2018) | | | x | | | | | | | |
| | (Ethirajan et al., 2021) | x | | | x | | | | | | |
| | (Dey et al., 2020) | x | | | | | | | | | |
| | (Jia et al., 2020) | | x | | | | x | | | | |
| | (Khandelwal & Barua, 2020) | x | x | | | | | | | | |
| | (Zhang et al., 2019) | | | | | | | x | | | |
| | (Paes et al., 2019) | | x | | | | | | | | |
| | (Sehnem et al., 2019) | x | | | | x | | | x | | |
| | (Farooque et al., 2019) | x | | | | | x | | | | |
| | (Piyathanavong et al., 2019) | x | | | | | | | | | |
| | (**Y. K.** Sharma et al., 2019) | x | | | | | | | | | |
| | (Lapko et al., 2019) | | x | x | | | | | | | |
| | (Braz et al., 2018) | | | x | | | | | | | |
| | (Mangla et al., 2018) | | | | x | | | | | | |
| | (Mishra et al., 2018) | x | x | | | | | | | | |

(*continued on next page*)

**Table 2** (*continued*)

| CSC CAT. | AUTHORSS | G1 | G2 | G3 | G4 | G5 | G6 | g7 | G8 | G9 | G10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (Zeng et al., 2017) | | | | x | x | x | | | | |
| | **TOTAL PER CATEGORY** | **14** | **13** | **5** | **12** | **7** | **6** | **2** | **2** | **1** | **0** |
| csc Business models and strategies | (Tozanlı et al., 2020) | x | | | | | | | | | |
| | (Manavalan & Jayakrishna, 2019a) | | x | x | | | | | | | |
| | (Tombido et al., 2018) | x | | | | x | | x | x | | |
| | (Mboli et al., 2020) | | | x | | | | | | x | |
| | (Ghosh et al., 2020) | x | | | | x | | | x | | |
| | (Hahn, 2020) | x | | | | | | | | x | |
| | (Zangiacomi et al., 2020) | x | x | | x | x | | | | | |
| | (Facchini et al., 2020) | | | | | | | x | | | |
| | (Garay-Rondero et al., 2019) | x | | | | | | | | | |
| | (Sundarakani et al., 2019) | | | | | x | | x | | | |
| | (Omar et al., 2019) | x | | | | | | x | | | |
| | (Asdecker & Felch, 2018) | | | x | | | | | | | |
| | (Hussain & Malik, 2020) | x | x | x | | | x | x | | | |
| | (González-Sánchez et al., 2020) | x | | | | | x | x | | | |
| | (Pohlmann et al., 2020) | | | x | | | | x | | | |
| | (Dubey et al., 2019) | x | | | | | | x | | | |
| | **TOTAL PER CATEGORY** | **10** | **3** | **5** | **1** | **4** | **2** | **8** | **2** | **2** | **0** |
| csc best practices | (Garrido-Hidalgo et al., 2019) | x | x | | x | | | | | | |
| | (Jensen & Remmen, 2017) | x | | | | | | x | | | |
| | (Mastos et al., 2020) | x | | | | | | | x | | |
| | (Bagalagel & Elmaraghy, 2020) | | | | | x | | | | x | |
| | (Shao et al., 2021) | x | | | | | | | | | |
| | (Frankó et al., 2020) | x | | | | | | | | | |
| | (Hetterscheid & Schlüter, 2019) | x | | | | | | | | | x |
| | (Bressanelli et al., 2020) | x | | | | | | | | | |
| | (Julianelli et al., 2020) | | | | | x | | | | x | |
| | (Van Engeland et al., 2020) | x | | | | | | x | | | |
| | (Santander et al., 2020) | | | x | | | | x | | | |
| | (Kühl et al., 2019) | x | | x | | | | | | | |
| | (Niu et al., 2019) | | | x | | | | | | | |
| | (Islam & Huda, 2018) | x | | | | | | | | | |
| | (De Angelis et al., 2018) | | x | | | | | x | | | |
| | (Bernon et al., 2018) | | x | | | | x | x | | | |
| | (Herczeg et al., 2018) | | | x | | | | | | | |
| | (Mulrow et al., 2017) | | | | | | x | | | | |
| | **TOTAL PER CATEGORY** | **10** | **3** | **4** | **1** | **2** | **2** | **5** | **1** | **2** | **1** |
| OVERALL TOTAL | | **49** | **33** | **25** | **18** | **18** | **16** | **16** | **15** | **15** | **5** |

a critical, practical, and holistic analysis of the major impediments when adopting CSCs.

Regarding *CSC business models and strategies category*, several G7 (8) have been highlighted together with G1 (10) deficiencies. The research domain looks, indeed, scarce of managerial considerations to support and enhance the practical implementation of SC changes.

Lastly, the *CSC best practices* category stressed the necessity of more practical cases (G1) that can be taken as a reference by interested companies.

The theoretical gaps can be also analysed singularly, as follows.

In detail, *Practical Gaps* (G1) were recognised as a lack of directions when managing the production in a CLSC context with uncertainties (González Rodríguez et al., 2020), lack of guidelines or roadmaps to implement I4.0 enabling technologies specific to the manufacturing and SC (Raut et al., 2020) and lack of applications guidance of BDA in the context of SCM (Ogbuke et al., 2020). Investigations about the implications of I.4.0 for SC operating models, received only limited attention in the literature (Hahn, 2020). Moreover, Garay-Rondero et al. (2019) discussed the deficiency of solid frameworks to provide guidance for IoT and Cyber Physical Systems (CPS) adoption in a SC context with clear guidelines and models addressing SC problems in an new technological environment. Lastly, a lack of general CSC practices was raised (Kühl et al., 2019).

*Systemic/integration gaps* (G2), integrating various aspects, are scarce in the research domain. For instance, Ramirez-Peña et al. (2020) denounced a lack of integration of the 3 TBL layers into the SCM, while an holistic view of implementing Circular Supply Chain Management (CSCM) in the Indian plastic industry was raised by Khandelwal & Barua (2020). Lapko et al. (2019) suggested a limited holistic understanding of CLSC considering multiple actors.

Regarding the *Theoretical/general gaps* (G3), deserve to be reported the evolution of science in the fields of I4.0 and AM (Borregan-Alvarado et al., 2020), studies related to BDA (Oncioiu et al., 2019) and to the relationship between SCM and Knowledge Management (Jermsittiparsert & Boonratanakittiphumi, 2019a).

Examples of *Gaps about barriers/risks/treats* (G4) can be observed in a deficiency of definition of synchronized integrated barriers of CSC and I4.0 (Ozkan-Ozen et al., 2020), challenges adopting decision making approaches in Sustainable Supply Chain (SSC) (S. Yadav et al., 2020) and CSC risks (Ethirajan et al., 2021).

On the other hand, *Gaps about potentialities/benefits* (G5) of the CSCs adoption have not been discussed in depth. Lack of Critical Success Factors (CSFs) for improving SSC performance through operational excellence approaches was stressed by Sehnem et al. (2019). Moreover, potential benefits of the emerging technologies in the I4.0 field of remanufacturing and product recovery systems have received less attention (Bagalagel & ElMaraghy, 2020).

*Gaps about Perspectives* (G6) did not collect relevant considerations. The existing studies on the I4.0 have mostly focused on analysing the technological and organizational impacts with a lack of focus on the societal and environmental perspectives (M. Sharma et al., 2020). Similarly, significant gaps regarding research into social sustainability (Barata et al., 2018; Gružauskas et al., 2018) and HRM-related topics and implications (Liboni et al., 2019) in SCM were denounced. On the other hand, effects on SSCM considering the IP perspective are lacking (Zeng et al., 2017).

*Strategical/business-based gaps* (G7) are characterized by a discussion deficiency about governmental policies, business models, and management decisions that can drive or impede the deployment of appropriate technologies (Zhang et al., 2019). The strategic intent required to integrate the concept of the CLSC into mainstream business activity (De Angelis et al., 2018) and discourse evaluating the managerial implications from the adoption of a more CE-based view (Bernon et al., 2018) are lacking.

A lack of measurable indicators is stressed by the *Measurable gaps* (G8) category. Indeed, studies on performance measurement indicators of intelligent SC (Xie et al., 2020) and adequate quantitative and qualitative indicators to measure performance of CSCs (Jain et al., 2018) are still lacking. Singh et al. (2019) highlighted limited research available for developing an index evaluating the effectiveness of SC coordination in the era of I4.0. While Sassanelli et al. (2023) stated that precise sustainability evaluation methods are still missed and should be proposed to set more strict benchmarks when monitoring CSC activities. An integrative view of the enabling technologies required to digitise firm processes, such as SCM market integration (Ardito et al., 2019), and empirical investigation about the role of SCM as an enabler of supply flexibility (Jermsittiparsert & Boonratanakittiphumi, 2019b) have been loosely defined. Several papers have suggested little consideration in investigating how and why digital technologies can create performance gains by improving and transforming SC capabilities (Ehie & Ferreira, 2019).

Other examples regarding *Gaps about enablers* (G9) are: limited research investigating I4.0 technologies for CSC to build a DSS (decision support system) (Mboli et al., 2020) and BDA implications for sustainable SCM (Chiappetta Jabbour et al., 2020).

Lastly, a unified accepted definition of I4.0 in the context of SCM (Chauhan & Singh, 2019), the standardization of green SC indicators (Morella et al., 2020) and a systematic foundation of models supporting the design of CPS with regard to applicable technical functions in the planning and control of SC processes (Hetterscheid & Schlüter, 2019) were unveiled as the major *Formal gaps* (G10).

Taking all into account, G1 (49) and G2 (33) gaps are the most diffused in the analysed research domain. This suggests that, besides the theoretical studies that usually focus on a singular aspect of the research context (I4.0, CE, CSC), articles discussing practical implications of the CSC adoption with a systemic and holistic point of view are needed. The following sections are aimed at detecting these barriers and proposing a CSC model helping to overcome the theoretical research gaps reported so far.

#### 4.1.2. CSC practical barriers

Thanks to the analysis of the selected articles and evaluating the most recurrent and important barriers in the cases presented in them, 17 practical barriers were identified and gathered in 5 main categories. The presentation order follows the reported priority ranking.

1 Legislative/political barriers:

- *Lack of tax policies and incentives* (B1): Kumar et al. (2021) stated that governments fail to encourage the process since there are no tax rebate policies to promote CSCM (Khandelwal & Barua, 2020) or incentives for greener activities and tax policies to promote circular models (Mangla et al., 2018);
- *Weak environmental laws and regulations* (B2): a deficiency in enforcement rules and systematic regulations for environmental was denounced by Jia et al. (2020), Khandelwal & Barua (2020) and Ozkan-Ozen et al. (2020);
- *Lack of global standards and performance measurements* (B3): effective mapping of performances and SC activities tracking (Kumar et al., 2021; G. Yadav et al., 2020) are lacking due to a weak performance measurement system and inexistent global standards and sharing data protocols (Luthra & Mangla, 2018).

2 Financial/economic barriers:

- *Limited financial resources and support* (B4): shortage of financial resources (Horváth & Szabó, 2019) and support (Dey et al., 2020) were identified and addressed;
- *High investments and implementation costs* (B5): to transform SCs into circular ones, current SCs need to be redesigned in parallel with the adoption of I4.0 enabling technologies (Ozkan-Ozen et al., 2020) that requires technical equipment, training, and consultancy (M. Sharma et al., 2020). These transactions, however, demand high investments and implementation costs;
- *Uncertainties about economic benefits and circular flows in the short run* (B6): the return of investment is mostly unknown and the uncertain nature of circular flows increases the risk (Ozkan-Ozen et al., 2020) affecting companies expectations and reluctancies in making investments (I. Kazancoglu et al., 2020).

3 Social barriers:

- *Resistance and fear against disruptive changes* (B7): the internal resistance to change makes the adoption very difficult (G. Yadav et al., 2020). Indeed, employees may fear a loss of jobs caused by the automation and the new capabilities required (Kumar et al., 2021);
- *Lack of skilled workforce* (B8): deficiencies in skills and capabilities are able to impact the result of CSC adoption because enhanced skills are required for managing the new I4.0 technologies (M. Sharma et al., 2020) and the workers have no experience of the circular approaches (I. Kazancoglu et al., 2020);
- *Inadequacy of knowledge and awareness (*B9): a conscious lack of CSCM initiatives (B9) was denounced both at an organizational point of view, leading to a lack in the motivation (Kumar et al., 2021), and from a customer perspective (Khandelwal & Barua, 2020).

4 Organizational barriers:

- *Lack of coordination and collaboration among the SC members* (B10): SC actors are reluctant to collaborate and support CSC initiatives (Farooque et al., 2019). This is due to a lack of common vision, fear of losing control, or a lack of trust between them (I. Kazancoglu et al., 2020);
- *Lack of appropriate training and educational programmmes* (B11): appropriate training and development programmes for SC members and HR are fundamental (Mangla et al., 2018). For instance, human–machine interaction is a promising approach for circular operations, however it requires a detailed and efficient training to be managed successfully (Ozkan-Ozen et al., 2020). Organisational culture and resource optimization are, indeed, fundamental factors for achieving sustainable goals through emerging technologies (Gupta & Singh, 2021);
- *Lack of organization willingness and trust* (B12): the transition from linear to circular flow requires redesigning the SC network while embracing a sustainable point of view and conducting, simultaneously, an I4.0 transition. Organizations, however, do not fully trust this new concept (Ozkan-Ozen et al., 2020) lacking a futuristic outlook (M. Sharma et al., 2020);
- *Poor management support and commitment* (B13): due to a lack of a full comprehension of business opportunities (Cezarino et al., 2019), vision, and financial resources, the management is usually reluctant in supporting activities for sustainable operations (Kumar et al., 2021);
- *Lack of effective strategic planning* (B14): a deficiency of the planning and management of CSCM concepts was reported by Mangla et al. (2018) and strongly confirmed by Khandelwal & Barua (2020).

5 Technical barriers:

- *Lack of technological resources and infrastructures* (B15): poor internet connectivity and lack of related infrastructures are imperative impediments to I4.0 and sustainable practices (M. Sharma et al., 2020);
- *Lack of compatibility and integration of technical platforms* (B16): besides the technological resources gaps, the systemic integration of new and old systems requires compatibility (M. Sharma et al., 2020). Different components and software need to interface and integrate with each other in a flexible way;
- *Lack of information systems and data management* (B17): while in the linear economy, the number of stakeholders is not high and relationships among them are usually one sided, in a CSC the complexity increases tremendously resulting in a greater need for data management skills (Ozkan-Ozen et al., 2020). Indeed, a lack of information systems and data management is considered a relevant barrier. The security and the capacity of data storage systems are also denounced as important issues.

Table 3 (and its legend), summarising the barriers diffusion in relation to the selected articles, are displayed. Moreover, a further characterization of the papers regarding the dimension of the industry (Small and Medium Enterprises (SMEs)) and the economy addressed (emerging or not), was added to better understand the link with the practical gaps.

A first consideration that can be traced from the analysis concerns the characterization of the papers. Indeed, out of the thirteen selected, seven considered possible barriers in the implementation of CSCs in emerging economies, two in SMEs, while the remaining four addressed the topic in a general environment of application. This suggests that the difficulties and impediments related to the implementation of CSC flanked by I4.0 technologies are more frequent and, thus, need a higher attention especially in an emerging economy scenario. *Legislative/political barriers* (B1, B2, B3) are ranked as one of the major impediments (occurring 25 times, of which half of them in emerging scenarios). Therefore, when government policies, incentives and regulations are lacking, companies might face several troubles and financial shortages.

However, according to this analysis, in general the most diffused barriers are B2, B4, B6, B9, B10, B13 and B15, which belong to all the 5 different categories, highlighting the systematic and holistic impact of CSCs on the political, economic, technical, social and organizational layers.

### 4.2. The CSC model

The analysis of the theoretical gaps and available models raised a deficiency of research studying the integrated domain of I4.0, CE, and CSC to suggest practical and systemic implications for the CSC adoption. This work is aimed at compensating this lack by proposing a CSC transitional model addressing the evolution from a linear to a CSC. Thanks to the following model, firms approaching CSC are provided with useful insights to adopt and successfully manage the circular transition. The model (presented in Fig. 3 and Tables 4, 5, and 6, converging in the validated overall version of Fig. 4) characterizes the transition towards a CSC providing per each of its phases the link with the five main CSC categories, the principal warnings (i.e., the main occurring practical gaps), the most useful practices and approaches needed to cope with these warnings, and the main I4.0 technologies adopted to implement CM strategies. In Fig. 3, the considerations of the experts involved in the model validation phase were exploited to modify and improve the structure of the model and are reported in red.

The model is structured on the 5 categories introduced in the paper by Taddei et al. (2022): CSC business models and strategies, challenges and barriers, I4.0 enabling technologies, performance tools and indicators, best practices. They have been assessed to understand how each of them impacts the timeline concerning the CSC transition, from its initial adoption up to its full achievement.

To do so, the transition has been distinguished in 4 main subsequent phases: conceptualisation, design, implementation, and measurement. Each phase has been represented with a loop circle stressing the use of the PDCA (Plan-Do-Check-Act) method to trigger a continuous improvement process. In particular, the measurement phase requests to provide performance evaluation feedback causing revision and, eventually, corrective actions for the new iteration of the conceptualization phase.

The 4 main phases are, hence, characterized by the 5 categories, distributed among them according to the content and in relation to the sequence of the CSC transition. In this sense, the categories of CSC best practices, challenges and barriers and I4.0 enabling technologies have

**Table 3**
CSC practical gaps literature analysis (B1: Lack of tax policies and incentives; B2: Weak environmental laws and regulations; B3: Lack of global standards and performance measurements; B4: Limited financial resources and support; B5: High investments and implementation costs; B6: Uncertainties about economic benefits and circular flows in the short run; B7: Resistance and fear against disruptive changes; B8: Lack of skilled workforce; B9: Inadequacy of knowledge and awareness; B10: Lack of coordination and collaboration among the SC members; B11: Lack of appropriate training and educational programmes; B12: Lack of organization willingness and trust; B13: Poor management support and commitment; B14: Lack of effective strategic planning; B15: Lack of technological resources and infrastructures; B16: Lack of compatibility and integration of technical platforms; B17: Lack of information systems and data management).

| | | | Legislative political barriers | | | Financial economic barriers | | | Social barriers | | | Organizational barriers | | | | | Technical barriers | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Authors | Smes | Emerging economies | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 | B11 | B12 | B13 | B14 | B15 | B16 | B17 |
| (Kumar et al., 2021) | | | x | x | x | x | x | x | x | x | x | | | | x | x | x | | |
| (Ozkan-ozen et al., 2020) | | | | x | | | x | x | | | x | x | x | x | x | | x | x | x |
| (G. Yadav et al., 2020) | | | | | x | x | x | | x | | | x | x | | x | | | | |
| (Cezarino et al., 2019) | | X | x | x | | x | | | | x | x | | | | x | | x | x | |
| (Luthra & mangla, 2018) | | X | | | x | x | | x | x | x | x | x | x | | x | | x | x | x |
| (M. Sharma et al., 2020) | | X | | x | x | | x | x | x | x | x | | | x | x | | x | x | |
| (Horváth & szabó, 2019) | X | | | | x | x | | x | x | x | | x | | x | x | x | | x | x |
| (I. Kazancoglu et al., 2020) | | X | | x | x | | x | x | | x | x | x | x | x | | | x | | |
| (Dey et al., 2020) | X | | x | | | x | | | | | | | | | x | | x | | x |
| (Jia et al., 2020) | | | x | x | x | x | | | | x | | x | x | | | | x | | x |
| (Khandelwal & barua, 2020) | | X | x | x | x | x | x | x | | | x | x | x | | x | x | x | | x |
| (Farooque et al., 2019) | | X | x | x | | x | x | x | x | | x | x | | | x | x | x | | |
| (Mangla et al., 2018) | | X | x | x | | | | x | | | x | x | x | | x | | | | x |
| Total | 2 | 7 | **7** | **9** | **8** | **9** | **7** | **9** | **6** | **7** | **9** | **9** | **7** | **4** | **11** | **4** | **10** | **5** | **7** |
| Total per barrier category | | | **24** | | | **25** | | | **22** | | | **35** | | | | | **22** | | |

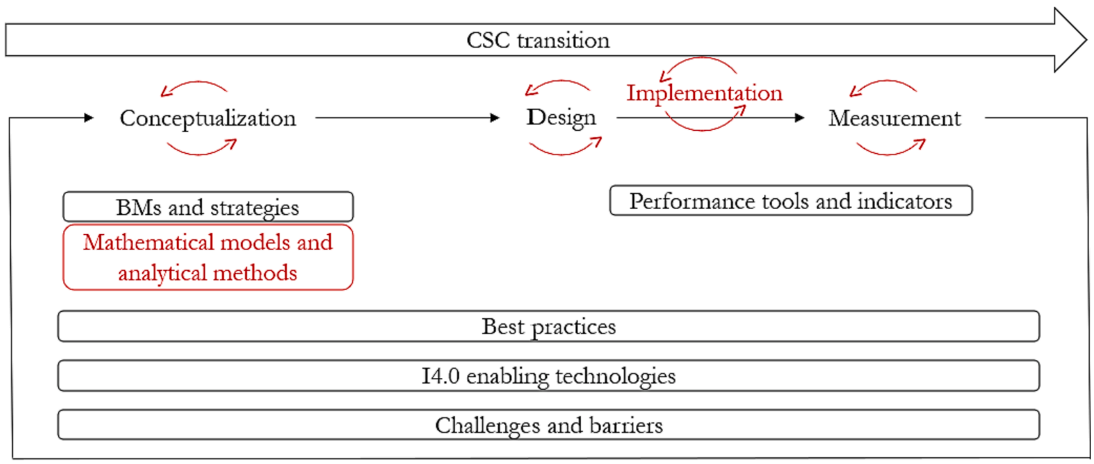


**Fig. 3.** CSC model.

**Table 4**
Conceptualization phase.

| Why? | How? | What? | |
|---|---|---|---|
| Encountered practical gaps | Proposed practices and approaches[1] | Adopted I4.0 technologies and CE strategies | |
| B7: Resistance and fear against disruptive changes<br>B10: Lack of coordination and collaboration among the SC members<br>B11: Lack of appropriate training and educational programmes<br>B13: Poor management support and commitment<br>B14: Lack of effective strategic planning | Guidance for reorganizing structure and processes, identifying synergistic approaches to form channel partners and sources of conflicts during the CSC transition (Nandi et al., 2020).<br>A model to enhance SC capabilities and co-creation strategy with partners and customers, optimised through the use of Cloud and BDA technologies (Mihardjo et al., 2020).<br>Best practices for the CSCM as configuration organisational functions, coordination of organisational functions, closing resource loops, slowing resource loops and narrowing resource loops (Geissdoerfer et al., 2018).<br>Model proposition of a IoT enabled decision support system (DSS) for CBMs that effectively allows tracking, monitoring and analysing products in real time with the focus on residual value (Mboli et al., 2020).<br>A conceptual model illustrating how PSS BMs impact SC collaboration through increased product longevity, closure of resource loops and resource efficiency (Kühl et al., 2019).<br>Practices as structural flexibility, open and closed material loops in technical and biological cycles and closer collaboration (De Angelis et al., 2018). | Cloud<br>BDA<br>IoT | CBMs<br>3Rs<br>WM<br>M&EE |

[1] Environmental and economic aspects slight predominance.

been considered transversal, impacting the entire transition, CSC performance tools and indicators have been considered for the last two phases, while CSC business models and strategies is referred only to first

**Table 5**
Design phase.

| Why? | How? | What? | |
|---|---|---|---|
| Encountered practical gaps | Proposed practices and approaches[1] | Adopted I4.0 technologies and CE strategies | |
| B8: Lack of skilled workforce<br>B15: Lack of technological resources and infrastructures<br>B16: Lack of compatibility and integration of technical platforms<br>B17: Lack of information systems and data management | UAV (Unmanned aerial vehicles) system that, together with BDA, supports industries in automating inventory tasks and traceability (Fernández-Caramés et al., 2019).<br>Circular model to reuse scrap electronic devices integrating reverse logistics and AM (Nascimento et al., 2019).<br>Methodology for asset tracking, based on UWB radio technology and RFID, supporting global asset management for I4.0 (Frankó et al., 2020).<br>A hybrid model based on recurrent neural networks (RNN) to enhance safety and transparency in food SCs (Khan et al., 2020).<br>End-to-end solution for reverse SCM based on cooperation between different IoT communication (Garrido-Hidalgo et al., 2019). | IoT<br>BDA<br>Cloud<br>AM<br>A Rob | 3Rs<br>WM<br>M&EE<br>CD |

[1] Environmental and economic aspects slight predominance.

one.

Through the dimensions of the *CSC best practices* category, successful CSC examples and practices have been provided, and suggest different methods and managerial approaches suitable in each stage of the transition.

The I4.0 enabling technologies guide the approaching companies mostly in the central phase thanks to the improvements during the design activities. However, their use is crucial even in the initial phase and during the measurement one, for instance to manage massive quantities of data. Since the practical gaps analysis has shown several difficulties and barriers in the CSC transition, the model provides accurate warnings to alert companies and support them in overcoming challenges that might undermine the process. This is particularly relevant in the initial phase of the transition to efficiently avoid drawbacks or impediments in the following phases. However, practical gaps are spread even in the implementation and the performance monitoring

**Table 6**
Measurement phase.

| Why? Encountered practical gaps | How? Proposed practices and approaches[1] | What? Adopted I4.0 technologies and CE strategies | |
|---|---|---|---|
| B3: Lack of global standards and performance measurements | $CO_2$ emission level and logistics costs reduction thanks to the I4.0 adoption strategy (Gružauskas et al., 2018).<br>Conceptual framework, including the LCA, to examine food loss and waste (Luo et al., 2021).<br>KPI capable of measuring the impact of energy consumption on the Nakajima's 6 big losses (Morella et al., 2020).<br>LC emissions, waste recovered, carbon maps indicators to compare traditional and circular production systems (Genovese et al., 2017).<br>Carbon emissions reduction achieved through CE practices (Nasir et al., 2017).<br>Coordination index among the SC actors (Singh et al., 2019).<br>CEPA methodology, LCA and LCC to exploit quantitative assessments of CBMs (Rocca et al., 2021). | IoT<br>BDA<br>Cloud | 3Rs<br>WM<br>M&EE |

[1] Environmental and economic aspects significant predominance.

phases, as highlighted afterwards.

The remaining *CSC BM and strategies* and *Performance tools and circular indicators* categories have been respectively considered in the conceptualisation and measurement phases due to their content. The first category provides outcomes which are the foundations of a managerial decision oriented to the circular transition and responsible for the management of the last one.

During the model validation (Section 5), the further category of *Mathematical models and analytical methods* has been added thanks to the experts' advices, embedded to the *CSC BM and strategy* category. This category is functional to better set the ground of the Measurement phase in which CSCs need to be monitored in quantitative and qualitative terms and to, eventually, improve the process through a continuous and circular improvement.

### 4.2.1. *Conceptualization*

The model begins with the CSC conceptualization phase. It is an introductive and preliminary step in which firms experience and kick-off the CSC pathway. This phase involves the 3 transversal CSC categories (CSC best practices, challenges, and barriers and I4.0 enabling technologies), the characterizing one (CSC BM and strategies), and the further one suggested by the experts (*Mathematical models and analytical methods)*.

In this initial phase, companies approaching CSCs are provided and can benefit from several models, frameworks and guidelines offering guidance and supporting directives. During the strategy definition, planning and management, the review has suggested a slight concentration on the economic and environmental dimensions, while leaving social considerations for the following phases. This predominance, is however, something to be carefully managed. As highlighted in Section 4.1.2, indeed, the transition could scare companies' employees of a possible job loss caused by the automation and the new capabilities required (B7). According to this warning, it is strongly important to be prepared to face a potential internal resistance, promptly handle it and, when possible, prevent it to enhance a further smooth development. The mentioned prevention might be partly realized through training and educational programmes (B11) which are still lacking in the field of adoption.

Compared to the following 3 steps, the conceptualization phase has reported a poor debate around the I4.0 technologies. At the beginning, indeed, technologies have been mainly considered as instruments to foster the predictive analysis and the exchange and monitoring of information, as demonstrated by the significant predominance of Cloud, BDA and IoT. The information flow and, consequently, the coordination and collaboration among the SC members (B10) is something that practitioners should particularly consider and preserve. Its failure might hinder the entire transitional process. Therefore, specific SC actors' selections, development programmes, and multidisciplinary systems are needed.

The importance to adopt and structure circular strategies and more complex and narrow types of BMs involving dynamic management of the resource loops has been highlighted. CBMs implementation encourages the design of CSCs, allowing products at the end of their Life

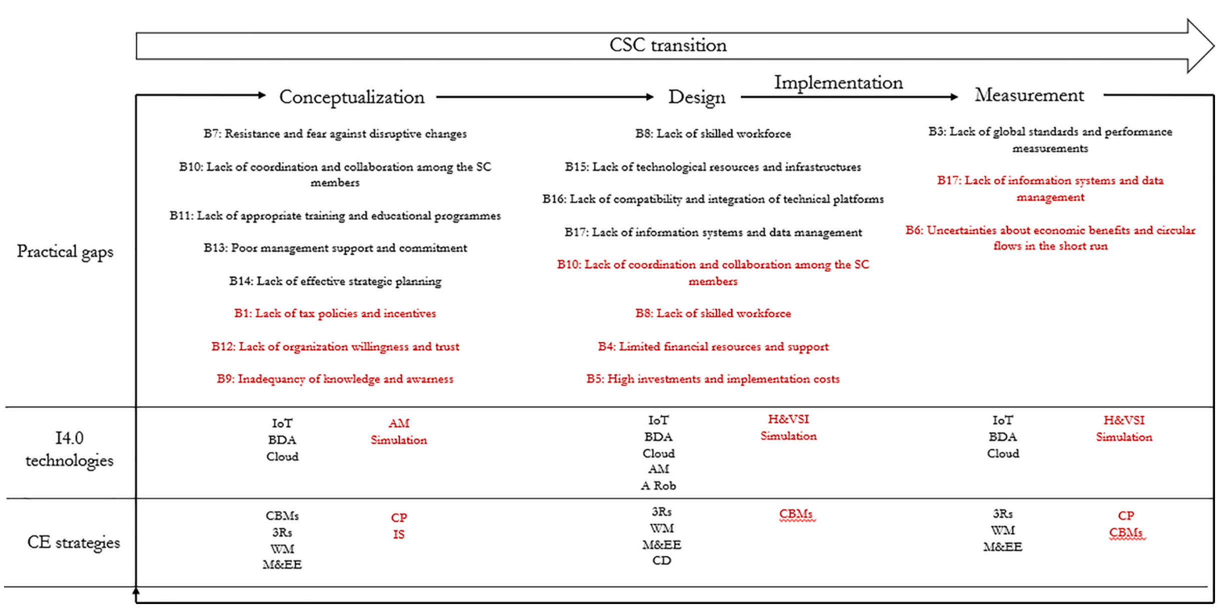


**Fig. 4.** CSC model validated.

Cycle (LC) to re-enter the SC, while Circular Design (CD) practices foster the circular transition in the subsequent and more operative steps. Moreover, Reuse-Recycle-Remanufacturing (3Rs), WM, and M&EE should be further considered as useful approaches for the CSC transition and implementation.

To enhance the approaching firms' knowledge and readiness, successful promising approaches and practices have been listed hereunder.

Firstly, a path, suggested by Nandi et al. (2020), can be followed when realizing a CSC transition. It provides guidance for reorganizing structure and processes, identifying synergistic approaches to form channel partners and identifying sources of conflicts. Achieving a fully circular model of adoption implies its application both internally and externally, involving suppliers and customers in the activities and leading to an essential development of relational capacity. According to this transition, even customers become key participants of the CSC strategic network, raising the need of their loyalty and satisfaction to establish longer-term relationships.

A best practice to enhance SC capabilities with partners and customers, optimised through the use of Cloud and BDA technologies, was proposed by Mihardjo et al. (2020), arguing the importance of co-creation strategy based on collaboration value. The strategic input is derived from external factors associated with customer experience and internal factors related to core SCM competences.

Some main means and best practices for the CSCM (as configuration and coordination of organisational functions; closing, slowing and narrowing resource loops) were proposed by Geissdoerfer et al. (2018). Moreover, the approach highlighted essential factors in the pro-active multiple stakeholder management and long-term perspective within short term actions. Managerial practices that companies can implement to design CBMs and to capture value from them were investigated by Ünal et al. (2019). The managerial commitment, as moderating factor between the value network and the customer value proposition is identified as essential for reaching the intended goals of CBMs. In addition, an interdisciplinary approach is essential to investigate the CE, considering its multifaceted and complex nature.

An IoT enabled DSS for CBMs that effectively allows tracking, monitoring, and analyses of products in real time with the focus on residual value was proposed by Mboli et al. (2020). The approach applied DSS and the ontological model in a real-world use case and demonstrated viability and applicability. It addressed the requirement of real-time monitoring of products LC using I4.0 technologies (i.e., IoT and 5G).

A conceptual model illustrating how PSS BMs impact SC collaboration through increased product longevity, closure of resource loops, and resource efficiency was identified by Kühl et al. (2019). It also determined 6 related contextual factors including economic attractiveness, firm sustainability strategy, policy and societal environment, product category, SC relationships and technology.

A shift from product ownership to leasing and access in SC relationships, the relevance of structural flexibility and start-ups in regional or local loops, open and closed material loops in technical and biological cycles, closer collaboration within and beyond immediate industry boundaries and public and private procurement were presented (De Angelis et al., 2018) as preliminary implications for CSCs and as levers for CBMs.

Finally, the analysis has demonstrated that a company approaching CSC should always consider fundamental aspects to reach a successful handling such as a strong and substantial management support (B13) and an effective strategic planning (B14). These issues have proved to be undervalued organizational barriers so far and, therefore, practitioners should be warned.

A summary to advise and support approaching firms is presented in Table 4.

#### 4.2.2. *Design*

The design phase has been built considering the 3 transversal categories (CSC best practices; challenges and barriers; and I4.0 enabling technologies). In this second phase, more operational and practical aspects have been discussed in terms of methodologies and model propositions. The design initiates the implementation and employment of practices, technologies, and approaches to realize the CSC transition. As in the previous phase, the analysis tends to suggest a combination of economic and environmental perspectives. However, in this case, warnings regarding the social sphere have been stressed: among others, the requirement of technical skilled workforce to assist and manage the process (B8). Therefore, even social aspects should be taken into consideration since they can undermine the transitional implementation and realisation.

I4.0 technologies represent useful enabling tools to support the development and are essential to foster a CSC. Their comprehensive application is able to bring significant performance improvements in SCM by enabling a holistic approach from the extensive SC integration as well as information sharing, connectivity and transparency. Moreover, these technologies allow huge performance improvements within individual SC processes (such as procurement, production, inventory management, and retailing), enabling integration, digitization, automation, and novel analytical capabilities. The analysis has shown a predominance of IoT, BDA, and Cloud, with a synergic implementation of AM and A Rob in specific cases. Indeed, IoT improves decision-making, real-time monitoring and communicating, responsiveness, proactivity, productivity, efficiency, quality controls and flexibility at the process level. BDA contributes to performance improvements, real time problem solving, superior qualities development, forecasting and planning, operational frameworks, predictive model development, decision making and planning. Cloud enhances collaboration, coordination, integration, quick and independent access to data from any part of the SC, decision making, and planning.

Therefore, the I4.0 technical adoption impacts 3 main fundamental aspects:

- production and resource management (recycling of waste, high-efficiency systems, product design, manufacturing and remanufacturing processes);
- stakeholders (predictive analysis, coordination and collaboration);
- information (monitoring, controlling, and transferring of data).

The most significant technological approaches and practices encountered in the analysis have been reported afterwards to enhance practitioners' interest and know-how and foster a further development.

Firstly, Fernández-Caramés et al. (2019) provided the design and evaluation of a UAV (Unmanned aerial vehicles) system that, together with BDA, supports industries in automating inventory tasks and traceability. Different tests were performed in a real industrial warehouse, concluding that the system can collect inventory data remarkably faster in comparison to traditional manual tasks and estimate the items position thanks to their tags signal strength.

A circular model able to reuse scrap electronic devices integrating reverse logistics and AM was recommended by Nascimento et al. (2019). To enable the transition from linear to CBMs, which reuse wasted materials, 5 prominent needs were identified: appropriate product LC planning; integrated LC options; better alignment between maintenance; reuse and recycling strategies; the proposal of an integrated management method; considering maintenance plans and operations, standardisation and adaptability of systems.

A novel, working, reliable, low-cost, and scalable solution for asset tracking, supporting global asset management for I4.0, was proposed by Frankó et al. (2020). The solution uses high accuracy indoor positioning, based on Ultra-Wideband (UWB) radio technology, combined with RFID-based tracking features. The UWB use ensures the accuracy of the system even for warehouses of SMEs without significant computation requirements. In this way, the cost remains low, while the solution is still highly scalable due to the Ultra High Frequency (UHF) RFID technology.

A hybrid model based on recurrent neural networks (RNN) to enhance safety and transparency in food SCs was introduced by Khan et al. (2020). Long short-term memory (LSTM) and gated recurrent units (GRU) were used as a prediction model and the genetic algorithm (GA) optimization was jointly included to optimize the parameters of the hybrid model. Through this method and, thus, the deployment of IoT and Blockchain technologies, the food industry benefits in three main areas: provenance, payments, and management.

On the other hand, electric vehicles and traction batteries were used as an example to prove how I4.0 can be integrated into the recycling process (Kintscher et al., 2020). The case involved the development of a marketplace, connected to a robot, to exchange information. The robotic system is capable of analysing the condition of the battery and transmitting a holistic approach for an information exchange architecture between the several actors of the SC.

An end-to-end solution for reverse SCM based on cooperation between different IoT communication standards was proposed by Garrido-Hidalgo et al. (2019). The CSC framework was addressed in a case study based on the Audi A6 Li-ion EVB (electrical vehicle batteries) pack. It is composed of a forward flow of products from suppliers to customers and, once reached their EoL, these are removed from their electrical vehicle and shipped to the RLI. Through a comparative analysis (latency, investment, flexibility, data rate, communication range, battery life, and reliability) of IoT standards, RFID for short-range, BLE for local and LoRaWAN for long-range communication were selected.

The mentioned technologies foster and enable the circular development with a LC thinking approach, enhancing the circularity and waste minimisation principles, and leading to indicate the most used CE strategies of the design phase (3Rs, WM, M&EE, and CD).

Certainly, the technical adoption and circular practices implementation require several characteristics that are essential for a successful result and need to be acknowledged by practitioners and approaching firms. Firstly, strong Internet connectivity, technical infrastructures (B15) and information systems (B17) are essential to register, share, storage and analyse huge amounts of collected data. Moreover, to optimise the effort, resources, and final outcome, technical platforms should be compatible (B18). In this way, the transitional process can proceed smoothly thanks to the flexible integration and interface of the old and new system.

A summary of the Design phase is presented in Table 5.

#### 4.2.3. *Measurement*

As previously reported, also the measurement phase is characterized by the 3 transversal categories (CSC best practices; challenges and barriers; and I4.0 enabling technologies). In addition to them, the phase also involves the *CSC performance tools and indicators* category outputs, requiring innovative tools, indicators, and frameworks. However, the previously performed gaps analysis highlighted a lack of global standard and performance measurement (B3) that characterizes the third phase, with a poor proposal of quantitative and qualitative measures in the research field. The performances tracking is useful not only for an external point of view, but also for an internal one, to monitor the initial plan and eventually suggest adjustments through circular and continuous improvements. Therefore, enrichments and focus on these aspects are still needed.

The majority of reported indicators are referred to environmental efficiency and waste reduction (WM, 3Rs, and M&EE practices). Among other, the Life Cycle Assessment (LCA) has proved to be a useful tool for SCs willing to become circular since it is able to determine the entire environmental impacts and suggest circular approaches, as highlighted in the framework by Julianelli et al. (2020) and Shoaib-ul-Hasan et al., (2021).

Regarding the I4.0 technologies implemented in the measurement phase, references are scarce. However, a majority of IoT, BDA, and Cloud is evident even in this case. The importance of information sharing, connectivity, and transparency is primary for the performance assessment and improvement of a transitional firm. Among other, Gružauskas et al. (2018) highlighted how the adoption of IoT, BDA, Cloud and A Rob technologies in the agri-food sector is fostering the competitiveness advantage in the long run limiting trade-offs between sustainability and cost-effective performances. The obtained results showed that, by implementing the autonomous vehicles strategy along with the consolidation, warehouses $CO_2$ emission level can be decreased of 22 % accompanied by a reduction of logistics costs. In the same industry, a conceptual framework to examine food loss and waste issues within food SCs was proposed by Luo et al. (2021). The approach includes various methods such as stochastic programming, simulation, LCA, and empirical analysis. The willingness to optimise and minimise wastes has been stressed by others. A new KPI capable of measuring the impact of energy consumption on the Nakajima's 6 big losses (breakdowns, setups, minor stoppages, speed loss, quality defects and start-ups) was developed by Morella et al. (2020).

A deficiency of a systematic and comprehensive evaluation of the 3 layers of the TBL is present, with only few papers adopting a holistic or social approach of investigation, and the majority concentrating on environmental aspects (with the numerous emissions indicators). In this sense, Genovese et al. (2017) compared the performances of traditional and circular production systems across a range of indicators like direct, indirect, and total lifecycle emissions, waste recovered, virgin resources use and carbon maps. The paper asserted than an integration of CE principles within SSCM can provide clear advantages from an environmental point of view. The environmental gains, in terms of carbon emissions, achieved through some CE principles in the context of sustainable, green and CLSC were demonstrated by Nasir et al. (2017), using the case study of a construction industry.

Moreover, practitioners should be informed that many of the tools proposed in the literature are often qualitative and very generic in the formulation, as the case of Xie et al. (2020) proposing visibility, leagility (combination of lean and agility), personalization, information governance, SC warning, green, innovation, and learning indicators to enable the monitoring and evaluation of SC performance. In addition, the adoption of a coordination index among the SC actors for an effective benchmarking of the SC performance in the I4.0 era was provided by Singh et al. (2019). In total, 32 factors were considered using the graph theoretic approach to evaluate the coordination of an Indian organization SC.

In sum, through an enhanced monitored CSC, practitioners should concentrate more on this last measurement phase to enrich their portfolio and reach optimal outcomes. In this sense, recently Rocca et al. (2021) have defined a novel CE Performance Assessment (CEPA) methodology that, together with classic LCA and LC Cost (LCC) methods, is able to exploit quantitative assessments of CBMs. CEPA outputs consist in a set of specific KPIs, mainly based on the Material Flow Analysis, regarding resources LC circularity and the quantification of economic and environmental benefits related with CE. A summary to advise and support company in the Measurement phase is presented in Table 6.

The overall validated version of the model (deriving from Fig. 3 and Tables 4, 5, and 6) have been summarized in Fig. 4. As said also for Fig. 3, further considerations emerged during the model validation with experts have been added in red, while the ones collected from the literature analysis are still in black.

Section 5 provides the full disclosure of the validation through the experts' feedback.

## 5. Discussion

To verify the scientific value and reliability of the model and discussing about its applicability in industrial companies, a survey has been conducted through MS Forms, involving ten selected academic experts in the fields of operations management, supply chain management, bioeconomy and circular economy, economics and environmental science & technology. The experts analysed and discussed the proposed model, by verifying the completeness and coherence of each phase with the detected practical gaps, the CE strategies, and the I4.0 technologies. A summary of the feedback collected through the survey is reported and further discussed below, underlining both theoretical & practical contributions, and managerial & policy implications.

The first question allowed to verify with the experts the model foundations, by checking the definition of the five CSC categories by Taddei et al. (2022). All the respondents agreed on the proposed categories and validated them. Some experts suggested additional categories (the *Mathematical models and analytical methods* embedded in the *CSC BMs and strategies*, as explained in Section 4.2).

The second question investigated the experts' perception of the five macro categories about practical barriers raising from the literature and deeply described in Section 4.1.2. As shown in Fig. 5, financial and economic barriers were recognized as the most impeding factors during the CSC transition, with 40 % of respondents indicating them as first choice. Technical barriers were considered relevant too, while social barriers were acknowledged as the least impactful. What emerged is perfectly in line with the trend coming from the literature analysis reported in Section 4.1.

In the third question, respondents were provided with the full disclosure of the seventeen practical barriers (listed in Section 4.1.2) and were asked to rank the five most important ones. Two respondents assigned to B2 (Weak environmental laws and regulations) the highest relevance, and 60 % of them indicated it in the top five (in particular, 3 of them in the top 3). Other relevant barriers, being mentioned by more than 30 % of respondents, have been B1 (lack of tax policies and incentives), B5 (high investments and implementation costs) and B15 (lack of technological resources and infrastructures). This result confirms the answers to the previous question, because the ranking of practical barriers from a macro perspective is consistent with the ranking of the specific barriers. In fact, the most important barriers listed above belong to the three high priority ranked categories (financial/economic, legislative/political, and technical). In addition, barriers B2 (Weak environmental laws and regulations) and B5 (high investments and implementation costs) emerged as recurrent even in the literature analysis reported in Section 4.1.2. However, the literature analysis provided a more balanced output, considering the five most important barriers equally distributed among all the five different categories.

In the fourth question, respondents were provided with the structure of the model presented in Section 4.2. All of them agreed with the model construction and structure in 3 main phases (conceptualization, design, and measurement). In particular, an expert suggested the need to specify and detail the model according to the context and sector, another one according to the involved stakeholders. About the first point, the intention was to construct a generic model suitable to be tailored to the different application contexts. Notwithstanding, the model is based on the literature analysis of different and specific areas and its output provides sector-specific approaches as shown in Table 4, 5 and 6. A future development might consider different sectors or even different SCs to provide a more specific related knowledge. Further investigation might also research the integration and dynamics of stakeholders and SCs.

Another expert highlighted the importance of continuous improvement through the measurement phase outputs. About this last point, the model was refined after the validation and each phase was considered as a loop cycle in the perspective of continuous improvement. Another expert suggested to add an implementation phase between development and measurement. Actually, the measurement phase should follow the design phase after the implementation of the designed directives. Further investigations might be pursued about practical aspects of this additional phase.

The expert also suggested to implement a measurement phase at each stage. Here, considering each phase as a loop cycle, the "measurement" of the as-is situation and the analysis of the feedback with the undertaking of corrective actions, was already considered in the model.

With a complete vision of both the practical barriers and the three phases of the model (the implementation phase was not existing at that stage in the model), the survey involved the experts in the selection of the most impactful barriers to each of the three pre-determined phases of the model in order to compare them with the theoretical results coming from the literature analysis. About the conceptualization phase, respondents agreed on the following barriers as the most impactful: lack of effective strategic planning (B14), lack of tax policies and incentives (B1), lack of organization willingness and trust (B12), and inadequacy of knowledge and awareness (B9). On the other side, the literature analysis reported: lack of effective strategic planning (B14), resistance and fear against disruptive changes (B7), lack of coordination and collaboration among the SC members (B10), lack of appropriate training and educational programs (B11) and poor management support and commitment (B13). Even if minor differences can be seen, the vision coming from experts and literature are similar since in both cases the highlighted barriers belong to the social and organizational macro categories.

The design phase shown a coexistence of technical barriers (lack of technological resources and infrastructures (B15), lack of compatibility and integration of technical platforms (B16)), organizational barriers (lack of coordination and collaboration among the SC members (B10)),

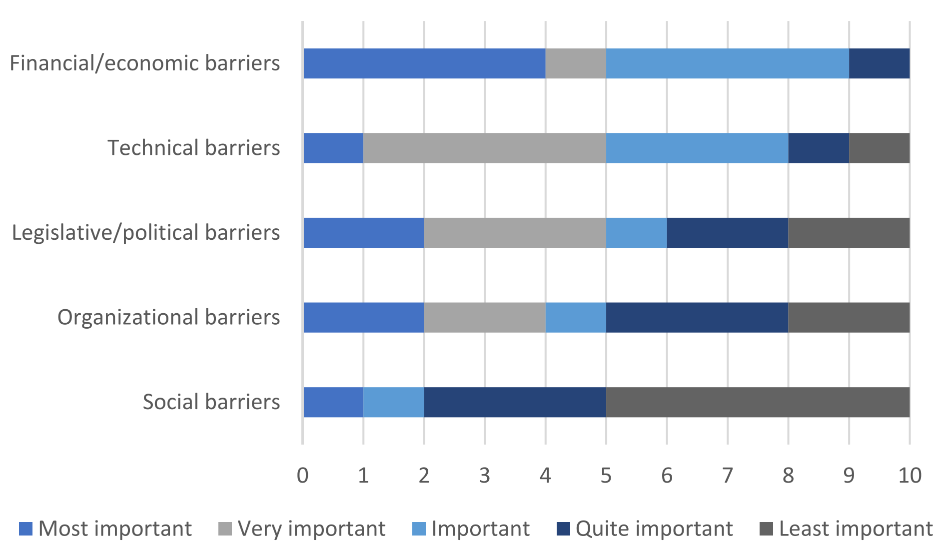


**Fig. 5.** Level of importance of practical barriers categories according to the experts.

social barriers (lack of skilled workforce (B8)), and financial/economic barriers (limited financial resources and support (B4), high investments and implementation costs (B5)). Therefore, the experts' experience remarked the systemic difficulties of this practical phase comparing to the theoretical aspects previously emerged during the analysis.

As expected by the authors, the most relevant barrier for the last phase (measurement) was identified in the lack of global standards and performance measurements (B3). In fact, 60 % of respondents identified it as pivotal. In addition, lack of information systems and data management (B17), and uncertainties about economic benefits and circular flows in the short run (B6) appeared relevant too. From the literature context, only the barrier lack of global standards and performance measurements (B3) emerged. The last consideration underlines the technical impediments recognized by experts even in the measurement phase. As already said, the complete output of the model with its revision after the validation is reported in Fig. 4.

A detailed graph of respondents' answers to question five is presented in Fig. 6.

Then, the survey has been articulated in a series of questions, specific per each phase of the model. For each of them respondents were asked to:

- detect the most relevant practical barriers;
- order the I4.0 technologies identified from the literature analysis among the 9 available (BDA, A Rob, AM, Simulation, AR, H&VSI, IoT, Cloud and Cyber-security) and eventually add any other relevant one among those not included;
- order the circular strategies identified from the literature analysis among the 12 available (CP, CBMs, WM, disassembly, 3Rs, servitization, IS and eco-industrial parks, M&EE and CDPs) and eventually add any other relevant one among those not included.

For the conceptualization phase, the most impactful practical barriers have been considered (among those reported in Table 4) the lack of

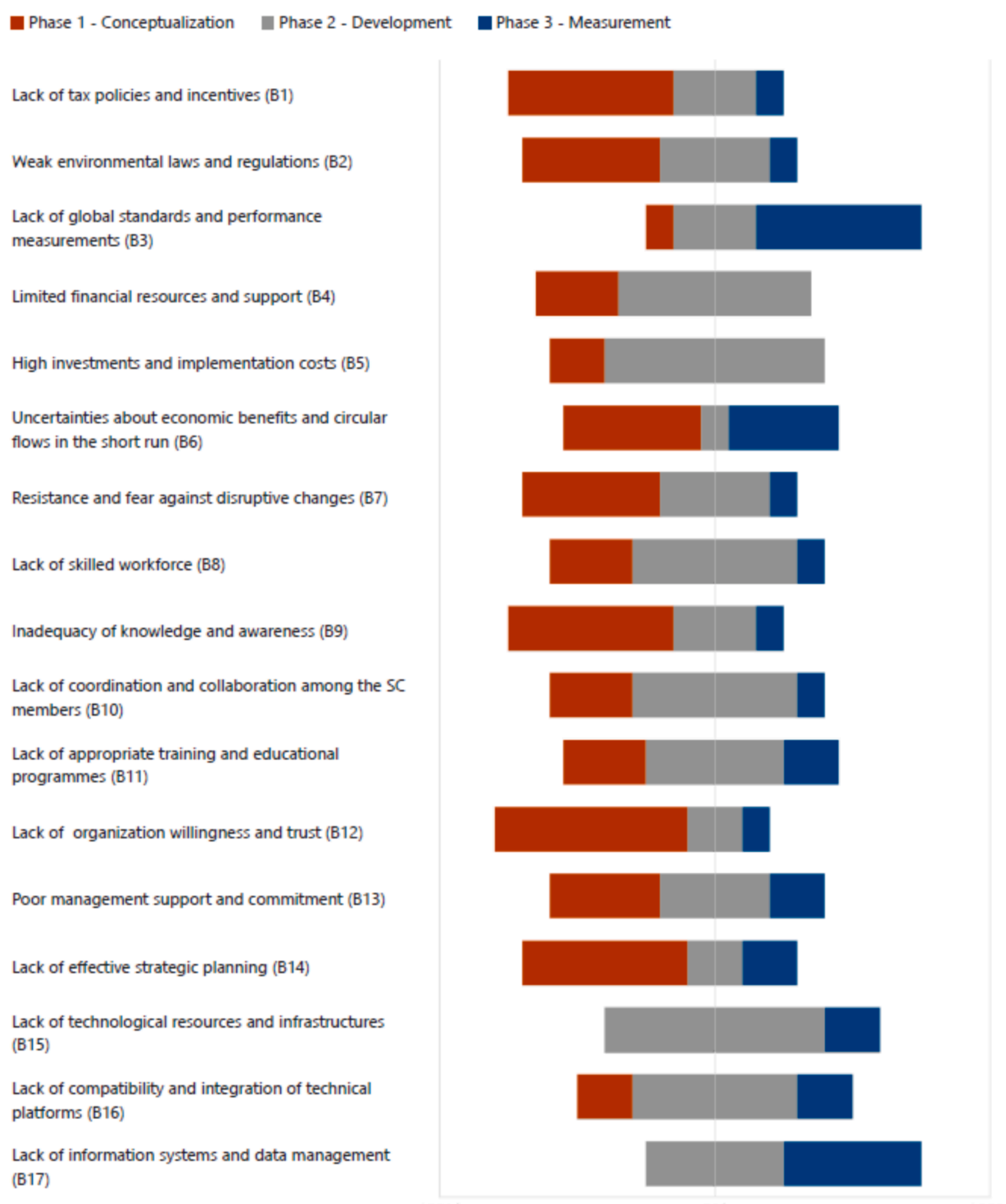


**Fig. 6.** Impact of practical barriers to the CSC model phases (Question 5 results).

effective strategic planning (B14) and the lack of coordination and collaboration among the SC members (B10). I4.0 technologies have been ranked in the following order of importance: IoT, BDA, Cloud and 3 respondents have suggested to add also AM and Simulation. In addition, more than the 70 % of respondents identified CBMs as the most relevant circular strategy, suggesting the addition of cleaner production (CP) and industrial symbiosis (IS).

Instead, for the design phase, respondents indicated as main barrier the lack of technological resources and infrastructures (B15). The following I4.0 technologies were detected: IoT, BDA, AM, Cloud, A Rob (suggesting also to add H&VSI, and Simulation). Finally, the main circular strategies were identified in 3Rs and CDPs (suggesting to add also CBMs).

In the measurement phase, the barrier lack of global standards and performance measurements (B3) appeared very impactful. Concerning I4.0 technologies, the 90 % of the respondents identified BDA as the most important one among the 3 proposed in Table 6 (IoT, BDA, and Cloud) and suggested the eventual addition of H&VSI and Simulation. Circular strategies have been ranked in the following order: M&EE, 3Rs, WM (and CBMs and CP were suggested to be added).

Overall, the feedback collected by CSC experts successfully validated both the methodology adopted to develop the proposed model and the model itself, valuing it as a valid artifact to describe and analyse the CSC transition. CSC experts remarkably highlighted the financial and technical issues encountered to realize the circular shift.

### 5.1. Contribution to knowledge and practice

The results of this research are contributing to both knowledge and practice. From a theoretical perspective, this study extends the knowledge in the CSC research domain starting from the five main categories previously defined in literature. First of all, this research provides a systematization of the theoretical gaps, listing them in ten groups and unveiling the link of each of them with the five main CSC categories). In addition, five main groups of practical barriers have also been defined and declined in seventeen specific barriers. Finally, the model proposition and its validation are also contributing to the research field. they enlarge the CSC knowledge, compensating the two most relevant and identified theoretical gaps (the scarcity of practical references (G1,) and systemic approaches (G2)). In addition, provides a clear picture of the transition towards a CSC, providing per each of its phases the link with the five main CSC categories, the principal warnings (i.e., the main occurring practical gaps), the most useful practices and approaches needed to cope with these warnings, and the main I4.0 technologies adopted to implement CM strategies.

In addition, the model offers practical and systemic directions and advices to guide companies and organizations interested in approaching CSCs in each step of their transition. Systematisation and categorisation of methods, approaches, and warnings are provided to support and enhance the adoption of digital technologies and circular strategies during the entire CSC process. In this way, the major practical impediments and barriers, identified in Section 4.1.2, can be overcome leading to a successful and smoother transition.

### 5.2. Managerial & policy implications

Findings have also managerial and political implications. They help policy makers in fostering the CE adoption at a systemic SC level, unveiling the main barriers (both theoretical and practical) to cope with and raising the need of tax policies, incentives, and standards to foster the transition towards CSC. Results also flank managers in the decision-making process oriented to a CSC transition, providing useful information related to the likely barriers that can be encountered along the path and to the approaches, methods and I4.0 technologies useful to address CE strategies. Updating managerial actors with sustainable insights and new approaches available contributes to the generation and raising of awareness and to gain a sustainability recognition in the specific industries involved. In addition, the actual application of circular paradigms can enhance the reputation, quality, and competitiveness of the company itself.

## 6. Conclusions

This paper contributed to the CSC research domain (composed of three sub-research layers (I4.0, CE, and SC)) with three main results (10 theoretical gaps, 17 practical barriers gathered in 5 groups, and a CSC transitional model addressing the evolution from a linear to a CSC). The model provides practical support, useful insights, and warnings to guide practitioners in the management.

To develop the model, an inductive research methodology inspired to DRM has been built, grounded on the categorization in 5 dimensions of the literature related to CSC performed by Taddei et al. (2022) (CSC I4.0 enabling technologies, CSC performance tools and indicators, CSC challenges and barriers, CSC business models and strategies and CSC best practices). In addition, a systematic literature review allowed to detect a set of theoretical gaps and practical barriers related to CSC. Theoretical gaps (i.e., literature open points needing further investigations) showed a prevalence of Practical Gaps (G1) and Systemic/ Integration gaps (G2). This led to further literature research discussing practical implications of the CSC adoption with a systemic and holistic point of view. The final results, obtained through the validation with experts, led to highlight 7 most diffused and prioritized barriers: B1 (lack of tax policies and incentives), B2 (weak environmental laws and regulations), B4 (limited financial resources and support), B5 (high investments and implementation costs, B10 (lack of coordination and collaboration among the SC members), B15 (lack of technological resources and infrastructures) and B16 (Lack of compatibility and integration of technical platforms). These barriers belong to 4 out of the 5 different CSC categories previously defined by Taddei et al. (2022), highlighting also how CSCs can systematically impact multiple spheres.

Grounded on these results, the model was developed and proposed in Section 4.2. The model is aimed to support companies to move from a linear to a CSC, addressing each phase of this transition (conceptualization, design, implementation, and measurement), in response to all the 5 CSC categories indicated by Taddei et al. (2022). In addition, the model has been characterized with practical barriers occurring in each phase of the transition, and with the most suitable practices and approaches needed to manage them, and also with the I4.0 technologies (BDA, A Rob, AM, Simulation, AR, H&VSI, IoT, Cloud and Cybersecurity) better supporting the realization of the CE strategies (CP, CBMs, WM, disassembly, 3Rs, servitization, IS, eco-industrial parks, M&EE and CDPs).

To increase its reliability, the model was validated with 10 selected experts in the field of CSC. Respondents' feedback certified and improved the valuable structure and contents of the model, its phases, the practical barriers, the I4.0 technologies, and the CE strategies. Respondents, moreover, particularly stressed the magnitude of CSC transitions on technical, financial, political, and organizational aspects and raised the need to further explore the implementation phase of the CSC transition (that has been added to the model during its validation).

This work could be seen as an initial step to pave the way to future contributions oriented to the presented approach and willing to compensate the highlighted gaps. Doing so, the domain will be strengthened with deeper knowledge from which approaching firms could benefit. Indeed, the main limitation of this work is that the proposed CSC model has been verified through academic experts, but has not been validated in a real industrial case. This would be useful to gain proof and confirmation of the model effectiveness and accuracy also in the practice domain, unveiling the gaps, technologies and circular strategies that could be linked to companies with different characteristics (e.g., of different size, or belonging to diverse industries). Therefore, future research could leverage on the model proposed to collect feedback about its application from a practical point of view and to develop best cases to cope with the set of both theoretical and practical barriers listed in this research.

Finally, the theoretical gaps presented in the paper unveiled the need to propose new solutions, practical approaches, and models to enhance the CSCs implementation and foster their diffusion. In addition, from a theoretical point of view, precise and quantitative sustainability evaluation methods should be developed and suggested, and CSCs dynamics and strict benchmarks need to be addressed to monitor their activities.

## CRediT authorship contribution statement

**Emilia Taddei:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Claudio Sassanelli:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Paolo Rosa:** Writing – review & editing, Supervision. **Sergio Terzi:** Supervision.

## 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

The data that has been used is confidential.

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