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Full length article

Dynamic capabilities for a "circular accounting" and material flows in a circular economy

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ABSTRACT

Tools as material flows cost accounting contribute to the introduction of the circular economy in companies, but praxis of these tools adapted to circular environments are scarce and the lack of accounting references makes its application difficult, particularly in SMEs. In addition, the circular economy requires of specific dynamic capabilities for environmental accounting practices to reflect the different alternatives for closing materials, stocks, and resources loops. To address the dimensioning of circular flows and their relative costs, this study offers a simplified application at a small scale of material flows cost accounting methodology based on the results of an agri-food case study in Spain using a dual approach, Ultimately, the accounting implications derived from the introduction of circular models are defined in this study to analyze firms' specific circular accounting capabilities applied by small companies to less complex processes than those usually studied in the previous literature.

1. Introduction

Governments and institutions are promoting a circular economy (CE) to transform linear production and consumption patterns into circular flows of materials and resources. The CE is an economic model based on innovations for closing the material loops within a waste hierarchy framework (Marín-Vinuesa et al., 2023), one which promotes high-value material cycles instead of only recycling for low-value raw materials, as in the case of traditional recycling (Ghisellini et al., 2016). Due to the massive volume of resources consumed and the consequent waste generated by global production, all actors involved in the sustainability challenges must consider the CE model (Reike et al., 2018).

At present, a broad alliance of stakeholders seems committed to fostering CE transition (Kirchherr et al., 2023), and the physical flows balance is essential for the CE, capturing the attention of managers and accountants in evaluating material flow inefficiencies—and understanding the economic relevance of the losses—in the processes (Schmidt et al., 2015). Methodologies for material flow cost accounting (MFCA) are subsequently considered, primarily for circular models within environmental management accounting (EMA) (Christ and Burritt, 2016; Wagner, 2015), and they arouse particular interest for companies that are progressively introducing a circular business model (Aranda-Usón et al., 2020; Cainelli et al., 2020).

For companies, MFCA's introduction implies having a production management method that supports specific objectives—including greater material efficiency—through cost reductions beyond the existing environmental management framework (Kokubu and Kitada, 2015). Thus, the scope of applications is broadened, and the method can enable an enhanced identification of inefficiencies and cost-saving opportunities to contribute to improved economic performances (Schmidt, Götze, and Sygulla 2015), particularly in a CE. However, MFCA applications adapted to circular environments are scarce and the lack of accounting references and praxis makes their application difficult for the EMA, particularly in SMEs.

In the accounting literature, CE implications for EMA have not been a central argument among scholars despite their interest, and it is only recently that Arjaliès et al. (2023) pointed out material flow accounting as a research topic for CE-related accounting. Although the academic community has focused extensively on the concept of CE, most of the recent accounting literature is focused on introducing CE in businesses and its implications, and there remains a need to systematize accounting practices applied to circular processes, such as the application of MFCA to circular models.

Previous environmental accounting studies focused predominantly

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on the MFCA application in large production processes and outside the scope of the circular model. Bierer et al. (2015) apply an extended MFCA according to the requirements of life cycle-wide analysis, Rieckhof et al. (2015) offer a flow-based view for resource-efficient management control, Sulong et al. (2015) study the introduction of MFCA as an environmental management accounting tool, and Walz and Guenther (2021) exhaustively list the possible effects of MFCA when applied in a company. These authors analyzed MFCA from an accounting perspective, but remarkably few analyses have focused on its application to circular processes, such as Amicarelli et al. (2022), who applied the material flows for material valorization according to the CE paradigm.

If we specifically delve into MFCA's application in CE models, we find a topic in an incipient phase. The number of scientific papers found is minimal when the analysis is restricted to works explicitly related to accounting, MFCA, and CE. Bux & Amicarelli (2022) highlight the role of the MFCA in the meat sector for efficient waste and by-products accounting, Nishitani et al. (2022) explore MFCA as an accounting tool to direct the CE in a sample of Japanese-listed companies, Pauliuk (2018) provides an accounting framework for tracing stocks and flows of materials and quantifying them in physical and monetary units in a steel cycle, and Zhou et al. (2017) apply a modified MFCA model adapted to the CE as an extension of accounting procedures and methods. Indeed, there is little evidence of the practical implementation of MFCA in CE-related applied processes. However, specific applications of MFCA to the CE are still understudied and need to be empirically analyzed.

From the state-of-the-art analysis, it can be argued that MFCA provides an environmental management control tool that connects accounting and management systems (Wagner 2015), but its specific application to the CE is still understudied and needs to be defined. In addition to the limited accounting studies focused on the characterization and measurement of material flows, a gap has been detected in research regarding the adoption of MFCA models in organizations' internal accounting, mainly to measure circular economy-related activities. The accounting implications derived from the CE have in particular received little empirical support, in spite of the relevance of the accounting-related dynamic capabilities when introducing the CE (Scarpellini et al., 2020a).

Given these considerations, this study's main objective is to enhance the knowledge about MFCA, wherein the characterization and measurement of resource flows are carried out within the circular model for material loops closing. The relationship between MFCA applied to the CE and accounting capabilities in firms is also addressed in this study, in order to contribute to an incipient debate in the circular accounting discourse (Etxeberria et al., 2023; Llena-Macarulla et al., 2023).

This article does in this way address a methodological challenge in the existing CE accounting research and outlines the importance of increasing the circular MFCA application to support appropriate decisions on CE transition. Insights gained from this study do therefore contribute to the CE literature, strengthening previous EMA studies and providing additional evidence about the factors contributing to CE implementation in SME. To achieve these main research objectives, this paper analyzes a case study of the agri-food sector in Spain through an action research method for the definition of internal MFCA processes applied to circular models.

The paper is structured as follows: The research background is summarized after this introduction. Subsequently, the methodology applied is described. In the results section, a simplified MFCA adapted to the CE principles is then applied in an agri-food cooperative as a case study, in order to reflect on the main implications of this research after a brief discussion. Finally, the conclusions drawn from this study are then summarized.

2. Background

2.1. MFCA in a circular economy

Several authors have studied the CE in the scientific literature, discussing its concept (Kalmykova et al., 2018), the specific taxonomy (Urbinati et al., 2017), or the theoretical basis (Korhonen et al., 2018). Some of the most important theoretical influences are cradle-to-cradle and industrial ecology (Geissdoerfer et al., 2017). In a circular scenario, material flow analysis methods are applied to track material resources (Rostek et al., 2023), and improved disaggregated reporting of waste for ecological cycling is needed to evaluate the environmental impact of material loop closing (Mayer et al., 2019).

At a micro level, academics have mainly addressed the measurement of the CE from the perspectives of resource productivity, scarcity of critical raw materials, emissions, and pollution (Lieder and Rashid, 2016), or to minimize disposal of waste generated by companies (Oliveira et al., 2018). Although material flows have been analyzed in the CE literature, accounting and controlling resources, such as the production of physical inputs and outputs, still need to be studied among accounting scholars. This is in addition to the application of material flow tools partially derived from the material input/output balances (Wagner, 2015).

The concept of MFCA emerged with the idea of more closely evaluating the cost and physical properties of material flows occurring throughout the production phase, not just at the end of the cycle (Wagner, 2015). MFCA's application has gradually increased and has been studied by different researchers since it is one of the most fundamental environmental management accounting (EMA) tools (Jasch, 2006). MFCA broadens conventional accounting's scope to include concepts such as corporate sustainability and eco-efficiency (Wan et al., 2015). However, MFCA's application requires profound access to information regarding the physical flows in the processes involved—especially those linked to the flows of materials and resources in a short-term management approach—even though it has also been demonstrated to be a valuable tool for the budget phase (Christ and Burritt, 2016).

MFCA—as an environmental management accounting tool—differs from most other environmental management tools because it aims to reconcile the environment with the economy and cost accounting. This fundamental difference makes it essential to perform a specific analysis of MFCA in a CE-related accounting landscape (Scarpellini et al., 2020a) because material flows are an essential goal of environmental management accounting and controlling.

Given these considerations, this study intends to answer the research question regarding the specificity of MFCA as an EMA tool applied to CE models (RQ1). MFCA is thus applied to a CE-related study case to determine whether cost accounting in production processes requires a specific development within the MFCA framework.

2.2. Circular MFCA applied to account processes and a theoretical perspective

Regarding the theoretical framework, the analysis of MFCA applied to CE is a recent topic in the literature, and the definition of the internal accounting processes developed for its application still needs to be explored. So, although this work has an eminently applied approach, it proposes a first theoretical approach to what underlies the application of the circular MFCA, and from the perspective of the specific capabilities applied to accounting processes by organizations.

In our study, the theoretical framework of dynamic capabilities (Teece et al., 1997) enabled other authors to understand better the importance of a firm's capabilities for the CE. Chari et al. (2022) argue how dynamic capabilities can enable circular and resilient supply chains; Khan et al. (2020) identify circular dynamic capabilities that may stimulate companies towards CE implementation; Kristoffersen et al. (2021) provide empirical evidence of a business analytics capability for the CE, and, through a literature review, Seles et al. (2022) analyze different firms' dynamic capabilities as enablers for the CE transition.

In summary, dynamic capabilities influence an organization's ability to direct its tools from a circular perspective and can favor standardized environmental measurements and controls (Barón Dorado et al., 2022; Marrucci et al., 2019). This theoretical framework has been applied to analyze various aspects of the CE, such as circular innovation (Marín-Vinuesa et al., 2023; Scarpellini et al., 2020b), how capabilities might be reconfigured for closing material loops (Khan et al., 2020b), or applied to proper accounting of recyclable material flows and alternatives to linear production steps (Gonçalves et al., 2022).

The theoretical perspective of dynamic capabilities also applies to CE-related EMA practices (Marco-Fondevila et al., 2023). In fact, EMA practices are considered relevant to managing operational planning and decision-making processes to achieve a circular model (Schaltegger et al., 2022; Stanescu et al., 2021). Portillo 2022 provides insight into how accounting can enable or constrain the transition to a circular business model through specific business' capabilities in an environmental management framework applied to measuring and valuing related intangible assets and their management. However, few authors have explained the extent to which the accounting-related dynamic capabilities facilitate the CE, and their application of specific accounting practices is still in the early research phase (Scarpellini et al., 2020a).

This study does therefore delve into an incipient line of inquiry focused on the specific accounting capabilities applied to MFCA, wherein firms introduce CE-related activities (Pieroni et al., 2019). A second research question (RQ2) is thus proposed to reflect on accounting companies' capabilities specifically applied to MFCA processes when they must be adapted to the CE, considering capabilities with higher complexity and specificity than other management accounting processes.

2.3. Circular MFCA on a small scale

Previous studies combining MFCA and EC proposed an analytical framework for assessing two cases—either Japanese companies (Nishitani et al., 2022) or sectors with a high intensity of resources, such as steel (Zhou et al., 2017). Regarding the first case, a study by Nishitani et al. (2022) linked the application of the MFCA to environmental and economic performance in a sample of large Japanese companies. Regarding the second case, the study by Zhou et al. (2017) proposed MFCA's extension in a case study to define the flow measurement phases, taking into consideration the closing of loops in steelmaking. These two examples indubitably represent seminal studies on MFCA, opening up a research field that has been scarcely explored and that demands further analysis in strategic sectors of the EU, such as agri-food and their applications to smaller companies.

In the agri-food sector, case studies have approached the transition of this sector to sustainability (Muñoz Torres et al., 2022), and some authors assessed the MFCA's application to various sectors: May and Guenther (2020), assessing the production of juices; Dekamin and Barmaki (2019), examining the production of soybeans; Bamidele Fakoya (2012), studying the brewing process; and Katherine Leanne Christ and Burritt (2017), focusing on hospitality. These case studies are of interest, as are recent advances in the agricultural and agri-food sectors in the EC: Amicarelli et al. (2022) for potato waste costs, or Bux and Amicarelli (2022), Rabasedas et al. (2023) for meat industries.

However, the most significant challenges of this topic lie in optimizing the MFCA process as per the characteristics of the CE applicable to different sectors and organizations.

Given these considerations, another study objective lies in analyzing the extent to which MFCA methodologies specifically applied to CE-related processes can be simplified and applied to small-scale businesses such as the agri-food companies initiating the CE (RQ3). Hence, a specific methodological development is required to answer the research questions posed.

3. Method and case study

The aim of this research requires a qualitative and dual interpretive approach to explore the context in which accounting practices take place (Correa-Ruiz, 2019). We used an "action research" methodology to describe actions unfolding over time in an agri-food cooperative in Spain, the objective of the action research being obtained through detailed, in-depth data collection involving multiple sources of information, and within a collaborative research project that implied a higher level of participation in comparison with case-study research (Rossi and Luque-Vílchez, 2020). Researchers use case studies to analyze the circular accounting processes and explore the related theoretical framework (Costa et al., 2023; Marco-Fondevila et al., 2023), the latter also being applied to material flows and waste management (Dekamin and Barmaki, 2019; Demuytere et al., 2024; Walz and Guenther, 2021).

3.1. Data sources and analysis

This research was structured into 3 phases. First, the collaborative project was defined and presented to the selected organization. Second, the empirical analysis of flows was modelized for allocating environmental costs during the production process to propose MFCA and its specific adaptation to the CE. Third, a qualitative analysis of the organization's perception of introducing CE-related accounting processes was carried out, using semi-structured interviews as a secondary methodological approach and with professionals from the organization being studied.

First, the collaborative project was developed with the Pastores Group from the Cooperativa Oviaragón-Grupo Pastores, which comprises approximately 1500 members from the sheep sector in Aragón (Spain) and neighboring provinces, and which has roughly 500,000 sheep. It is a leading cooperative in the evolution of the sheep sector in Spain, committed to offering its customers high-quality meat with maximum safety. The lambs are raised in 400 villages to ensure profitability and sustainability. The specific case study was applied from 2020 to 2023 in a cheese plant in the province of Teruel—close to a dairy sheep farm with 1065 sheep from the cooperative itself.

The second phase included an empirical analysis of flows in terms of MFCA and the measurement of circular implications. The privilege of sharing a collaborative project with the company offered an opportunity to obtain information about the internal accounting integration processes. In particular, this research was partially carried out with the environmental manager and the general manager, who was at the same time responsible for company communication for CSR and sustainability reports.

During the second phase, different methods for improving the quality of the research were adopted. The most important source of data was due to the direct involvement of the technicians and the accounting department. Two specialized technicians and the plant's director were also involved in the project and provided detailed figures of processes and first-hand knowledge and experience. The researchers captured specific information during the meetings and the events they attended. The cooperative provided raw accounting data of the plant's expenses and consumption, which were classified by the research team for cost allocation and assignment to material flows, resources, and waste.

The production volume of the cheese plant is 535,000 litres of milk per year, of which the cheese factory consumes 325,000 liters. Fig. 1 summarizes the phases of the production and cost analyses involved.

The system's limitations were established during the second phase of analysis, which excludes agricultural work on producing livestock feed and distributing and selling cheese. However, all the materials, energy, and water necessary for cheese production have been incorporated. By means of production process specifications, the MFCA calculation

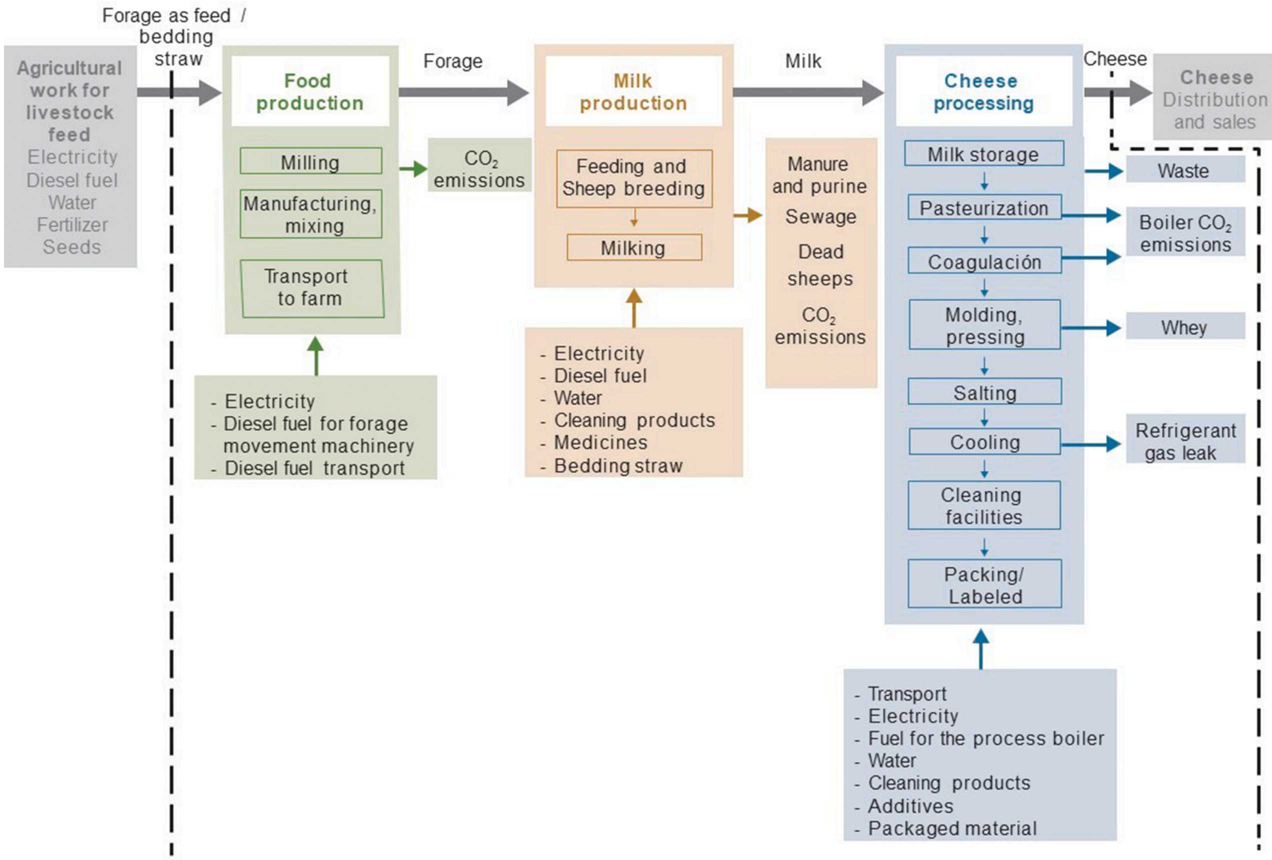

Fig. 1. Process flows in the case study.

methodology and related EC specifications were also designed in the second analysis phase.

For the third methodological phase, a "triangulated" research strategy was applied to collect information at different times and perspectives in order to support the overall research findings. The general goal of this phase was to define the cooperative's awareness of the CE-related principles and how the organization introduced sustainable accounting processes. Five semi-structured interviews were thereby conducted, predominantly targeting middle managers and managers at the organization in order to analyze CE implementation, as well as the specific accounting processes and MFCA.

The profile interviewees were technicians and managers, two women and three men with university degrees or higher, and aged between 40 and 55. The interviews—delivered in advance to the interviewees—were organized into three sections. They were recorded and conducted by the researchers. They included open questions regarding the interviewees' perceptions and opinions and questions regarding specific factors related to CE introduction and the stakeholders' interests by using a Likert-type scale, to which the professionals could add further explanations (Table 1).

3.2. MFCA methodological notes

The seminal work of Zhou et al. (2017) serves as a solid foundation for our MFCA methodology, which we have tailored to the context of the Circular Economy. However, we have taken a step further by proposing a simplified version of circular MFCA, making it readily applicable to simple production processes and SMEs.

The case study analyses costs associated with waste materials and fluid, gaseous and material dresses that are not turned into products and involves the following aspects:

a) Boundaries of the analysis
b) The proportion of the cost
c) Waste and impact reduction
d) Process analysis and modification

Three standpoints reflected in Table 2 are referred to as internal resource value loss and external environmental costs.

The MFCA modelling was simplified and implemented in a small agricultural installation, providing helpful information for the EMA. The simplification is marked, on the one hand, by the elements physically separated in the production process and, on the other hand, by the primary materials, energy, and water involved in the process. Quantitative information is based on the company's financial accounting and technical data provided by suppliers to ensure an environmental impact.

4. MFCA adapted to the circular economy

4.1. Main results

Table 3 summarizes the plants' main operating conditions.

Considering the inputs in Table 2, MFCA was applied from the functional unit of 1000 liters of milk or its equivalent of 200 kg of cheese. Table 4 lists the cost estimates in economic and environmental terms.

Estimating economic and environmental costs enables us to visualize their distribution per product unit (Fig. 2).

These were broken down according to the three cost centers into which the process for the simplified MFCA has been divided, and considering the consumption of 40 liters of mains water (20 liters for cattle consumption and milking cleaning and 20 liters for cheese processing and cleaning). Fig. 3 outlines the distribution of costs.

Fig. 4 presents the distribution of the impacts derived from the above

Table 1
List of semi-structured interviews' main questions.

Main questions	Type
Is the implementation of CE considered a priority in the entity? Will the circular economy increase the level of collaboration between companies in the entity's value chain to share goods and services? The entity measures the flow of resources and waste for reporting. In the entity, common infrastructures are shared with the providers? Does the entity share common infrastructures with customers? Please, specify Does the entity use joint software systems or systems similar to those of other entities/associations, etc.? The entity encourages the shared use of assets among workers (renting, the fleet of corporate vehicles or similar, etc.). Please, specify Are the environmental policy and circular economy initiatives communicated to the entire workforce in the entity? Please specify. In the entity's environment (local or regional scope), is waste that could be used as resources available? Please specify.	Open short questions and Likert scale
Do you know the Material Flow Cost Accounting (MFCA) methodology or the UNE-EN ISO 14,051? Do you think it could be implemented in your entity? Considering the activities that your company/entity can carry out for implementing circular economy measures, what participation does the accounting department have in them (out of 100 %)? Please specify specific accounting processes related to the CE.	Open short question
What is the CE measure for your company/entity? Order from the most relevant ones and provide your opinion about each one	*Six highest relevance - to least relevant 1*
Recovery of waste in the company itself Dematerialization, eco-design Use recycled materials Economy of services (offer/contract services instead of sale/purchase of supplies and facilities/equipment) Recycle products at the end of their useful life. Valorize waste together with other companies (symbiosis) Other activities: Please specify	

flows.

Along with the product, the outputs of CO_2 emissions and four liters of whey per kg of cheese produced were also considered. The whey is used as fertilizer or livestock feed due to its nutritional qualities, thus closing this loop—except for gaseous effluents measured through the product's carbon footprint.

In response to the first research question (RQ1), we concluded that a conventional MFCA does not provide specific measurements of the material loops' closing. Despite its undoubted utility for improving performance in environmental accounting, the results reveal that the MFCA requires a particular adaptation to provide the information inherent to closing the material loops within the CE framework, thus suggesting the study's specificity with respect to research into the so-called circular MFCA (RQ1).

4.2. MFCA's adaptation to material loop closing

A simplified methodology for the circular MFCA, waste recovery phases and use in new processes (RQ3) were analyzed in the case study. In this respect, the results obtained clearly reveal that emissions are released into the atmosphere and measured in CO_2 equivalent units, precipitating the carbon footprint mentioned above. The vast majority of materials consumed become part of the final product, with the following exceptions, and for which the analysis of the material loop closing provides the following details:

- Cattle consume water to clean the milking parlor (daily) and cheese factory (in all production). All the cleaning products used are biodegradable; hence, they are reused for irrigation in agricultural areas near cheese factories.
- Manure: Straw from cattle beds; their droppings become an excellent fertilizer for neighboring farms.
- Whey: Remarkably, 80 % of the milk used is converted into whey in the process, 67 % being comprised of fat, 0.8 %–1.5 % being soluble protein (80 % casein), and 4.5 %–4.9 % being lactose, which makes it highly interesting—both for fertilizing adjoining agricultural land and for feeding the livestock.

Cheese packaging created using food-grade polyethene was excluded from the study because it can be considered domestic waste recycling, accounting for greater than 50 % of recycling in Spain, according to the data from the sector (cycloplast).

The electricity consumed has an emissions rate of 0.27 $kgCO_2eq/kWh$, according to the electricity supplier contracted. The manufacturer's datasheet reveals that the diesel consumed in the machinery necessary for the mixtures and handling of fodder for livestock has emissions of 2.72 $kgCO_2eq$/liter of fuel and that the gas oil used in the facilities' boiler for the relevant processes and air conditioning has emissions of 3.33 $kgCO_2eq$/liter of fuel. This means gaseous waste escapes from the loop in the form of emissions.

Fig. 5 reveals how the three cost centers indicated were identified for

Table 2
Main standpoints of simplified circular MFCA methodology (adapted from Zhou et al. (2017).

Calculation system: Internal resources flow cost accounting and external environmental costs	
Set resource flows Data acquisition Calculation of internal resources and costs Estimation of circular flows	The inputs in each production stage are as follows: Feed production: forage as feed, bedding straw, electricity for crushers and feed conditioning, diesel for the mixing machinery, and forage transport from the mixing plant to the dairy where the cattle are. Sheep rearing and raw milk production: diesel fuel for forage transport machinery from storage to feed dispensers, and electricity for milking, milk cleaning and storage, and cleaning products. Cheese processing: electricity for cheese processing and refrigeration; gas oil for the boiler; air conditioning and hot cleaning water; facility cleaning products; rennet; and other chemical components for coagulation, brine, and packaging.
Evaluation system:	
Definition of cost centers and data collection Circular flows calculation	C1: Food production—manufacturing, mixing, and dispensing through automated processes. C2: Sheep breeding and raw milk production—milking, cleaning, and milk storage C3: Cheese processing—pasteurization, coagulation, molding, salting, cooling, storage, and cleaning facilities
Circular management system:	
Propose a simplified scheme of circular flows. Evaluation and feedback	Specific analysis of material loop closing was performed for a particular case. In this phase, two specific cost centers are added: the C4 "circular output" and C5 "circular input" cost centers. These centers are used to analyze the destination of the waste generated, and to characterize input flows from a circular perspective (such as recovered materials and renewable resources).

Table 3
Production data.

Milk production per sheep	Production of 500 litres of milk per year
Consumption per sheep	One ton/year of feed, 150 kg/year of straw as bedding for cattle and 1950 litres of water between consumption and cleaning of the milking parlor.
Consumption by-products	7000 litres of milk a week are processed on three different days to make two types of cheese—namely, tubs and bars. The bar format uses 1000 liters of milk with a production ratio of 1 kg of cheese for every 4 litres. The tub format utilizes 3000+3000 litres of milk with a ratio of 1 kg of cheese to 5.5 litres of milk. These cheeses are packaged and delivered directly to the sales channel.
Milking processes and milk treatment	Milking is performed in a controlled manner using automatic systems. Subsequently, there is filtering and transfer of milk, as well as analysis and microbiological quality control. Every day the equipment is milked and cleaned using biodegradable products. The milk is kept in refrigeration/isothermal tanks at a temperature less than—or equal to—6 °C for a maximum of 5 days. To facilitate coagulation, the milk is heated to a temperature of nearly 30 °C, rennet and other coagulants are added, and it is left to stand, maintaining the temperature for about 40 min until it coagulates. Subsequently, it is gradually reheated to 33–34 °C for about fifteen minutes and molded. Once molded, the product is transferred to the cold chamber at approximately 4 °C and is kept there for a minimum of one hour. The product is subsequently transferred to a room between 8 and 10 °C, where it is packaged in 250 g tubs and in 1.4 kg bars.
Processes and maintenance	In the cheese factory, the equipment is cleaned using biodegradable products every day. A critical point in energy consumption is the pasteurization phase—a relationship between time and temperature—76 °C for 20 s. 93 % of the product is in tub format and 7 % in bar format. From the moment it leaves the Fresco Handling Room, it is kept refrigerated between 0 and 4 °C until dispatch.
Functional unit and production	1000 litres of milk (minimum production that is conducted in the cheese factory). The finished product ratio was 5.3 litres of milk per kilogram of cheese produced per the weights and productivities indicated.

Table 4
Estimated costs (euros) and environmental impact (kgCO_2eq/kg).

C1: Food	€3.38	0.19 kgCO_2eq/kg cheese
C2: Breeding and Milking	€0.16	0.26 kgCO_2eq/kg cheese
C3: Cheese	€1.68	1.77 kgCO_2eq/kg cheese
Total	€5.22	2.22 kgCO_2eq/kg cheese

the MFCA, and to which the two output cost centers were added—one circular and one not circular. Thus, the manure obtained as the output from the first cost center is reused outside the system's limits as an organic fertilizer—to procure the material with which the fodder for livestock is obtained. It incurs no economic cost for the company—neither a benefit nor a loss; however, through this methodology, this cost could be added to—or subtracted from—the finished product cost. The same occurs with the wastewater obtained in cost centers C2 and C3, which, being free of polluting elements and having an organic composition, is used for agricultural irrigation to obtain fodder. Finally, the waste in C3 is used as either feed for cattle, thus incorporating it into C1, or as a fertilizer outside the system's limits. All of them, like manure, incur zero economic costs for the company; hence, these aspects are not included in the study. The circular flows that enter the livestock as feed are identified in cost center C5, which is defined to house those circular inputs that reduce the system's cost. In the empirical analysis, 100 % of the whey was regarded as a fertilizer outside the system's limits, but in this case it should be subtracted from the sum total of final product costs.

Given the proposed MFCA's application in CE environments, simplified versions of this tool should be extended to many more companies and processes than those currently being applied. It is undeniable that any EMA model is more likely to be applied in larger companies, and it must be taken into account that, according to Bassi and Dias (2019), there is a positive correlation between the size of a firm and its engagement in the CE. However, SMEs can also implement a simplified, although practical, measurement of those circular flows and specific centers of analysis where costs are allocated that are not usually included in the MFCA boundaries.

4.3. Circular cost accounting and managerial implications

In response to the second research question, a qualitative analysis was conducted of the organization's perception of the introduction of circular processes, and the main implications for accounting management were considered. Through the semi-structured interviews, we found that CE is important to the organization. However, the interviewees did not know the MFCA methodology in detail, even though three considered it as interesting to the organization in the future.

In the case study, professionals associated MFCA application with reducing material losses, in line with other authors' reports (Schmidt et al., 2015). Furthermore, the perception of three of the interviewees was that these tools favored the improvement of various aspects of environmental performance, such as energy consumption, water withdrawals, and CO2 emissions, in line with the analysis provided by Jesse et al. (2023) in the EMA framework, or the reduction of the waste produced (Oliveira et al., 2018). Even though MFCA continues to encounter numerous barriers to its implementation, we appreciate that it is in a more advanced phase of acceptance and exhibits better prospects than it did earlier (Christ & Burritt (2016).

Regarding the implementation of CE processes (Table 5), waste

Fig. 2. Distribution of costs (euros) and environmental impact (kgCO_2 eq/kg) per kilo of cheese produced.

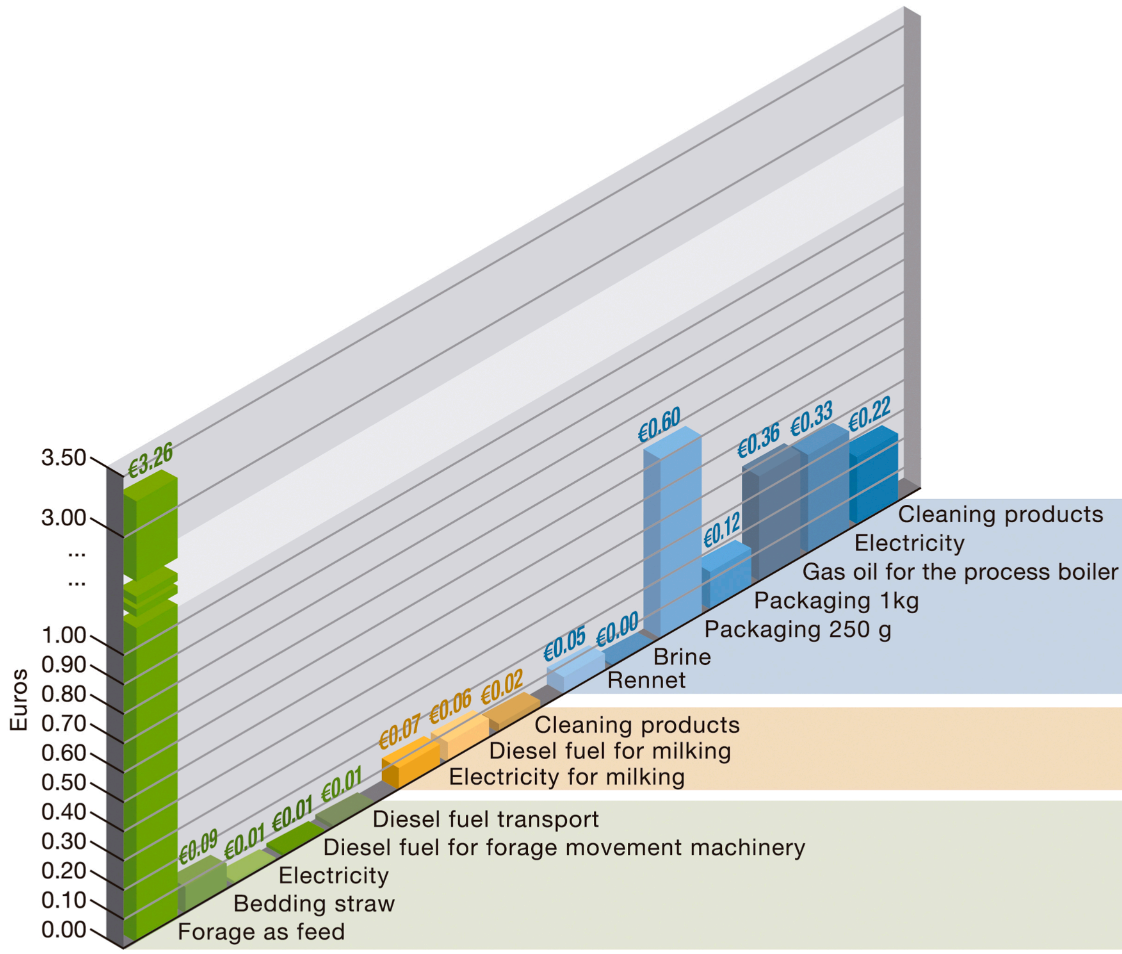

Fig. 3. Detailed distribution of costs (euros) per kilo of cheese produced.

recycling and the consumption of recycled materials were the two activities most indicated by the interviewees for the organization (on a 10-point Likert scale).

The interviewees were asked to order the activities according to relevance (Table 6), and in order to analyze the organization's capabilities of implementing CE-related activities. A score of one was assigned to the most minor relevant activity for the organization, with a six-point score corresponding to the most relevant activity.

Interviewees' opinions were later obtained to define the organization's capabilities related to MFCA and accounting capabilities for the CE to answer RQ2. The responses demonstrate that the R&D and innovation departments play a major role in implementing the CE, far from the limited participation granted to accounting or financial departments.

Some interviewees highlighted that the accounting department's participation is increasingly needed in developing projects and CE-related activities. Hence, one pertinent conclusion involves developing a specific circular economy-related management accounting for processes analyzed from the CE perspective (RQ2). Thus, circular management accounting includes defining and measuring the closing of material loops, taking into account CE-related cost centers related to the end of the process and the input (Fig. 6).

With the implementation of MFCA methodologies adapted to the CE, the direct and indirect costs related to material flows can be defined in significant detail (through the measurement of environmental impacts in physical units and relative costs) in cost centers specific to the material loops, thus expanding the description provided by Zhou et al. (2017). In addition, MFCA appears complementary to the life cycle assessment (LCA) tools (Bierer et al., 2015; Marrucci et al., 2022; Rieckhof and Guenther, 2018). Thus, some interviewees highlight the relevance of training in CE, the application of advanced management integrated systems, and the development of soft skills as general factors allowing accountants to work with MFCA. In addition, an unprecedented collaboration with other agents in the value chain is considered necessary, something which substantially modifies the position of the accounting department, usually focused on the use of financial accounting rather than on internal accounting development for EMA.

4.4. *Brief insights from the dynamic capabilities perspective and main contributions*

As a reflection, we could affirm that companies immersed in the transformation toward a CE must analyze costs and measurement of indicators surpassing the traditional consideration of environmental aspects, because this also implies other specific aspects, such as capabilities to collaborate with other organizations to close the material loops, in line with the claims made by Franco (2017).

Accounting departments, especially those responsible for cost accounting and controlling, play an essential role in managing material flows by generating databases with consistent information elements between physical units, costs, and inventories. Specific capabilities for measuring and managing information about consumption, waste and flows in physical units and their impacts must be developed by companies that adopt a circular business model (as pointed out by (Scarpellini, 2022), due to their social implications. In addition, EMA's circular dynamic capabilities of defining and measuring impacts derived from CE introduction and investments increase circular innovation and improve the management of intangible assets (Portillo-Tarragona et al.,

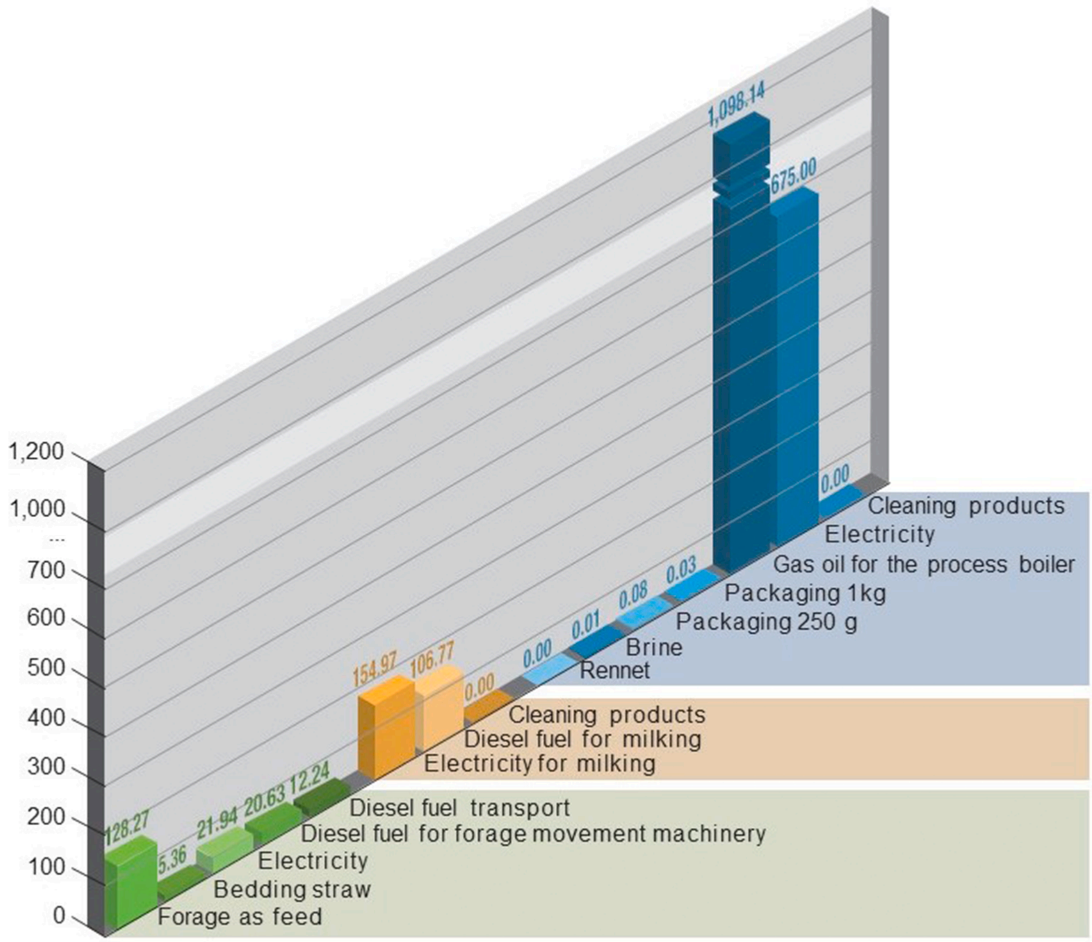

Fig. 4. Detailed distribution of impacts (kgCO_2eq/kg) per kilo of cheese produced.

2022).

For CE implementation, the need to improve organizations' accounting capabilities and develop other dynamic-specific ones for EMA is evident because the definition and measurement of performance is required in terms of circularity through accounting information on material flows. MFCA systems adapt to CE-related principles, although in their application for small-scale production, they also allow an adequate degree of accountability for CE activities and servitization, as well as meso-level and collaborative models.

- For organizations, this study provides a methodology that facilitates the efficient management of natural resources and inputs from a CE perspective, applying specific dynamic capabilities of companies to improve their circular measurement and reporting.
- The application of MFCA adapted to CE principles enables the allocation of costs for different options regarding material loop closing and the corresponding accounting reflection in terms of materials, stocks, and resources, which is a topic of current interest for companies. Our findings enhance previous research on CE in the context of accounting focused on SMEs, emphasizing the significance of MFCA in facilitating decision-making about resources and sustainability. It offers insights into EMA challenges to implementing CE principles and optimizing the cost of CE practices on a small scale.
- Likewise, commitment to organizations' CE and the specific accounting capabilities related to the CE are addressed in a collaborative framework, as MFCA is a tool that also addresses the supply chain (Walz and Guenther, 2021).
- For practitioners, measuring the quantitative impacts and reporting about them is equally important on an environmental accounting basis and in the framework of the new EU taxonomy for 'green' products and services. Understanding and acknowledging the potential impacts of the CE becomes essential for companies and their stakeholders. This result corroborates the need to develop dynamic capabilities for the EMA practices that firms apply during the implementation of CE-related activities, CSR, reporting, and sustainability accounting (Aranda-Usón et al., 2022; Di Vaio et al., 2023; Scarpellini et al., 2020a). Consequently, sustainability reports have to contain information regarding the extent to which companies have managed to introduce the CE.
- In support of CE promotion policies, accountants could have a pivotal role in facilitating the transition to a CE by adopting the new standards to inform investors and other stakeholders about sustainability and to provide specific figures and impacts to finance investments in CE in pursuance of the European Taxonomy (European Parliament, 2020). CE-related activities and impacts are currently an important part of the information reported within the EU (Directive (EU) 2022/2464 as regards Corporate Sustainability Reporting, 2022) by large firms, which will also apply to SMEs in the coming years.

5. Conclusions

The findings of this study enhance previous research into implementing a simplified application of MFCA in a CE context for small companies, being different from the extant knowledge base.

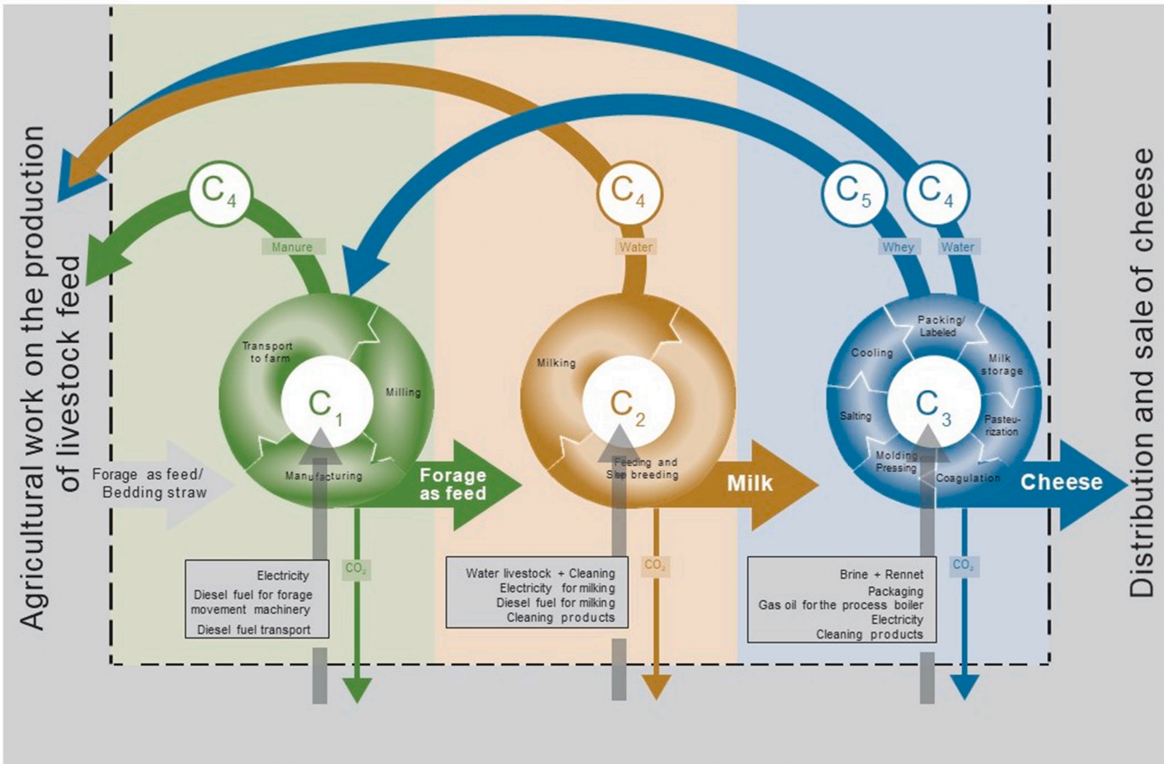

Fig. 5. Detailed distribution of flows by cost centers.

Table 5
Degree of relevance assigned to CE activities for the entity (10-point Likert Scale).

	B1.1-WAST Internal waste recovery	B1.2 DESM - Dematerialization	B1.3 RECM Materials rec.	B1.4 SERV - servitization	B1.5 - REC Recycle	B1. 6 VALC values common waste
MEAN	6.2	7.0	7.2	6.2	7.3	6.3
MEDIAN	7.0	7.0	8.0	6.0	7.5	6.5
MODE	NA	6	8	6	NA	NA

Table 6
CE activities' ranking based on their relevance and viability for the entity (Maximum score per activity: 30 points).

Waste recovery in the company itself	Dematerialization and eco-design	Consumption of recycled materials	Service economy (servitization)	Recycling of products at the end of their useful life	Symbiosis (joint valorization with other companies)
26	20	15	31	13	7

Among the key findings were the evident effects experienced by small companies in practice following the application of CE-adapted MFCA. In terms of critical factors for CE adoption, the study highlights the pivotal roles that accountants play in influencing CE adoption, especially in small companies, overscoring the importance of proactive EMA practices. We acknowledge that there remains a need for more clarity regarding how accountants can measure circular flows in technical production processes. However, the proposed simplified models that integrate essential circular measurement into cost accounting can effectively mitigate these limits.

First and foremost, it is important to note that our proposal of circular-adapted MFCA is an inevitable simplification of a complex tool, but the main objective of this research is to provide evidence regarding the circularity accounting applied to date. The past, present, and future of MFCA is still complex, but it must combine elements of sustainability paradigms and models. The study highlights the challenges that exist to considering MFCA to be flexible, and not a watertight tool closed to the continuous changes proposed by the EMA. Aside from its necessary standardization, exemplary adaptations of these practices can be proposed that lead to the introduction of MFCA as a robust and quantitative EMA methodology, one that can aid companies in prioritizing the selection of the most feasible options for implementing CE practices.

Overall, by applying specific measurements to perform MFCA, managers can also take advantage of the connection between the

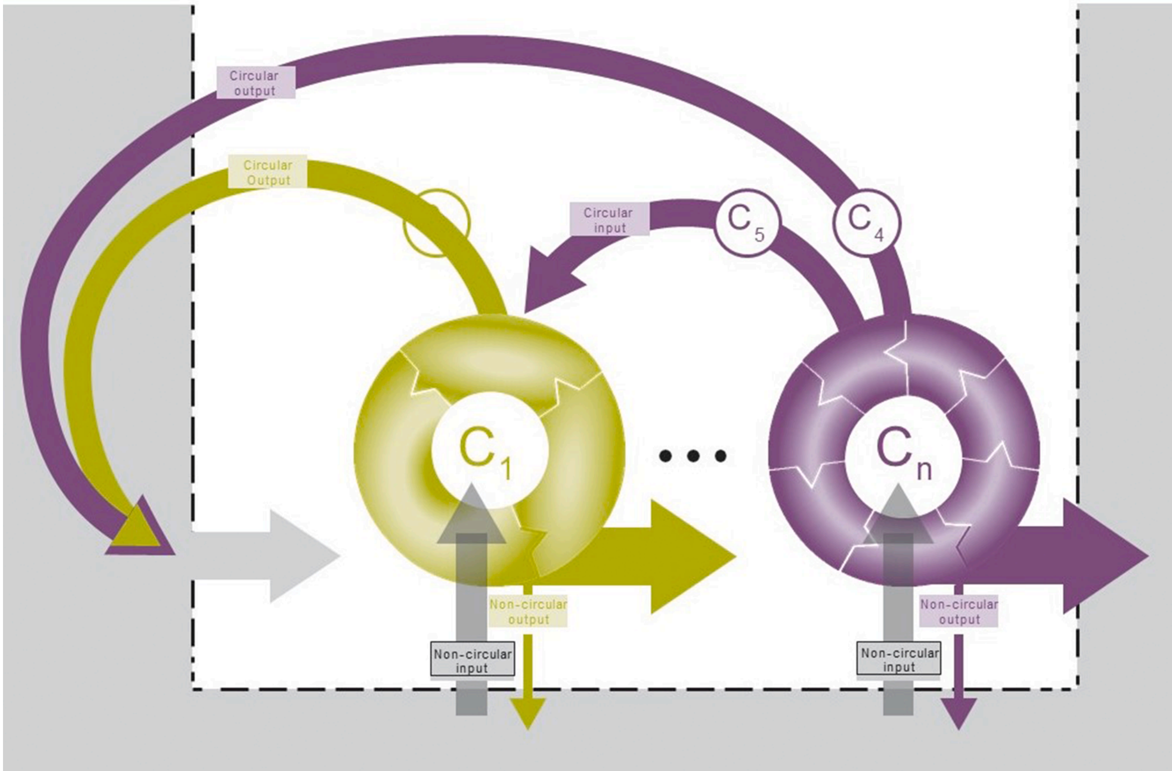

Fig. 6. Material flow cost accounting for the circular economy.

classification, sizing and systematization of material flows and information disclosure, which is of particular interest in the face of increasing sustainability reporting standards that include CE measurement, also for SMEs in the coming years.

For academics, this research makes progress in defining specific accounting capabilities and practices applied to CE introduction within the theoretical framework of dynamic capabilities. Specifically, the recent literature reveals significant knowledge gaps concerning specific accounting capabilities that lead to CE adoption. These capabilities imply enhancing EMA applications, the soft skills of accountants applied to accountability, and new EMA tools for fast adaptation to the CE regulations, servitization, and meso-level and collaborative models in the supply chain. This study does therefore enhance knowledge to better understand the theoretical aspects of CE adoption from an EMA perspective and their application for small-scale production.

These results also support decision-makers and policymakers for implementing CE policies, given that information provided by MFCA may influence policy decisions related to waste management in a region. The empirical case study findings also contribute to the knowledge base for policymakers in order to develop strategies to assist CE adoption in small firms. Furthermore, policymakers can be important actors in promoting the dissemination and application of material flow accounting among firms, the active participation of accounting at a *meso* level to achieve an effective material loop closing, and the development of specific accounting standards, for example, by encouraging MFCA-related quality standards.

This study is the first approach to an unprecedented simplified application of MFCA to CE models that could serve as the basis for future research. Moreover, this research can be used to apply items considered for the simplified r MFCA for the circular economy or to explore the semi-structured interview in other companies and their related accounting practices.

Despite its application and advances in knowledge, this study has some limitations. The empirical analysis was predominantly limited to a specific sector case study in Spain and, therefore, was not directly applicable to other companies' processes, structures, or structural characteristics. Furthermore, despite the efforts to conduct an accurate textual analysis of the interviews, some notable difficulties arose due to the lack of uniformity of answers provided and the number of semi-structured interviews conducted. Therefore, additional comparative studies applied to other sectors and processes are recommended to validate the methodological approach adopted. New lines of inquiry focused on overheads in a circular MFCA would in particular be recommended.

CRediT authorship contribution statement

Alfonso Aranda-Usón: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Investigation. **Sabina Scarpellini:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **José M. Moneva:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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