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Connecting consumption and production systems from the perspective of the product user: a foundational multilevel systems model of circularity realized at the economy-scale

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The Circular Economy (CE) concept continues to garner significant attention from stakeholders. Yet, what a CE entails in its realized state remains insufficiently articulated, particularly for product users. This study introduces a multilevel systems model that conceptualizes an economy-wide, fully implemented CE from the perspective of the product user. The focus is on the foundational tenets of CE theory, namely the flows of materials, products, and components in the specific context of durable consumer products. The model's development follows a sequential method and is empirically tested and refined through a Delphi study involving 14 experts in CE and sufficiency. First, this model clarifies the composition, elements, and structure of the consumption system in a realized CE. Notably, elements often relegated to the background, such as contextual settings, are foregrounded to enable a more comprehensive analysis of factors involved in CE behaviors. The model provides a structured foundation for systematic exploration of potential implications for product users, which can be expanded in future research to include additional dimensions (e.g., social and ecological). Second, the multileveled nature of the model and mapping of the diverse flows and interactions shaping product users' reality in a realized CE allows for systematic integration of consumption (i.e., more concrete from the perspective of the product user) and production (i.e., more abstract) systems. As such, the model introduces an integrated product-system lens for bridging multi- and interdisciplinary areas of sustainable consumption and production. The paper concludes by outlining avenues for future research and potential applications of the model.

KEYWORDS

Circular Economy, production-consumption systems, multilevel models, systems thinking, product user, qualitative modeling

1 Introduction

The concept of a Circular Economy (CE) is gaining in popularity, due to its potential to foster more sustainable production and consumption (Hondroyiannis et al., 2024; Kirchherr et al., 2023). In the context of a CE, terms like "consumption" and "consumer" have been replaced with "CE Behaviors" (e.g., reuse, sharing and recycling) and "product user", capturing how resources are no longer extinguished. Instead, products reaching their "end of use" are directed to other users or actors (e.g., remanufacturers or recyclers), thereby retaining the inherent value in products, components and/or materials via innovative business models and infrastructure designed to support such resource flows (International Resource Panel, 2018; Stahel, 2016; Camacho-Otero et al., 2018). However, product users' roles in realized CE systems (i.e., fully implemented at the economy-level) are under-researched (e.g., Arekrans et al., 2022) and there is a call for "person-centered perspective on circular behaviors" (Colley et al., 2024). In doing so, there is a need to take more systematic exploration of what a CE entails (Hassan and Faggian, 2023), including integrating the consumption system with that of production (Geels et al., 2023). To accomplish both goals, we propose a "multilevel systems model" (MLSM), organizing system components based on proximity to the product user. This model was tested, and refined via a Delphi study.

This model has many uses; for instance, product or service providers can employ it to map their ecosystem, spot gaps (e.g., missing consumer information or spare parts provisioning), and identify the need for collaborators in the value chain. Also, it can be further developed to depict CE systems as complex and open, which can allow for the mapping of implications of responses to transition challenges, primarily unintended consequences and policy incoherence (Davies et al., 2024), including a CE under the principles of decoupling (Voulvoulis, 2022) and degrowth principles (Calisto Friant et al., 2025). As such, the MLSM presented in this paper advances the understanding and application of CE principles.

1.1 The lacking product user perspective in Circular Economy research

In a CE, the economic system is structured to retain the value of products and reduce the environmental impact from economic activities (Ghisellini et al., 2016). However, CE research tends to favor the production side of such a system, focusing on business models, supply chains, engineering, and technological solutions. It often ignores the human dimension or social implications of a CE, such as the consumption system and people's daily lives in a circular "society" (Calisto Friant et al., 2024; Leipold et al., 2023; Corvellec et al., 2022; Jaeger-Erben et al., 2021; Liu, 2025; Schröder et al., 2020). Despite the crucial role of product users in the uptake of CE strategies in the economy as a whole (Gomes et al., 2022), product user behavior aspects remain insufficiently understood (Macklin and Kaufman, 2023; Pasqualotto et al., 2023; Borrello et al., 2022).

Circularity realized at the economy-scale—in its ideal and fully-envisioned state (which depends on the pathway; e.g., Bauwens et al., 2020)—entails fundamental changes to the daily life of individuals in their role as, e.g., citizens and product users (Maitre-Ekern and Dalhammar, 2019; Greene et al., 2024; Machado et al., 2019). Consumption in a CE is predominantly researched in the context of CE transitions, such as barriers and drivers to consumer adoption and influences of decision-making in the current linear system (Camacho-Otero et al., 2018; Pasqualotto et al., 2023; Santos-Corrada et al., 2023; Singh and Giacosa, 2019; Vidal-Ayuso et al., 2023). Accordingly, not only are we missing a comprehensive understanding of what a realized CE (i.e., fully implemented CE principles at the economy scale) might entail for individuals, but the research that is conducted is arguably taking a production-side lens to the study of consumption, focused on consumers' role in circular business models (e.g., Bücker et al., 2022). Given ongoing CE transitions worldwide (Campoli et al., 2024; Yamaguchi, 2021), and the many envisioned pathways and versions of a CE (Bauwens et al., 2020; Calisto Friant et al., 2025; Kirchherr et al., 2023), it is crucial to gain a better understanding of their respective implications, considering also the potential costs and benefits of normalized circular consumption, such as a high "consumer work" load (Hobson et al., 2021) under varying system conditions. Without such insights, the risks consist of: (1) CE transition strategies being incomplete and thereby potentially ineffective in bringing about the CE transition (e.g., Dupoux et al., 2025); (2) unintended negative consequences (i.e., that, if anticipated, could potentially be mitigated); and (3) a lack of mechanisms to ensure that the transition delivers positive outcomes for quality of life (e.g., Vollebregt et al., 2024).

1.2 Lacking integration between consumption and production systems

In addition to an incomplete understanding of the consumption system of a CE, a poor integration exists with its counterpart: the production system. This is a problem that is plaguing sustainability research at large; while production research focuses on technology, engineering, and business, consumption research looks to culture, norms and behaviors to drive structural changes (Marrucci et al., 2019; Bengtsson et al., 2018; Wang et al., 2019). However, the transition to a CE and more-sustainable solutions are dependent on a range of actors, situated in both systems, which is why their integration enables a more comprehensive analysis of sustainability issues. To this end, and to capture the complex interactions between human societies, technologies, and natural environments, there is a need to consider ecological, technological, social, and institutional processes and dynamics together (Andersson et al., 2024). An effective integration of the two systems could enable, for example, product design interventions (e.g., for increased repairability) to be viable within the communities and economies they are planned for (e.g., adoption and socio-cultural appropriateness), and the achievement of the desired environmental and sustainability benefits (i.e., impactful). For this reason, the perspective of *consumption-production systems* (Tischner, 2024), especially for "faster and deeper [sustainability] transitions", is crucial (Geels et al., 2023).

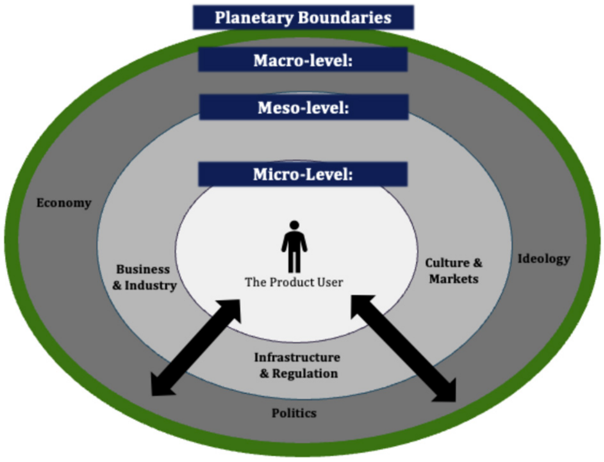

FIGURE 1
A Multilevel Systems Model (MLSM) from the perspective of the product user.

Existing approaches to integrate the two systems, such as participatory approaches (Amasawa et al., 2024), the Multi-Level Perspective (Geels, 2002) or socio-technical approaches (e.g., Hermann et al., 2022; Greene et al., 2024) focus on the transition to a CE and take fragmented perspectives, such as on specific technologies or system levels. As such, they are insufficient to create a comprehensive idea of what the consumption system consists of in a realized CE that clearly aligns with, and informs, the production system. For this task, systems models are helpful tools, especially for dealing with such complexity (Ke et al., 2023; Richert et al., 2017).

1.3 A Multilevel systems model

To systematically and transparently capture possible implications of the behaviors of higher system level components in a future state of a CE (e.g., economic principles and business operations) on individuals located at the lower levels of the system (e.g., cost of goods and personal values), a so-called "multilevel systems model" (MLSM) constitutes a useful tool. In these qualitative models, system components, such as places and actors, and their relations, such as resources or information flows, are organized into proximal (i.e., concreteness) vs. distal (i.e., more abstraction) locations based on the object of study at the center of the model (Bronfenbrenner, 2005; Milfont and Markowitz, 2016) (Figure 1).

A multilevel systems perspective is necessary for fully understanding product users' experience and behaviors (Jensen, 2007; Hackman, 2003) as embedded in a larger system (Polanyi, 1944; Bronfenbrenner, 1992; van de Vijver et al., 2008; Chen et al., 2021). By using abstraction to deal with complexity (van Gigch, 1991, p. 3, 19), MLSMs are sometimes referred to as an interdisciplinary "system of systems" with the capacity to provide holistic information for policy and decision-makers (Iacovidou et al., 2017; Iwanaga et al., 2021).

While a CE is often represented as a multilevel model (e.g., Kirchherr et al., 2017; Ghisellini et al., 2016; Prieto-Sandoval et al., 2018), such models have yet to put the individual product user at the center (Section 2.2), despite the potential benefits of doing so (Section 2.1).

The overarching aim of this paper is two-fold. First, we seek to clarify product users' role in a realized CE in terms of what system components (e.g., actors and objects) are necessary for engaging in CE Behaviors, thereby enabling circular resource flows from the perspective of the product user. Second, we aim to contribute to a more comprehensive view of consumption and production systems in sustainability research more generally, and in the CE field specifically. To accomplish this, we develop a "Foundational CE Multilevel Systems Model" (F-CE-MLSM), capturing the necessary system components (e.g., actors and settings) and relations (i.e., flows) within the interconnected consumption and production systems of a CE ("CE systems") for durable consumer products. To manage the complexity of such systems, we adopt a strict material flow perspective, thus excluding economic, technical and social factors. However, the F-CE-MLSM is created with the intention of it being a foundation onto which these other dimensions may be added in future research (Section 6 and 7).

2 Background

2.1 The importance of MLSMs for a CE

MLSMs that take the perspective of the product user can provide a systematic and transparent concept of which, and how, higher system level actors and their activities impact the product user, such as how overarching culture and marketing efforts perpetuate personal norms and values (Boulet et al., 2021; van de Vijver et al., 2008). This effect can be referred to as the MLSM's *verticality*. The MLSM also captures *horizontality* in terms of the interaction between system components located at the same level, such as how the multitude of lower system level components (e.g., transportation options and social settings) provides context for the product user's experience and behavior (Bronfenbrenner, 1977; Zhijun and Nailing, 2007). "Multilevel studies [...] are informative because they provide a broader perspective within which to situate individuals' decision-making" (Milfont and Markowitz, 2016, p. 113), as well as broader experiences—capturing how systems afford individuals with only limited agency.

Future-oriented MLSMs (i.e., those depicting yet-to-be states of an alternative economic system realized at the economic scale), such as that of a realized CE, can increase transparency. In futures studies, "transformation" refers to the process of discerning what higher system level information about an alternative economic system means for lower levels of that system at which the individual resides (Wangel et al., 2019). For this transformation, MLSMs provide structure, which can ensure completeness and thereby improve accuracy (Sale and Carlin, 2025; McIntyre, 2017; Ostrom, 2007; Hackman, 2003)—leading to enhanced quality of future-oriented sustainability research.

2.2 The multileveled nature of a Circular Economy

The conceptualization of a CE as being made up of systems levels, "scales" (e.g., Ghisellini et al., 2016) or "dimensions" (e.g., Feng and Lam, 2021) is well-established in CE research (e.g., Kirchherr et al., 2017; Ghisellini et al., 2016; Ahmed et al., 2022) and policy (Hartley et al., 2020). Reference to levels of a CE system can also be seen in the concept of circular businesses as "downstream" (i.e., consumer-interfacing) vs. "upstream" (i.e., business-internal and not involving the consumer) (e.g., Henry and Kirchherr, 2020). However, existing MLSMs of a CE tend to place either resources, process or product at the center (Oliveira et al., 2021) (c.f. Figure 1) and are inconsistent when it comes to what each vertical level consist of, such as where cities, businesses and supply chains are located (e.g., Merli et al., 2018; Alaerts et al., 2019; Chizaryfard et al., 2021; de Jesus et al., 2018). Yet, this placement should depend on the specific system and issue under study (Moraga et al., 2019; van Gigch, 1991). Current MLSMs of a CE do not account for consumption appropriately (Moraga et al., 2019), including only very limited factors, such as information and labeling (Ghisellini et al., 2016), need satisfaction (Alaerts et al., 2019), consumer acceptance and cost savings (Feng and Lam, 2021). Overall, existing CE MLSMs predominantly capture the production system. As for sustainable provisioning systems (i.e., elements related to the satisfaction of human needs; Fanning et al., 2020, p. 104), these have been depicted as multileveled, but without focusing on the individual (International Resource Panel, 2024).

2.3 The content of a CE system

Naturally, the specific components and flows that make up a CE system depends on the modeling tradition. For example, agent-based models focus on agents or entities (e.g., Walzberg et al., 2023), material flow analysis looks at stocks and flows (Makarichi et al., 2018), while dynamic systems models capture system behaviors and feedback (Valtere et al., 2025). Some CE conceptualizations also focus on specific CE activities or strategies (Ellen MacArthur Foundation, 2013).

Existing qualitative MLSMs of sustainable consumption are limited and are rather rudimentary when it comes to capturing the system components (i.e., nouns, such as actors) involved from the perspective of the individual (Boulet et al., 2021; Sun et al., 2019; Akenji and Chen, 2016). They often fail to include more basic components in CE Behavior engagements, such as products themselves. Many such MLSMs focus on the link between consumer behavior and environmental objectives through intervening mechanisms, such as "trust", and "moral values" (e.g., Grabs et al., 2016; Sheoran and Kumar, 2020). In contrast, MLSMs centered on individuals often include important contextual information absent in other CE models, including physical places and contexts, such as work and neighborhoods (Bronfenbrenner, 1979), ability (Akenji and Chen, 2016), awareness, and competencies (Grabs et al., 2016; Sheoran and Kumar, 2020). In our research, we failed to identify an MLSM that explicitly contain what is common in CE and sustainable consumption research, such as the necessity of having access to tools for repair (e.g., Nazli, 2021), the existence of unwanted products at end-of-use (Macklin and Kaufman, 2023), and optimal use of diverse sets of skills (see Buyukyazici and Quatraro, 2025).

In summary, although comprehensive considerations for system components and flows making up the experience of product users are crucial for optimizing the CE systems, models that consider and integrate such factors are largely lacking in the CE and sustainability literature. The Foundational CE Multilevel Systems Model (F-CE-MLSM) introduced in this paper contributes to filling this gap.

3 Methodology

A systematic modeling process was required to develop a foundational MLSM capable of effectively integrating and managing the complexity of diverse circularity activities realized at the economy-scale. The following sections introduce the 10 iterative steps, divided into two stages (Section 3.1), used to develop the F-CE-MLSM (Section 3.2), and to assess the quality of the F-CE-MLSM (Section 3.3).

3.1 Process overview

Multilevel systems modeling can be conducted in 10 iterative steps, divided into 4 parts (left hand-side; Figure 2) (Svensson-Hoglund et al., under review-c). This process of modeling is represented as two stages (right hand-side; Figure 2). In Stage 1, an initial F-CE-MLSM was developed (Parts 1-—3), and in Stage 2, this F-CE-MLSM was validated and refined via a Delphi study (Parts 4a, 4b, and 4c; right hand-side Figure 2).

Below, we outline the execution of the two stages, as represented in Figure 2.

3.2 Model development (stage 1)

"Components" is an umbrella term used to represent nouns within the CE system, such as actors and objects. Relations between these components are represented as "flows" (e.g., transfers, transactions, or movements) of physical and nonphysical resources which are necessary for CE Behavior engagements to take place (Step 1; Figure 2).

To define circular material flows (Part 1, Step 2; Figure 2) in a realized CE, flows and components were organized based on a framework of the five CE loop strategies: (1) *simplifying* (i.e., reduce the total amount of materials in the economic system, aligned with sufficiency); (2) *dematerializing/narrowing* (i.e., reduce the amount of materials used in product units, aligned with efficiency); (3) *slowing* (e.g., reuse, repair, and remanufacturing); (4) *intensifying* (i.e., PSS model and sharing), and; (5) *closing* (i.e., recycling and replacing of primary materials with secondary materials) (Svensson-Hoglund et al., under review-a), influenced by Reike et al. (2018). These loop strategies have been used to conceptualize CE Behaviors as a multi-process

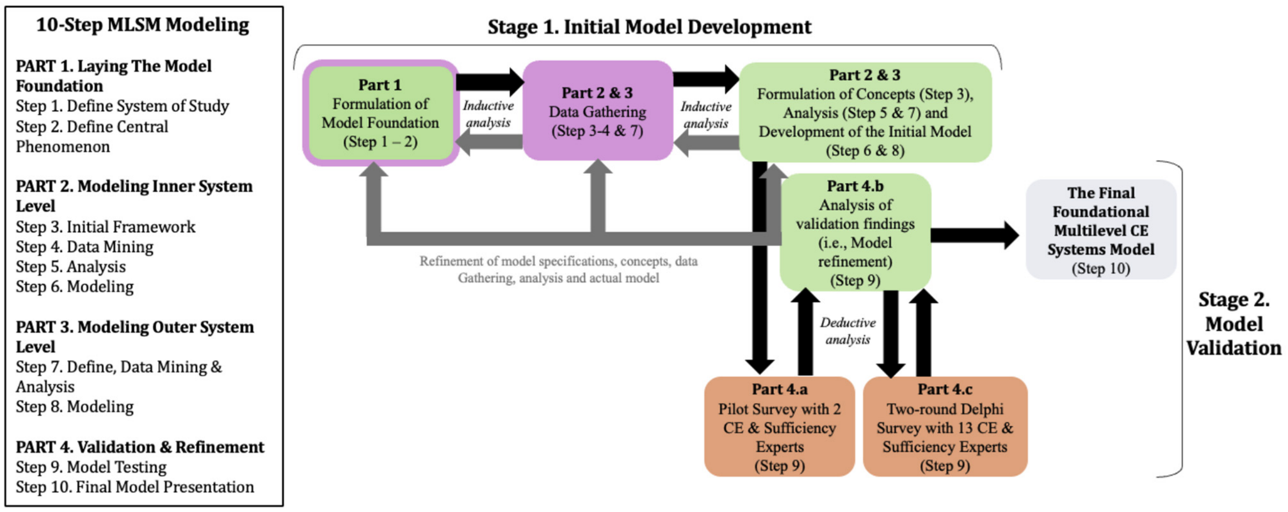

FIGURE 2
The Simplified Modeling Process (see Section 1, Supplementary material 1, for more details), with the four parts of the 10 steps corresponding to the parts in the flow chart on the right hand-side. Green elements constitute actions in which the modeler is making decisions; pink/purple elements represent data gathering activities related to the literature, and orange elements represent model testing and refinement activities. Adapted from Svensson-Hoglund et al. (under review-c).

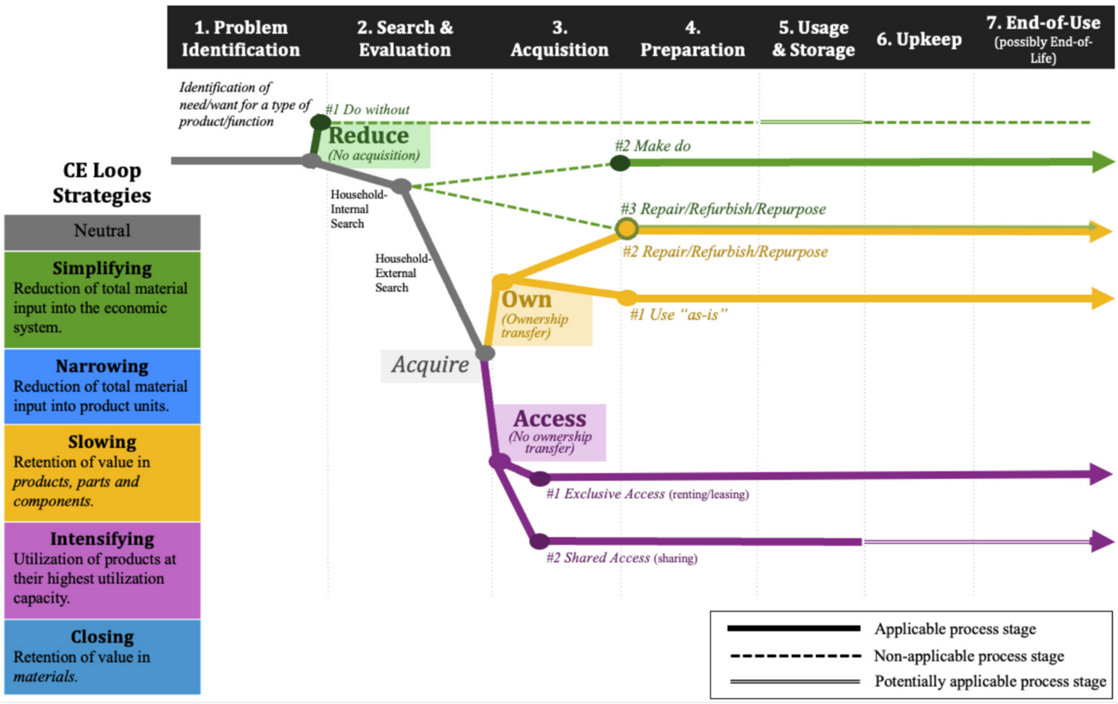

FIGURE 3
The Seven-Stage CE Behavior Process Framework, with the CE Loop Strategies on the left hand-side.

stage "CE Behavior Process Framework" (Svensson-Hoglund et al., under review-b), contextualizing product users' CE Behaviors as part of different loop strategies and in different situations (e.g., Macklin and Kaufman, 2023) (Figure 3). The method behind the development of these two frameworks and their validations are described in Section 2 of the Supplementary material 1.

The identification of components and flows was initiated at the innermost system level, referred to as the "micro level" (Part 2, Step 4 and 5; Figure 2). For this, four tabular-formats of the CE Behavior Process Framework (Figure 3) were created (the CE Behavior Process Pathway Tables; see Supplementary material 2) for each of the four pathways in Figure 3. These were critically evaluated

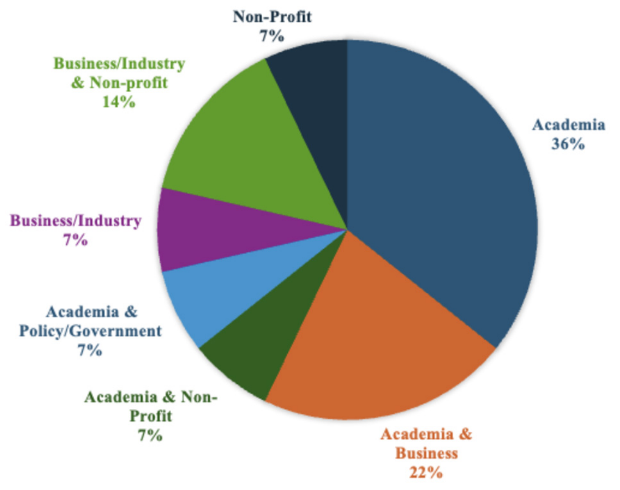

FIGURE 4
The primary background of the 14 Delphi survey participants.

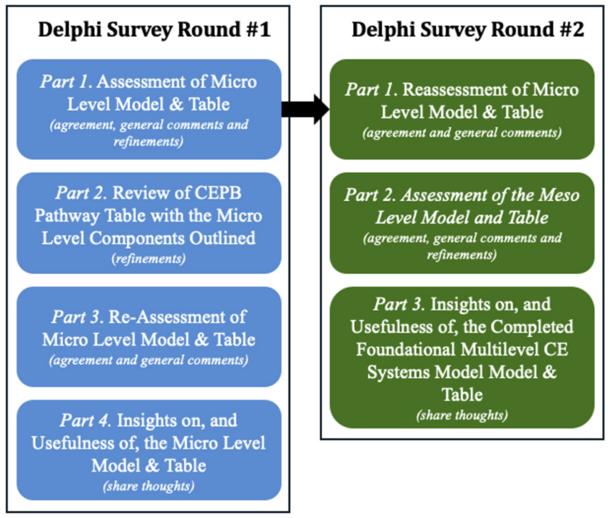

FIGURE 5
The Delphi survey structure and content.

to identify system components and flows necessary for the CE activities to take place (e.g., tools or physical places) and for the CE loop strategies to be realized. See Supplementary materials 1, 2 for more details.

The resulting system components were then assessed and synthesized into component categories and the flows outlined in the initial F-CE-MLSM (Part 2, Step 5 and 6; Figure 2).

The outer system level of the F-CE-MLSM is referred to as the "meso level". To identify the components at this level (Part 3, Step 7 and 8; Figure 2), the identified micro level components and flows were assessed to discern essential components and flows needed for these components to be available, and, therefore, for the product user to be able to perform CE Behavior process activities, such as there being a provider of Necessities (Supplementary material 2). Components at the meso level were *not* directly experienced by the product user (i.e., beyond their direct experience). In these steps, we identified actors (providers) based on activities or operations that they would need to undertake to enable the CE activities at the micro level. Again, the focus was not on facilitating activities (i.e., reducing friction, such as time and effort), but on what was needed to make the CE Behavior possible.

3.3 Model validation (stage 2)

In Stage 2 (Figure 2), a Delphi survey, consisting of two rounds, was used to gather feedback and data on the F-CE-MLSM, and reach consensus (Beiderbeck et al., 2021; Skulmoski et al., 2007). Comprehensive details regarding our complete method and process (Figure 2), including the expert selection process and survey document are provided in Supplementary material 2.

In total, 14 experts based in the E.U., U.K., and U.S., and possessing backgrounds and expertise primarily in academia, business/industry, non-profit, and policy/government (Figure 4), took part in a two-round Delphi survey that lasted 30 days (see Survey Document in Section 4, Supplementary material 1).

The core task of the expert group consisted of providing critical feedback and commentary about the accuracy and level of detail of the F-CE-MLSM and accompanying Table. To support expert participation, the Model was presented through a video. In addition, participants were invited to co-author the manuscript and contribute feedback on draft versions, establishing a collaborative review process similar to a "peer check" (Belk et al., 2013).

The survey consisted of two rounds, in which the micro level (the innermost system level at which the product user is residing) was introduced in the first round and meso level considerations (outer system elements, not directly experienced by the product user) were added in the second round (Figure 5).

Acceptance rates were calculated using a Likert-type scale representing average acceptance, which was measured on a scale of one—seven, with seven meaning strong agreement and one meaning strong disagreement. These ratings were analyzed as an average percentage of participant ratings to capture the spread.

Feedback from Delphi study participants was coded and characterized based on the implications of the specific feedback into three categories: clarifications, remedies, or changes. Participant feedback was categorized as a *clarification* if it consisted of suggested alterations to the F-CE-MLSM that would serve to *increase understanding* of its existing elements. Clarifications were automatically incorporated into the F-CE-MLSM unless they added significant details, in which case Delphi participants were asked to vote (requiring a majority decision) in the subsequent review round. Participant feedback was categorized as a *remedy* if it consisted of suggested alterations that would serve to *address an omission or misrepresentation*. Remedies were always incorporated into the F-CE-MLSM. Lastly, participant feedback was categorized as a *change* if it consisted of suggestions to *alter the main idea* of the Framework. Such changes, if suggested by >50% of participants, would be automatically incorporated into the revised Framework; changes suggested by 25-—49 % of participants would go to a

Delphi participant vote in the subsequent round, and be decided via a majority vote in the subsequent round.

Due to the minor nature of the alternations incorporated at the Meso level following the Delphi survey round 2 feedback, and the already high acceptance rate, a third survey round was not considered necessary (see Figure 5).

It is important to acknowledge that the Delphi study results could have been different had the participants had more access to each other's feedback (i.e., a modified Delphi) and/or worked in more of a co-creation process. As such, the resulting F-CE-MLSM presented herein should be regarded as a basic conceptual model for future research, which may focus on further development and validation, e.g., through stakeholder workshops (c.f., Macklin and Kaufman, 2023).

The final F-CE-MLSM and Table with definitions are presented separately in Section 4, with the Delphi study findings summarized in Section 5.

4 The foundational CE multilevel systems model

The Foundational CE Multilevel Systems Model (F-CE-MLSM) comprises the components and flows required for engaging in CE behaviors within a fully realized CE. For example, repairing a hand mixer (i.e., a CE Behavior) requires tools, knowledge, manuals, and other resources (Figure 6). "Components" constitute an umbrella term for the relevant actors, objects, settings, data, and structural components (identified by letter in Figure 6). "Flows" or relations (identified by numbers in Figure 6) is an umbrella term for transfers, transactions, or movements of resources through, between, and/or by the different components. Both components and flows can be physical, such as the movement of a tangible product or tool, as well as intangible (i.e., non-physical), such as digitized products and transfer of knowledge.

In the F-CE-MLSM, the components and flows are organized according to proximity vs. distance to the product user; while *the micro level* captures product user "interfaces" (i.e., what/who the product user is interacting with directly), *the meso level* consists of the "hidden side" of the relevant flows, actors and their activities that operate beyond the direct experience of product users (see Henry and Kirchherr, 2020; Bronfenbrenner, 1979). A macro level was not included due to the delimitations to material flows.

Within the F-CE-MLSM, "micro level components" (i.e., directly experienced by the individual product user) are identified by capitalized letters A—F in Figure 6. "Micro-meso determinants" exist at the interface between micro- and meso-levels and are capitalized letters G—N in Figure 6. The Micro-Meso determinants represent actors, objects, settings, data and structural components that are at least partially directly experienced by the individual product user. For example, a reuse store (e.g., Transfer Setting Provider, or determinant "J"; Figure 6) connects the product user with the meso-level system of reused product provisioning. In this example, the "storefront" is a Transfer Setting Provider component (determinant "J") that is directly experienced by the product user when they enter the store. "Store management", on the other hand, is an aspect of the same component (determinant) that affects the product user's experience, but which is likely not directly experienced by the product user, hence that aspect is located at the meso level.

Importantly, the F-CE-MSLM is neutral to the type of CE Behaviors (e.g., commercial and non-commercial); the components and flows *depict system functions*, such as the function of a product necessity (which may consist of a sophisticated, high-tech repair tool or home-made, low-tech tool) or product provider (who may be a multinational company or the neighbor who lent the product to the product user).

The components (letters) and relations (numbers) in the F-CE-MLSM (Figure 6) are further clarified and defined in Table 1. To facilitate the simultaneous processing and use of the F-CE-MLSM (Figure 6) and Table 1, they are both included as Figure 6 and Table 1. Hereafter, we use the term "F-CE-MLSM" to refer to both Figure 6 and Table 1.

Starting with the content of the micro level, the F-CE-MLSM (Figure 6 and Table 1) suggests that the ability to perform CE Behaviors and move forward in the CE Behavior process, such as acquire a product or conduct a repair (Figure 3), relies on the presence of the following so-called *"Micro Key Components"* (i.e., the system content closest to the product user): (A) *the Product* (e.g., a cell phone, sweater or sofa); (B) *Transfer Settings* (i.e., physical places where micro key components are picked up or dropped off, such as a store front, recycling station or mailbox of the product user); (C) *Enabling Technologies* (e.g., platforms for resale and communication); (D) *Product Necessities* (e.g., physical and digital tools, manuals and spare parts for repair, refurbishing, cleaning and usage); (E) *Knowledge and Skills* (e.g., how to locate a product or conduct a repair), and; (F) *Transportation* (e.g., public transport, private, rental).

Importantly, Enabling Technology (C), such as a computer for searching for a reused item, constitutes another Product (A), apart from the one the product user is searching for (e.g., a bike for rent) and thereby comes from a Product Provider (G), which may be a library with computers for temporary use, or a traditional transaction provider. For simplicity, aligned with the CE Behavior Process Framework (Figure 3), the acquisition of such an enabling technology entails, or entailed if already acquired, a separate CE Behavior Process (i.e., problem identification, search, etc.) and also F-CE-MLSM.

Product Necessities (C) refers to tools and information related to product-related services or activities, such as maintenance and repair. Enabling Technology (E) consist of tools and resources for engaging in e.g., searches and putting a product up for resale at the EOU (Figure 3). Knowledge and Skills (E) are non-product specific, while Product Necessities (D) are more applied to specific brands and even models. However, Product Necessities (D) in the form of information may translate into more generalizable knowledge and skills, i.e., the product user's Knowledge and Skills (E).

Next, at the intersection between the micro and meso levels are the *"Micro-Meso Determinants"*. Certain aspects of the micro-meso determinants are experienced directly by the product user (e.g., storefront and staff interactions), while other aspects (e.g., store management and supply chains) are only indirectly experienced (blue and gray; Figure 6). These components determine the existence of the Micro Key Components and consist of providers. The F-CE-MLSM (Figure 6 and Table 1) is neutral regarding the

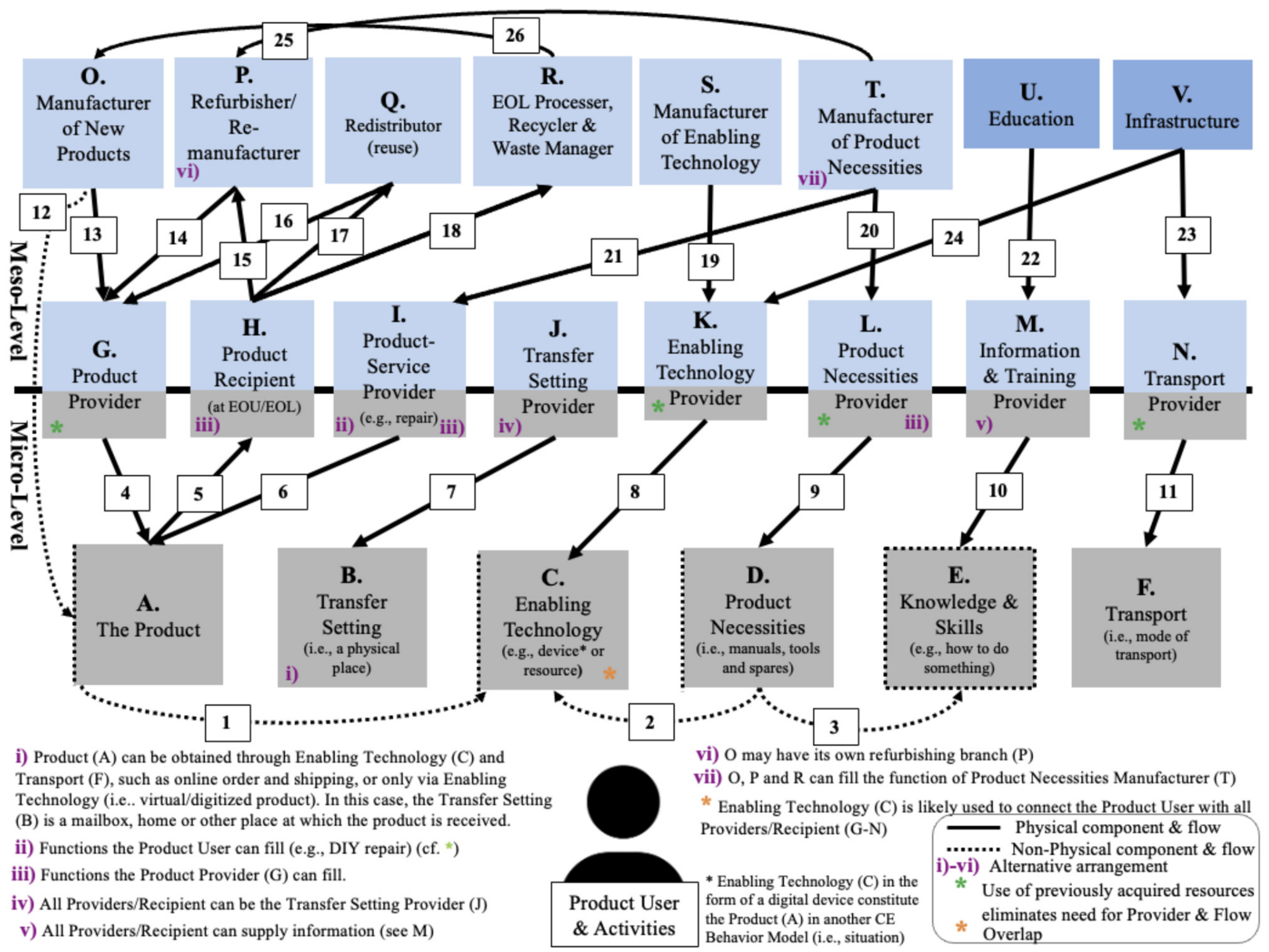

FIGURE 6
The foundational CE multilevel systems model (F-CE-MLSM), consisting of Key Micro Components (i.e., system components closest to the product user), with so-called "micro level determinants", stretching into the meso level (i.e., has aspects that are not directly experienced by the product user, such as the operations "behind the scenes" of an organization or business), as well as further removed Meso level determinants needed for the activities in CE Behaviors to be possible. Components (i.e., actors, objects, settings, data, etc.) are represented by letters; flows or relations (i.e., transfers, transactions, movement of resources, etc.) are represented by numbers; and alternative components or functions are denoted with roman numerals. Dotted lines of components indicate partial or full intangibility, such as digital. Possible alternative arrangements are depicted in purple roman numerals to capture potential varieties of the system. Use of previously acquired resources (e.g., the product user already has access to a tool needed for the repair in question), which eliminates the need to acquire it, is denoted with green asterix. Overlaps are denoted in orange asterix.

type of CE Behaviors, whether they are commercial or non-commercial, or related to citizenship, such as sharing and giving, or the objects involved are high- or low-tech. As such, all system components, including object and providers, denote *functions* in the CE system, such as to provide products (component G), which can be anyone from a neighbor to a multinational corporation, or constitute a necessity (component D), which may consist of a high-tech, sophisticated diagnostic tool or a piece of duct tape.

Lastly, located the furthest away, and only indirectly experienced by the product user, are the *"Meso Determinants"* and flows (i.e., gray; Figure 6). These components are necessary for the micro-meso level functions to exist, such as refurbishers/remanufacturers (P; Figure 6) supplying product for the product provider (component G); in essence, the meso determinants constitute the sources or recipient of the Micro Key Components (i.e., where the component is coming from or where the product ends up).

In the F-CE-MLSM, purple roman numbers denote alternative arrangements and relevance of components or flows, to capture the possible variety of a realized CE, depending on the characteristics of the same. For example, purple "i)" denotes that the transfer setting (component B) is not applicable in case product (component A) can be obtained through enabling technology (component C) and transport (component F), such as online order and shopping, or if the Enabling technology can receive the virtual/digitized) Product (e.g., Ereader).

Green asteria denotes how the product users may use previously acquired for example product (component A) or product necessities (component D), corresponding with the Reduce Pathway in the CE Behavior Process Framework (i.e., making do with what they have) (Figure 3)—eliminating the need for flow (4)

TABLE 1 Codes for Figure 6.

Key components of the micro-level (A-F) (Located closest to the product user)	
F-CE-MLSM Label	**Description and explanation**
A. The product	The *Product* (A) is acquired, repaired, shared with others, etc. This Product can be both physical (e.g., book) and/or virtual/digitized (i.e., intangible) (e.g., eBook or streamed movie instead of a physical version). For this reason, one side of the component box is marked with a dotted line in the F-CE-MLSM (i.e., to signify possible intangibility). Importantly, a product can be physical OR physical + intangible. The latter constellation consists of a physical product requiring software to function (e.g., software on a cellphone or an app used to gain access to data collected by a physical product, such as a scale) in which case the digital element is considered a part of the Product (A). Another example of a physical + intangible product constellation is when a digital device is needed to use the Product (A), such as an e-book requiring an e-reader to be utilized. Also, physical + physical product constellations are possible, such as how a DVD requires a DVD player and TV. In this case, the digital device (e.g., TV or eReader) is separate from the Product (A) and is considered an "Enabling technology" (C)—see below. This digital device constitutes a Product (A) in another MLSM where it relies on the same type of system components and flows as the current Product (A) [e.g., Product Provider (G), etc.] (see * in (C) below. On this note, to be utilized, some products require disposable products, such as how coffee makers need filters and (some) vacuum cleaners need vacuum bags. As disposables, these are not considered in the F-CE-MLSM.
B. Transfer setting i)	*Transfer Settings* (B) is a physical place at which the Product User is located when gaining access to/receives Product (A) (e.g., pick-up point), gets product services done (e.g., repair center), or relinquishes (e.g., recycling drop-off station) Product (A), or receives or relinquishes other key micro components, such as a tool (Product Necessities "D"). **i) Alternative component taking on function**: The function of a Transfer Setting (B) can instead be filled using Enabling Technology (C) (e.g., an online platform or phone) and Transport (F) (i.e., shipping/delivery). In this case, the Transfer Setting constitutes a mailbox, the Product User's home, or another place at which the Micro Components are received or sent away. In the case of a digital product (e.g., streaming a movie), only Enabling Technology (C) is needed for the transfer—see flow [1] below.

**C.
Enabling technology
*
 	
***
	Enabling Technology consists of the technological capabilities available to the Product User for managing the entire CE Behavior process engagement (i.e., searching, acquiring, preparing, using, sharing, and disposing of a product, including obtaining the required knowledge and skills).
	
	Enabling technologies exist in the form of:
	• *Digital Device** (e.g., phone, DVD player, eReader, and Wifi router), and/or;
	• *Resources*
	  ○ *Intangible* Resources (i.e., virtual setting/marketplace), such as online sharing platforms and repair forums (which require digital devices above to access, such as a computer or smartphone, see below)
	  ○ *Physical* Resources, such as a phone or internet connectivity (which the digital devices above require to function), as well as a physical bulletin board or printed newspaper listing products available for acquisition (i.e., sale or accessing, such as rental).
	
	For example, resources to locate a local bike rental can be intangible (e.g., an online directory of providers in the area), or physical (e.g., a printed directory of providers with numbers and a telephone to contact them). As such, one side of the component box is marked with a dotted line in the F-CE-MLSM.
	
	* Enabling Technology in the form of a digital device constitutes Product (A) in another F-CE-MLSM. In other words, if such a device is needed, it constitutes an additional "Problem identification" in its own CE Behavior Process (i.e., going from stage 1—7; Figure 3), e.g., accessing a computer at the local library to conduct searches for a refurbisher (i.e., "I. Product-Service Provider").
	
	Importantly, digital devices as Enabling Technologies are distinct from "Product Necessities" (D) (see below) in that Product Necessities are used for maintenance, repair, refurbishing, and repurposing specifically. An example of a digital tool that is a Necessity is diagnostic equipment (i.e., for troubleshooting), while a digital tool as an Enabling Technology constitutes, e.g., an app for organizing one's product inventory for easier household-internal searches (Figure 3) and/or receiving reminders of when and what type of maintenance to conduct. Enabling Technology (C) can sometimes be needed to access Product Necessities (D), see flow [2].
	
	***Overlap:** Enabling technology (C) is likely used to connect the Product User to all Providers/Recipient (G-N) in some way (e.g., phone or website).

D. Product necessities	*Product Necessities* enable the installations, maintenance, repair, refurbishing, and repurposing, and consist of: • Physical and digital tools (e.g., brush, screwdriver, and diagnostic equipment for troubleshooting) • Spare parts, and; • Instructions/manuals/guides Product necessities in terms of information are specific to the particular product brand or model, such as an instruction video on how to clean the filters of a dishwasher GE Profile model PDWT580P00SS or swap a broken screen on an iPhone 13. This is different from "Knowledge and Skills", which is more general. However, see flow [3]. Product Necessities (D) can be both physical (e.g., screwdriver) and intangible (e.g., instructions in an online video)—i.e., one side of the component box is marked with dotted line in the F-CE-MLSM. For the difference between Product Necessities (D) and Enabling Technology (C), see Enabling Technology (C).

(Continued)

TABLE 1 (Continued)

Key components of the micro-level (A-F) (Located closest to the product user)	
F-CE-MLSM Label	**Description and explanation**
E. **Knowledge and skills**	Product user *knowledge* entails awareness and familiarity of, e.g., suitable provider options (i.e., who can perform the service), proper usage (i.e., that is not creating unnecessary wear and tear or breakage), and the maintenance needs of the product (i.e., that certain interventions are needed and what they consist of). *Skills* are composed of abilities to, e.g., conduct a repair, or a cleaning (i.e., what is needed and how it is done), and how to use Enabling Technology (C), such as a sharing platform. Unlike Product Necessities (D), Knowledge and Skills (E) is not brand or model-specific; instead, it concerns the Product User's abilities across product models, types, and brands, such as how to sew together a tear in fabric or treat rust on a bike as part of a refurbishing. However, Product Necessities (D) in the form of information can feed into the Product User's Knowledge and Skills (E)—see flow [3]. Knowledge and Skills are intangible—i.e., all sides of the component box are marked with a dotted line in the F-CE-MLSM.
F. **Transport**	*Transport* encompasses any mode of transportation, such as a bike or car, for the Product User and the Product (A), and/or Product Necessities (D), and/or Enabling Technology (e.g., physical resources*, such as a printed provider directory), Alternatively, shipping/delivery of only the Product (A), Product Necessities (D) and/or Enabling Technology (C)* is used (see **i)**). *Enabling technology in the form of a digital device is considered a Product (A) in another F-CE-MLSM (see (C)).
Flows between key micro level components	
[1] **A–[1]→ C**	A virtual/digitized Product (A) requires Enabling Technology (C) to be delivered and used, such as an eReader (e.g., kindle) for an eBook, with the needed software. This flow [1] is intangible and is therefore marked as a dotted line in the F-CE-MLSM.
[2] **D–[2]→ C**	Product Necessities (D) in the form of information, guidance, or manuals can be accessed through an Enabling Technology (C), e.g., a website with a maintenance instruction video. This flow [2] is intangible and is therefore marked as a dotted line in the F-CE-MLSM.
[3]] **D–[3]→ E**	Product Necessities (D) in the form of product-specific information [3] (possibly obtained through Enabling Technology (C) -see [2]) feeds into the Product User's Knowledge and Skills (E) at a more general level of knowledge. However, this flow is different from more general (i.e., non-brand or model-specific) information and skill-building, which is provided by the Information and Training Provider (M) in flow [10]. This flow [3] is intangible (i.e., information converted to knowledge and skills) and is therefore marked as a dotted line in the F-CE-MLSM.
Micro-meso determinant components (G—N) **and the flows to micro key components** **Micro-Meso Determinant Components are located at the intersection between the Micro and Meso levels because while some parts of these components are experienced directly by the product user (e.g., a storefront), other parts (e.g., store management) are not**	
F-CE-MLSM label	**Description and explanation**
G. **Product provider** **G–[4]→ A** *****	The *Product Provider* (G) makes the Product (A) available for acquisition to the Product User [4], through e.g., rent, sale, sharing, or loan. As with all providers (G-N), this entity can consist of, e.g., a retailer or a friend. *** Use of previously acquired resource:** The Product User's utilization of a previously acquired Product (i.e., the Reduce Pathway in the CE Behavior Process Framework; Figure 3) eliminates the need for this provider and flow. This flow [4] is physical if the product is physical, and intangible if the product is virtual/digital. The latter relies on Enabling Technology (C), such as an eReader, to be delivered and used—see [1].
H. **Product recipient** **A–[5]→ H** **H–[17]→ Q** **H–[15]→ P** **H–[18]→ R** **iii)**	The *Product Recipient* (H) receives [5] the Product (A) at the "End-of-Use (possibly End-of-Life)" stage in the CE Behavior Process Framework (Figure 3) from the Product User. This entity can consist of: • Another product user (i.e., peer-to-peer reuse); • The product provider (G) (i.e., in Access-acquisition or Own with a take-back agreement; Figure 3), i.e., **iii) Alternative Component taking on function:** The Product Provider (G) takes on an additional function as Product Recipient (H); • An entity/organization acquiring the product, such as a reuse entity or waste collector (e.g., municipal). In this case, (H) is a "middleman" and sorts incoming products for either direct reuse (to Q Redistributor) [17], refurbishing/remanufacturing (P) [15]) or EOL management (to EOL Processing, Recycling or Waste Manager (R) [18]). This entity may be related to extended producer responsibility (EPR). This flow [5] is physical as virtual/digitized products are not typically returned.

(Continued)

TABLE 1 (Continued)

Key components of the micro-level (A-F) (Located closest to the product user)	
F-CE-MLSM Label	Description and explanation
I. **Product-services provider** **I–[6]→ A** **ii)** **iii)**	The *Product-Service Provider* (I) conducts, e.g., installation, maintenance, repair, and repurposing [6] on the Product (A) for the Product User. This flow [6] is physical in that a person conducts work, using tools. **ii) Alternative component taking on function:** The Product User can conduct the product service-related work and thereby take on the function of Product-Service Provider (I). **iii) Alternative component taking on function:** Product Provider (G) can conduct the product-related services and therefore take on the function of Product-Service Provider (I) in, e.g., offering home installations.
J. **Transfer setting provider** **J–[7]→ B** **iv)**	The *Transfer Setting Provider* (J) is responsible for the physical Transfer Setting (B), such as a store or collection site. This actor manages the setting and keeps it operational for the designated transfers to take place, such as the pick-up or drop-off of a product or other Micro Key Components, such as the provision of training for product users [7]. The Product User interacts directly with the physical environment and the personnel/volunteers there. **iv) Alternative component taking on function:** The Transfer Setting Provider (J) can be any of the Micro Key Components Providers, such as the Product Provider's (G) storefront, the Information and Training Provider's (M) training center, the EOU/EOL Product Recipients (H)'s collection point, or the Product-Service Provide (I)'s refurbishment workshop.
K. **Enabling technology provider** **K–[8]→ C** ***** *****	The *Enabling Technology Provider* (K) makes the Enabling Technology (C) available [8] to the Product User*. For clarity, Enabling Technology (C) refers to digital devices and resources (physical and intangible) for managing the entire CE Behavior process (Figure 3) engagement (i.e., searching, acquiring, preparing, using, sharing, and disposing of a product, including obtaining the required knowledge and skills). See (C). This flow [8] can be both intangible (e.g., app or website) and physical (e.g., a printed provider directory or bulletin board in the local community center)*. * The acquisition of a digital device in the form of a durable consumer product (e.g., phone, computer, or eReader) as an Enabling Technology (C) effectively constitutes another Product (A) (i.e., comes from a Product Provider (G) in another CE Behavior Process and F-CE-MLSM. (K) is likely a system component that the Product User has very limited contact with, perhaps only when acquiring the technology (e.g., buying an app) or when interacting with customer service, meaning that this component is more distal to the Product User. Hence, this system component is located further up toward the Meso level in the F-CE-MLSM (Figure 6). *** Use of previously acquired resource:** The Product User's utilization of previously acquired Enabling Technology (e.g., phone book, computer, or app) eliminates the need for this provider and flow.
L. **Product necessities provider** **L–[9]→ D** ***** **iii)**	The *Product Necessities Provider* (L) makes Product Necessities (D) available [9] to the Product User. This flow [9] can be both intangible (e.g., online video) and physical (e.g., printed manual or screwdriver). *** Use of previously acquired resource:** The Product User's utilization of previously acquired Product Necessities (e.g., tool) eliminates the need for this provider and flow. **iii) Alternative component taking on function:** The Product Provider (G) can take the function of Product Necessities Provider (L) by providing, e.g., spares and manuals for their products.
M. **Information** and **training provider** **M–[10]→ E** **v)**	The *Information* and *Training Provider* (M) supplies resources [10] that convert into Product User Knowledge and Skills (E). This entity can consist of repair cafes, providers of formal and informal training on repurposing and digital, or printed resources on refurbishing. Also, schools can provide such education (i.e., shop classes and home economics classes). This flow [10] can be both intangible (e.g., verbal instructions at a training center) and physical (e.g., a printed guide on decluttering). **v) Alternative component taking on function:** All Providers/Recipient can supply information, such as: • The Product Necessities Provider (L) personnel offering advice on how to conduct a cleaning procedure, or; • The Product Recipient (H) providing details on how to transfer the product (e.g., directions to drop-off).
N. **Transport provider** **N–[11]→ F** *****	The *Transport Provider* (N) provides the means of Transport (F) for the Product User, and/or Product (A), Enabling Technology (C)* and/or Product Necessities (D) [11]. This flow [11] consists of the movement of physical components and possibly the Product User, using the mode of transportation. * The transportation of Enabling Technology (C) in the form of a digital device (e.g., laptop for conducting searches) constitutes a Product (A) in another CE Behavior Process and F-CE-MLSM. Depending on the means of transport, the provider can consist of: • Public Transportation Authority • Private Transportation provider (e.g., taxi, car rental, or a friend offering a lift) • Shipping entity or postal service (see **i)** on online ordering and shipping/delivery) • *** Use of previously acquired resources:** The Product User's own means of transport (i.e., car or bike), eliminating the need for this flow and provider.

(Continued)

TABLE 1 (Continued)

The meso determinants (O—V) and the flows to micro-meso determinants Meso Determinants are only indirectly experienced by the product user through the flows to/from the meso-micro intersection	
F-CE-MLSM label	Description and explanation
O. **Manufacturer of new products** **O–[12]→ A** **O–[13]→ G**	The *Manufacturer of New Products* (O) determines/informs the *design* [12] of the Product (A). Manufacturers of New Products (O) supply *products* [13] to The Product Provider (G); it is possible for (O) and (G) to be the same entity, fulfilling both responsibilities, i.e., (G) may constitute (O)'s sales branch.
P. **Refurbisher/remanufacturer** **P–[14]→ G** **H–[15]→ P** **vi)**	The *Refurbisher/Remanufacturer* (P) supplies *products* [14] to the Product Provider (G); it is possible for (G) and (P) to be the same entity, fulfilling both responsibilities, i.e., (G) may constitute (P)'s sales branch. The Refurbisher/Remanufacturer (P) also receives EOU *products, parts, and components* [15] from the Product Recipient (H); it is possible for (H) and (P) to be the same entity, i.e., (H) may constitute (P)'s collection branch. **vi) Alternative Function:** Manufacturers of New Products (O) may have their own refurbishing branch.
Q. **Redistributor** **Q–[16]→ G** **H–[17]→ Q**	The *Redistributor* (Q) supplies *products* [16] to the Product Provider (G); it is possible for (G) and (Q) to be the same entity, i.e., product provider (G) may constitute (Q)'s sales branch of redistributed products. The Redistributor (Q) also receives EOU *products, parts, and components* [17] from the Product Recipient (H); it is possible for (H) and (Q) to be the same entity, i.e., Product Recipient (H) may constitute (Q)'s collection branch.
R. **EOL processor, recycler and waste manager** **H–[18]→ R**	The *EOL Processor, Recycler* and *Waste Manager* (R) receives the EOL *products, parts, and components* [18] from the Product Recipient (H); it is possible for (H) and (R) to be the same entity, i.e., Product Recipient (H) may constitute (R)'s collection branch.
S. **Manufacturer of enabling technology (S)** **S–[19]→ K**	The *Manufacturer of Enabling Technology* (S) supplies the Enabling Technology Provider (K) with the *technology* [19] for distribution; it is possible for (S) and (K) to be the same entity, i.e., (K) may constitute (S)'s sales branch. The Manufacturer of Enabling Technology (S) can consist of, e.g., an app developer or printer of repair provider directories. For clarity, Enabling Technology refers to digital devices and resources (physical and intangible) for managing the entire CE behavior process engagement (i.e., searching, acquiring, preparing, using, sharing, and disposing of a product, including obtaining the required knowledge and skills).
T. **Manufacturer of product necessities** **T–[20]→ L** **T–[21]→ I** **vii)**	The *Manufacturer of Product Necessities* (T) supplies the Product Necessities Provider (L) with the *product necessities* [20] for distribution. It is possible for (T) and (L) to be the same entity, i.e., (L) may constitute (T)'s sales branch. The Manufacturer of Product Necessities (T) also provides *product necessities* [21] to the Product-Service Provider (I) for use in its operations (e.g. spares for a repair). **vii) Alternative Function:** The function of the Manufacturer of Product Necessities (T) can be filled by the Manufacturer of New Products (O) (i.e., for their products). Also, Refurbisher/Remanufacturer (P), and EOL Processor, Recycler and Waste Manager (R) may recuperate spare parts and make available, thereby taking on the function of (T). For clarity, Product Necessities (D) are used in maintenance, repair, refurbishing, and repurposing activities and refer to, but are not limited to, spare parts, tools (e.g., screwdriver or diagnostic tool), and information (e.g., manual).
U. **Education** **U–[22]→ M**	*Education* (U) is the larger structural system component (i.e., not one designated actor) enabling the supply of *information and training resources* [22] to the Information and Training Provider (M), supporting (M) as the larger network or coalition of the repair café or repurposing course provider (U). This component can also consist of a department of education (i.e., impacting the nature and extent of shop classes and home economics taught in schools). All actors in the system rely on the education of their workforce. Due to the structural nature of this component (i.e., a higher level of abstraction), it is placed higher up in the F-CE-MLSM figure and colored in darker blue (Figure 6).
V. **Infrastructure** **V–[23]→ N** **V–[24]→ K**	*Infrastructure* (V) is the larger structural component (i.e., not one designated actor) enabling the development of necessary *infrastructure and services* [23-24] for the Transport Provider (N) and Enabling Technology Provider (K) to function; i.e., roads and internet connectivity. Actors in this function may consist of, e.g., governments, developers, private industry, utilities, and others. All actors in the system rely on infrastructure. Due to the structural nature of this component (i.e., a higher level of abstraction), it is placed higher up in the F-CE-MLSM figure and colored in darker blue (Figure 6).

(Continued)

TABLE 1 (Continued)

Key components of the micro-level (A-F) (Located closest to the product user)	
F-CE-MLSM Label	Description and explanation
Relationship between meso determinants	
T–[25]→ P	Manufacturers of Product Necessities (T) can supply *product parts and components* [25] to the Refurbisher/Remanufacturer (P) for their operations. According to **vii) Alternative Function**, this supply may also come from the Manufacturer of New Products (O) (i.e., for their products) and EOL Processor, Recycler and Waste Manager (R) (i.e., recuperated components from the waste stream).
R–[26]→ O	EOL Processor, Recycler and Waste Manager (R) can provide the Manufacturer of New Products (O) with *secondary materials* [26].

and (9) (Table 1) in the specific situation modeled. This assumes that these components (e.g., the tool) were obtained through these flows at an earlier point in time.

Lastly, orange asteria in the F-CE-MLSM denotes overlaps, such as how enabling technology (component C), such as a phone or internet, is used to connect the Product User to all providers (components G-N), which again may be non-commercial entities.

5 Results and analysis

In this section, the results from the Delphi survey used to develop and refine the F-CE-MLSM (Stage 2; Figure 2) are presented and analyzed. For the survey document assessed by the Delphi study participants, see Section 4, Supplementary material 1. In Section 5.1, we present the agreement rates and alterations made to the F-CE-MLSM. In Section 5.2, we summarize the participants' feedback regarding the use of a material flow perspective as a starting point for developing the F-CE-MLSM, as well as their thoughts on insights from the C-CE-MSLM and its usefulness and limitations.

5.1 Agreement rates and implemented feedback

In survey round 1, the participants assessed and refined a F-CE-MLSM of only the micro level, resulting in several clarifications to Table 1 and one minor change to the F-CE-MLSM (see Section 5.1.2); the enabling technology provider (K; Table 1) was moved closer to the Meso level as this provider is likely an actor with whom the product user has very limited direct contact with.

In survey round, after the first assessment of the Micro level of the F-CE-MLSM, the participants were invited to review the four CE Behavior Process Pathway Tables (Supplementary material 2), which were used to identify the components (i.e., data mining and analysis; Step 4 and 5 in Figure 2). One participant expressed that "The additional 'underlying' logic, actions, decisions, and details outlined in the [pathway] Tables were helpful for assuaging concerns regarding examples/details" (academic). When re-measuring their level of agreement with the Micro Level of the F-CE-MLSM, following the review of the CE Behavior Process Pathway Table on which the F-CE-MLSM was built, the results showed that it did not impact the average level of agreement with the Micro Level. Only four participants changed their rating; for two, the review of the Tables increased their confidence in the F-CE-MLSM, while it led two others to discover gaps in the F-CE-MLSM, leading them to decrease their agreement rating. One practitioner admitted that "trying to process/comprehend [the Tables] was a lot for my brain to handle," indicating that the cognitive load may have led some participants to not fully consider the Tables.

In round 2, the refined Micro Level of the F-CE-MLSM and Table were presented, earning a final agreement rate of 99 %. Next in this round, the Meso Level and Table was added, forming the complete F-CE-MLSM, earning an agreement rate of 90 % (Figure 5).

5.1.1 Implemented remedies

Remedies, or comments from Delphi participants intended to *address an omission or misrepresentation* in the initial F-CE-MLSM and Table, were incorporated into the final F-CE-MLSM.

Remedy #1—Definition of Knowledge and *Skills:* Knowledge and skills (component E) were initially defined as knowledge relating to "what" to do, while skills referred to "how" to do something. This was changed to knowledge relating to familiarity and awareness, with skills referring to ability.

Remedy #2—Distinguishing Education and Infrastructure: Education (component U) and Infrastructure (component V) were found to be conceptually different from other Meso-level components; "It's a bit like putting oranges, pears, apples and birds in the same group." (academic). On that note, these components are also in an "indirect relation with all the rest" or having a "horizontal effect" on the other components (e.g., actors) (academic) in that all actors rely on education for their workforce and infrastructure for their operation, making these components pertain to a higher system level. In total, this was brought up by four academics and two practitioners. To this end, these components were moved up and colored in a darker blue to denote a higher level of abstraction. In addition, it was noted in Table 1 that all actors in the system rely on these components.

5.1.2 Implemented clarifications

Several clarifications, intended to *increase understanding*, were incorporated into Table 1. The main ones consisted of the following clarifications:

- Product (A) is either completely physical (e.g., a printed book), partially digital (e.g., a phone with software) or completely digital (e.g., an Ebook).

- The Transfer Setting (B) can be a mailbox, the Product User's home, or another place where the Micro Key Components (e.g., a repair tool) are received or sent from.
- Enabling Technologies (C) exist in the form of digital devices (e.g., phone, DVD player, eReader, and Wifi router,), as well as resources, which can be intangible (i.e., virtual marketplace) or physical (e.g., phone or internet connectivity).
- The difference between Product Necessities (D) and Enabling Technology (C) is that the latter is used for managing the CE Behavior engagement (e.g., searching, acquiring and sharing), while Product Necessities are for activities, such as maintenance, repair, refurbishing and repurposing.
- Product Necessities (D) can feed into Knowledge and Skills (E) (flow [3]), but the latter is not brand or model-specific, unlike Product Necessities (e.g., a repair manual for a specific product model).
- Transport (F) also concerns the physical movement of Product Necessities (D), and/or Enabling Technology (C) (e.g., physical resources, such as a printed provider directory), not just the physical product.
- Examples of Information and Training Providers (M) were provided (e.g., schools).
- The Product Recipient (H) can also manage direct reuse (to Q Redistributor [17], refurbishing/remanufacturing (P) [15]) and EOL (EOL Processing, recycling or waste management (R) [18]).
- The Manufacturer of New Products can also take the role of Refurbisher/Remanufacturer (P).

5.2 Comments on insights, usefulness, and limitations of the model

The participants' feedback on the F-CE-MLSM (Figure 6 and Table 1) is summarized in Table 2, and presented in more detail in the following sections.

5.2.1 Taking a material flow perspective as a starting point

Regarding the delimitation of the F-CE-MLSM to material flows in a CE, the majority of the participants agreed (Table 2), saying, e.g., that "The material flow perspective is foundational for considering CE solutions" (academic), and; "In my opinion, the socio-cultural, financial, and technical elements need a starting point or anchor for thought experiments and discussion" even if alterations to the same may be necessary later on (practitioner). However, this delimitation may lead to the product user being credited with an unrealistic amount of agency, particularly given that both current-state and future product manufacturers employ marketing and product design efforts intended to steer and stimulate demand (academic).

In terms of additional dimension being added to this foundational model in future research, one practitioner expressed that, given how "culture is a different beast", it would be strategic to model the material flows and cultural factors separately, and then "try to layer them together later." One academic expressed that they: "cannot envision how social, financial and environmental aspects will be added to the [F-CE-MLSM]" (academic), especially given increased complexity that may defeat usefulness (academic)—identifying a challenge for future research and use of this F-CE-MLSM (Section 7).

5.2.2 Insights

The majority of the participants commented on the comprehensiveness of the F-CE-MLSM: "This is an extremely complex breakdown of product flow. I have never seen anything like it" (practitioner). One academic found that, while the F-CE-MLSM is complex, "we need to do this difficult mental work to avoid continued oversimplification and misunderstandings that are currently rampant in CE literature and research." To this point, in terms of insights, the F-CE-MLSM made five participants (two academics and three practitioners) realize the "enormity" in material flows in a CE, especially the many elements needed "to support a user in their use/maintenance/return/disposable of a durable consumer good" (practitioner) and the large number of actors that are involved (i.e. the complexity of the ecosystem) (academic). To this point, one academic found that the F-CE-MLSM captures how the further away one gets from the product user in the F-CE-MLSM, the higher the complexity. Another academic found that: "[the F-CE-MLSM] helps me think in detail about all the bits and pieces and players and parts. It helps identify all of the parts of the system". A practitioner expressed that, with the F-CE-MLSM, "we're finally visualizing pathways, which we lack so much in reuse/repair".

Two academics commented on the distinction between system elements that the product user experiences directly and those that remain indirect, external, or outside the product user's awareness. As one noted, "... the [F-CE-MLSM] is more useful to the Product User for elements that are directly affecting their direct behavioral impacts, while the more the distance grows (away from the User) the perspectives identified refer to larger socio-technical configurations outside of the direct experience of the user." (academic). In other words, while a policy may ultimately influence the product user, the user often perceives only its proximate effects, such as changes in the product or retailer, rather than the policy itself or its broader systemic implications. Thus, if the product user does not recognize the impact or influence of a particular system component, the utility of the F-CE-MLSM for informing or influencing the product user's behavior may be diminished, regardless of whether the F-CE-MLSM is employed by the product user themselves or by another actor seeking to affect user behavior. However, we note that a key purpose of the F-CE-MLSM is to convey and expand Product User understanding that such indirect components are still relevant and impactful, even if they were not originally perceived as such.

A practitioner speculated that: "In a realized CE, we will likely see a lot of competition in how providers can offer all or most of those elements in the most convenient/seamless way as that will be a competitive advantage and perhaps even command a premium price." While this may result in an enhanced product user experience, it likely comes with premium pricing, and the risk of market distortions.

TABLE 2 Summary of delphi study participant feedback regarding the material flow delimitation, insights derived, usefulness, and limitations of the F-CE-MLSM.

Details on insights, usefulness, and limitations of the F-CE-MLSM		Number of participants (not summative[a])
Starting with a material flow delimitation[b] (Section 5.2.1)	Agreed	8
	Disagreed or neutral/hesitant	2
Insights (i.e., takeaways and learnings) (Section 5.2.2)	General (positive)	2
	The "enormity" of material flows in a realized CE and the number of actors	5
	The difference between system aspects experienced directly by the product user, and aspects only indirectly experienced.	3
	The role of the product user in material flows	1
	General (No insights or Takeaways)	1
Usefulness (for context or actor, or lack thereof) (Section 5.2.3)	Specific Usefulness	
	To identify interventions points	3
	For assessment of sustainability potential of different consumption behaviors	1
	Simulations of social mechanism for behavior changes	1
	Define the goal of a CE	1
	Capture pathways to a CE and test scenarios	1
	Specific Lack of Usefulness	
	Uncertain how to add another dimension (e.g., social) to the Model	1
	General Usefulness (for all stakeholders)	0
	Businesses	5
	Consumers/Product Users	2
	Policymakers	4
	Academia and Education	4
	General Lack of Usefulness	1
	Theoretically useful, but need to demonstrate practical applicability (i.e., uncertain who the F-CE-MLSM is useful for)	3
Limitations[c] (Section 5.2.4)	The visualization is too complex and/or graphically unintuitive and relies on a video with step-by-step explanation to be accessible.	5
	Some components are conceptually different compared to the other components at their level, such as "knowledge and skills" (i.e., not a system component, but an inherent capability of the individual) and Infrastructure and Education, which are not actors, unlike the other meso determinants.	5
	While the F-CE-MLSM makes sense now, the future might change.	3
	"Determinants" indicates causality, which is erroneous.	2
	Digital technology of products is insufficiently considered	2
	Does not account for how EOL Processors, Recyclers and Waste Managers (R) need tools and information on design and material contents.	2
	Product user's need for space of use and storage is not captured.	1

[a]Participants are counted once for each detail they mentioned. For example, if someone mentioned both businesses and policymakers, they appear on each of these table rows.
[b]Two participants did not respond to this question, and one misunderstood the question.
[c]Herein, underrepresented changes to the Framework are also outlined (section 3.3).

5.2.3 Usefulness

The F-CE-MLSM defines "what needs to be in place and go 'right' for a CE to happen"—hence the goal of a CE (practitioner). To this end, a "primary importance" of the F-CE-MLSM lies in how it can capture pathways for the transition to CE, not necessarily that it depicts what a realized CE entails (academic).

As to specific types of uses, the F-CE-MLSM can facilitate a strategic understanding of the diverse linkages that can exist between material flows and environmental impact in a manner that allows for discussion about trade-offs and rebound effects (academic). To this end, the F-CE-MLSM: "allows for detailed assessment of the sustainability potential of different consumption behaviors", such as carbon emissions and water use (academic). In particular, the micro-level aspect of the F-CE-MLSM can be useful for identifying "barriers and bottlenecks" and potential intervention points in the system, meaning that "... the CE process experience can be improved in a way to make the CE action the 'default' or the preferable option", thus further enabling the operationalization of CE (one academic, supported by another academic and one practitioner).

Academia and education may benefit from the F-CE-MLSM as it offers as a more comprehensive research framework (two academics); it "... clarifies system details (e.g., skills, information, spaces, options, access, supporting infrastructure and actors), which has the potential to provoke much more clear and helpful research questions going forward..." (academic). Also, the F-CE-MLSM effectively: "... clarifies 'the system' for students" (academic), which may also benefit practitioners and their understanding of the CE system and product user's "CE experience" (academic and practitioner), including "...if/how to intervene in the system to support an efficient CE" (practitioner).

The system-level knowledge generated from the F-CE-MLSM can facilitate the emergence of business disruptors in the market (practitioner), particularly as it can be used by new business actors to model the costs and benefits of circular flows (practitioner). Businesses and other providers may also use the F-CE-MLSM to assess their current business model and areas of future development (two practitioners) in terms of becoming a "one-stop-shop" and meeting the comprehensive needs of their customers, "...from the product itself, to information, to transportation, to end-of-life management", while considering "optimal actor configurations to deliver superior user experiences at the lower costs (for competitive purposes)" (practitioner). Lastly, speaking to all the uses outlined, the model "... can help inform an effective policy mix." (academic).

5.2.4 Limitations

Five participants raised the problem of some components being conceptually divergent from other components at their level, suggesting that "Knowledge and Skills" should be considered an inherent capability of the individual, not a system component (academic). Similarly, Infrastructure and Education, which are not actors, are too different compared to other meso determinants (i.e., actual actors in the system) (four academics and one practitioner). This was, however, partially remedied by noting the difference of these two components (Section 5.1.1).

While comprehensive, three participants indicated the need for further applications of the F-CE-MLSM. To this end, in terms of usefulness, one academic expressed that: "I'm not sure about the usefulness because I am not sure of who the user may be," presumably because, as expressed by one academic: "it all feels quite complicated to me" (academic). One academic pointed out that these types of models are likely dependent on video explanations (as was provided as part of the survey) for optimal accessibility. See section 5.1.2 on how some saw the value in the complexity. A practitioner found that: "It would probably take me many hours to identify any gaps or missing connections"—indicating a limitation of the method used in this paper. Additional limitations of the FS-ML-CESM are presented in Table 2.

Next, we discuss the flexibility and future applicability of the F-CE-MSLM.

6 Discussion

The flexibility and adaptability of future-oriented models, such as the F-CE-MLSM, is essential given the rapidly evolving nature of industries, economies, and understandings of CE concepts, both academically and in practice. To this end, it is unrealistic to expect any group of experts to predict every future development or behavioral shift in CE systems. Therefore, flexibility is a core design principle for the F-CE-MLSM, ensuring it remains relevant and applicable across diverse and changing contexts. In this section, we elaborate on the distinct flexibility features of the F-CE-MLSM that enable future applicability and adaptability and thus support the model's stated goals: clarifying product user roles; and integrating CE consumption-production systems.

The F-CE-MLSM captures key system *functions* by delineating components and flows necessary in realized CE systems to enable circular material flows. Per design, these functions are not rigidly defined in the model; for example, the Product Provider (G; Table 1 and Figure 6) could be anyone from an individual neighbor engaged in informal, non-commercial exchange to a large multinational corporation operating formal, commercial value chains. Similarly, Product Necessities (D) span a broad spectrum, from sophisticated medical diagnostic devices to everyday items, such as duct tape. This agnostic quality of the model makes it capable of capturing a range of CE behaviors; commercial or non-commercial and individual or collective, including citizenship-related activities, such as product sharing or gifting. In addition, the model is also able to accommodate various technological contexts, including both high- and low-tech environments.

Further reinforcing its adaptability, the model explicitly incorporates overlapping functions via the concept of "alternative components taking on function" (purple roman numerals; Table 1 and Figure 6). This means that roles typically assigned to specific actors may be performed by others; for example, product users may undertake refurbishment activities themselves (i.e., "do-it-yourself"), effectively taking on the function of a product-service provider (I). This capability to capture fluid boundaries and role-shifting reflects the real-world complexity and dynamic nature of CE systems, where new actors, technologies, policies, and behaviors emerge over time.

Another important aspect of the model's flexibility is its deliberate delimitation to material flows. This boundary was broadly endorsed by Delphi study participants (Table 2) as a suitable and manageable foundation for mapping CE systems. This provides a clear foundational layer, designed to be extended to also capture social, governance, policy, or ecological dimensions in future research. By avoiding assumptions tied to, e.g., specific policy architectures or ideological frameworks, the F-CE-MLSM remains applicable across diverse organizational and economic configurations – including capitalist market economies, socialist state-organized systems, indigenous community economies, and other potential CE models.

In summary, the model's flexibility in mapping evolving CE systems arrangements and characteristics enables an effective understanding of product users' roles in circular material flows.

The delimitation to material flows also serves the model's second goal: integrating consumption and production systems. This boundary provides clarity on the systems' interface and interdependencies, while—as mentioned—allowing additional dimensions to be "layered" atop this foundation in future iterations (see Section 5.2.1). For example, governance and policy mechanisms, such as taxes, subsidies, Extended Producer Responsibility (EPR) schemes, and international treaties, may be applied to the model to examine how these external drivers influence the interconnected CE systems and reshape conditions. Thus, the F-CE-MLSM opens pathways for a modular and progressive approach to comprehensive CE systems analysis.

Nonetheless, it is essential to recognize the limitations in confining the CE systems to material flows. While this boundary reduces complexity and thus enhances manageability, it also restricts the model's ability to provide a fully holistic view of CE systems. Social, institutional, behavioral, governance, and ecological factors interact closely with material flows to shape CE outcomes. Focusing solely on physical material flows inevitably implies that, e.g., consumer behavior, cultural norms, power relations, and ecological impacts (e.g., biodiversity loss), are not captured, or only indirectly so. As such, their omissions from the F-CE-MLSM mean that critical drivers, barriers, and feedback loops are overlooked or underexplored, failing to capture emergent systemic properties and interdependencies crucial to effective circular transitions.

To address these inherent limitations, future research must incorporate additional systems dimensions alongside material flows, to reveal deeper interrelations and better inform policy and practice. Such an approach aligns with evolving frameworks regarding CE systems as socio-technical and socio-ecological in nature, requiring comprehensive integration of multiple factors for sustainability transitions to succeed.

In summary, the F-CE-MLSM adeptly balances specificity, manageability, and flexibility by combining a clear material flow foundation with the capacity for accommodating unforeseen changes and variations over time. The model serves both as a practical instrument for clarifying product user roles in diverse CE configurations and as a foundation for progressively integrating production and consumption systems as knowledge and contexts evolve. This flexible and modular design positions the model to remain relevant amid ongoing academic and practical advancements in the CE field and offers promising avenues for future research and application.

Practical applications and future research opportunities building on this flexible foundation are outlined in the following section.

7 Concluding remarks

7.1 The scientific contribution

The scientific contribution of the Foundational CE Multilevel Systems Model (F-CE-MLSM) (Figure 6 and Table 1), which takes the perspective of the individual product user (Figure 6 and Table 1), consists of a clarification and exploration of the CE from a consumption perspective. Specifically, we contribute both insights and methods to address a gap in the literature in terms of what CE and sustainable consumption entails for individuals in the context of durable consumer products. "Since the CE behavior of the [product] user is critical for the uptake of CE strategies in the economy as a whole" it is crucial to understand the context of the product user (one academic in the Delphi Study). However, "...a detailed picture of the micro-environment is largely missing from the CE literature" despite it being crucial for "gaining a better understanding of the potential costs and benefits of circular consumption" (academic in Delphi Study). The F-CE-MLSM brings to the foreground what is usually mere context in other models, such as actors, physical settings, tools, larger infrastructure and knowledge. To optimize the system for users, and thereby also for their providers, it is crucial to know the role of these components; if the impact of, e.g., the physical setting is unknown, it will not be adequately and strategically considered in business models, product design, and policy, etc.

In addition, this work complements the existing, abundant body of research on the CE production system by incorporating the perspective of the product user and broader components and relations that extend beyond the engineered product-focused system. As such, the F-CE-MLSM serves as a bridge-concept between the two often separated production-focused vs. consumption-focused areas of research and innovation—providing a larger context for practitioners and decision-makers in the CE transition.

The F-CE-MLSM is deliberately designed to be both foundational and adaptable, enabling it to accommodate shifting conditions of the future for two key reasons. First, it depicts essential functions needed to bring about circular resource flows, without specifying what or who is holding or serving these systems functions. As such, the F-CE-MLSM remains relevant and adaptable across different and evolving contexts (i.e., model neutrality that leads to flexibility). Second, the model is delimited only to material flows, which allows for systematic introduction of additional system dimensions and factors, such as policy, in future research. Together, we argue that these features enable the F-CE-MLSM to be applied across varied systemic contexts, including as a tool for exploring different configurations of a CE. This adaptability strengthens the model's ability to clarify the user's role in a dynamic and emerging CE, as well as meaningfully capture the integration of CE consumption-production systems.

7.2 Societal and practical significance

The societal and practical significance of the F-CE-MLSM lies in its ability to visually clarify the interconnected CE systems of production and consumption, breaking down disciplinary silos. This enables researchers and practitioners to identify and address system-level interventions for enhanced circularity and sustainability. To this end, the model can allow for the systematically mapping of trade-offs and rebound effects between material flows and environmental impacts, supporting the design of more circular and sustainable systems.

The application of the F-CE-MLSM can empowers systems stakeholders, such as designers, industry leaders, policymakers, and product users, to identify their loci of control within the system and act as agents in a transitioning economy. For example, product or service providers can use the model to map their ecosystem, uncovering gaps, such as insufficient consumer information or missing enabling technologies. This can also lead to the identification of collaborative opportunities along the value chain. As for product users, although the model initially frames individuals primarily as product users constrained by the systems, the model also increases their systems awareness, thus encouraging individuals in their role as citizens to participate in democratic processes of reimagining and transitioning interconnected consumption-production systems. As to policymakers, they can leverage the F-CE-MLSM to visualize circular material flows across product lifecycles, design and test CE policies through scenario analyses, and identify product ecosystem gaps and enablers—supporting comprehensive circular transitions. On this note, through its clarification of actor roles and control points within the system, the F-CE-MLSM can facilitate actor coordination and support participatory and systemic governance for circular transitions.

7.3 Future research

The F-CE-MLSM provides a foundational yet adaptable framework for future research into product users' roles in a realized CE, as well as consumption-production system integration. The F-CE-MLSM's flexibility across diverse systems, along with its capacity for integration of additional dimensions, makes it a robust platform for both research and practical application in CE transitions. Future research should continue to explore how to incorporate governance, policy, and broader socio-ecological dimensions to enrich the model's explanatory power, preferably without sacrificing the F-CE-MLSM's flexibility. In this context, it may be helpful to distinguish between further development of the F-CE-MLSM (i.e., preserving model flexibility) and its targeted applications (i.e., which seek greater specificity regarding particular states or conditions).

Delphi study feedback highlighted that, while the model makes the micro level (i.e., consumption system) more concrete, the meso level (i.e., production system) may be oversimplified and could therefore benefit from a more nuanced representation, without losing manageability in terms of model complexity. The model's current design also shows a slight bias toward the structural features of capitalist market economies, such as referring to actors as "providers" at the micro-meso intersection. This limitation should be acknowledged and addressed in future research. Further, future research should focus on adapting the F-CE-MLSM for use by specific stakeholders, such as policymakers, product designers, and marketing managers, and test its applicability to cases where the product user is not a private individual but, for example, a company employee or a group of employees with varying authority levels. The foundational approach of the F-CE-MLSM may also be extended beyond durable consumer goods to areas, such as consumables, broader resource management, or to more specific product categories, such as clothing vs. electronics.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

SS-H: Writing – review & editing, Visualization, Writing – original draft, Formal analysis, Conceptualization, Methodology, Data curation, Project administration, Investigation. JDR: Supervision, Writing – review & editing, Methodology, Writing – original draft, Validation. JLR: Writing – review & editing, Validation, Writing – original draft, Supervision. MK: Writing – original draft, Writing – review & editing, Validation. AV: Writing – review & editing, Validation, Writing – original draft. RG: Writing – review & editing, Validation, Writing – original draft. LM: Writing – review & editing, Writing – original draft, Validation. SG: Writing – original draft, Writing – review & editing, Validation. MC: Validation, Writing – review & editing, Writing – original draft. AG-S: Writing – original draft, Validation, Writing – review & editing. LN: Validation, Writing – review & editing, Writing – original draft. PD: Validation, Writing – review & editing, Writing – original draft.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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