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Adaptive Life Cycle Costing (LCC) Modeling and Applying to Italy Ceramic Tile Manufacturing Sector: Its Implication of Open Innovation

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Abstract: Converging business, sustainability, and technology is a challenge that manufacturing firms face to create value and be competitive. Energy- and raw material-intensive manufacturing industries are particularly aware of environmental issues and circular economy practices due to the large amounts of resources they use. However, manufacturing companies must also be mindful of economic sustainability in order to make their business profitable. For this, appropriate economic evaluation tools are needed, one of which is life cycle costing (LCC). LCC, when applied to the manufacturing context, is often considered as a simple extension of the life cycle assessment (LCA). This is the main limitation of LCC, as it only contributes to determining the economic value of environmental damage. This research aims to overcome this limitation, analyzing the Italian ceramic tile manufacturing sector as a case study in order to conceptually develop, through the abductive methodology, a calculation framework that extends the potential of LCC by including circularity parameters. Subsequently, the conceptual framework is empirically validated using sectoral industrial costs by configuring two scenarios (with and without circularity practices) and building a benchmark for individual firms in this industry. Finally, the research includes some considerations on the positive implications and potential of life cycle costing in an open innovation context.

Keywords: life cycle costing; open innovation; economic sustainability; circular economy; manufacturing; industrial management; ceramic tiles

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1. Introduction

The creation of value is a challenge that every company must face in order to create opportunities for growth, gratify investors and compete effectively in the markets [1]. The concept of value is very broad, ranging from the above-average attributes provided by a product or service to the consumer's certainty of obtaining high quality through a cost–benefit analysis [2,3]. From the firm's perspective, however, it is not enough to close the financial year with accounting profits to create value because this does not always mean that the company is covering the cost of all the resources. In the value generation process, the most current approach is the integrated one, which involves an evaluation of the entire supply chain by each company participating in the business. This means that inputs and outputs are analyzed with the aim of maximizing the value/cost ratio, including by specializing the role of the company to better focus on core business with clear added value [4].

Nowadays, organizations must broaden their vision from the supply chain to the value chain because key stakeholders are increasingly demanding that companies take responsibility for the social and environmental impacts generated by their operations [5].

The concept of the value chain has included that of sustainable development due to the current emphasis on responsible resource management in their environmental, social and economic dimensions. Therefore, the generation of sustainable value, as an extension of the value chain, not only increases the reputation of a company but also allows to identify and exploit new market opportunities, ensuring the growth and development of the organization [6].

The increasingly widespread awareness of the efficient management of resources, especially non-renewable ones, has been the favorable background for the emergence of the so-called circular economy [7]. The circular economy pursues the design of products and services that minimize the permanent consumption of inputs, both by saving their use and by recovering and/or reusing as much as possible. Circular economy practices are especially interesting for the energy- and raw material-intensive industries [8]. Even with a remarkably positive impact on the environment, circular practices must be sustainable in socioeconomic terms. Appropriate assessment tools are, therefore, needed to implement sustainability in business models in order to identify the best ways to measure the value created by the company and to capture the value generated in the supply chain.

In this perspective of impact assessment, a common methodology is implemented in the operational field by companies in the life cycle sustainability assessment framework (LCSA). This methodology evaluates the impact of a product or a process considering the environmental, economic, and social pillars of sustainability [9]. In specific, for the economic pillar, the LCSA methodology proposes life cycle costing (LCC) as the economic assessment tool [10]. The literature on the subject, although limited, suggests the existence of at least two categories of LCC: the conventional and the environmental LCC. Conventional LCC has a specific focus on the costs incurred by the company, taking into account the whole life cycle of the product. Environmental LCC focuses instead on the role of the actors involved, including in the analysis also externalities that should be internalized [11]. Nevertheless, for decision-making, the LCC is generally considered as a mere extension of the environmental sustainability assessment, and it continues to have significant limitations as the economic pillar of sustainability, combining environmental management and accounting perspectives [11]. It has an unclear way of defining system boundaries and, therefore, does not include different perspectives of the economic agents involved [12].

With these premises and to fill the gaps in the literature, this research aims to overcome the above-mentioned LCC limits through three-stage exploratory research. The research consists of a first descriptive analysis aimed at offering two sequential LCC models to evaluate the economic dimension of sustainability, starting from the Italian ceramic tile-manufacturing context. The ceramic industry is a sector with intensive use of raw materials and energy resources [13], for which sustainability issues along the supply chain are a critical factor [14]. To do so, two complementary schemes are presented. The first scheme is designed based on the continuous production process in the ceramic context from a life cycle perspective. In contrast, the second scheme follows and adapts the principles of the ISO standards for LCC, considering each ceramic product as an investment project. Both models integrate circular economy practices, which must be carefully assessed from the dual environmental and economic perspective. In the last stage of the analysis, the models are validated through a case study on the Italian ceramic sector.

Through the adoption of an operational scenario, this research shows an example of the possible use of a broader definition of LCC in a manufacturing setting. The research also illustrates the potential of an economic sustainability analysis from an open innovation perspective. Finally, the results obtained can provide inspiration for future economic evaluations of sustainability in production processes, even in sectors other than ceramics.

2. Theoretical Background

The ability of a company to sustain over time processes capable of creating value for the organization and for society is referred to as corporate sustainability (CS), and the commitment to maintaining this balance is corporate social responsibility (CSR) [15,16].

CSR has its conceptual foundation in five major economic theories that have been used as references. Agency theory explains the effectiveness of the organization as a way of coordinating and dividing tasks thanks to formal contracts that "the principal" offers to "the agent" in order to induce him to effectively perform the task assigned to him [17]. Stakeholder Theory, on the other hand, focuses on the relationship between businesses and their stakeholders to satisfy the interests of all those who can help or hinder the achievement of the organization's goals [18]. Legitimacy theory is based on the social acceptance of businesses for, which it is not enough to achieve good economic and financial results, but also to play an active role in the economic and social growth of the community in which it is established [19]. The institutional theory focuses on the social behavior of businesses in accordance with guidelines, rules, and laws [20]. Finally, resource-based theory (RBT) emphasizes the importance of an organization's internal variables over external ones by placing the company's distinctive resources and capabilities at the base of competitive advantage [21].

CSR and CS are two closely related concepts because the former is included in the latter, and both aim to grow business ethically [22]. CS intends to develop strategies to promote the growth and profitability of companies by creating long-term value for stakeholders without harming people, the planet, and the economy. In this process, CS focuses its attention on all players in the supply chain, seeking to identify new market opportunities [23]. On the contrary, CSR aims to analyze the results achieved by a company, especially in the social field, looking at the past [24]. Therefore, CS has a prospective vision, while CSR has a historical vision aimed at maintaining and growing the reputation of the company.

Among the most current strategies in terms of corporate sustainability is energy-efficient economy [25] and circular economy practices [26], also due to the adoption of appropriate policies by governments and transnational institutions [27]. The European Commission stresses that the circular economy will boost the European Union's (EU) competitiveness by protecting businesses against resource scarcity and price volatility [28]. Hence, this school of thought is sought like a regenerative economic model to overcome the currents models of growth and resource consumption [29]. The circular economy proposes a radical systemic change aimed at eco-design, the economy of functionality, reuse, repair, remanufacturing, and industrial symbiosis [30]. Implementing such changes requires companies to deeply transform the ways they create value from linear models that create added value through manufacturing processes based on the flow of materials [31] to circular models capable of capturing the value of waste [32] to maintain a constant flow of value in many different supply chains in order to reduce the depletion of resources [33]. The industrial system, at the end of the production and consumption cycle, must develop the capacity to absorb and reuse waste and slag. Accordingly, the circular economy refers to a development model where the waste of one company becomes the raw material of another [34]. In other words, it is a model that regenerates itself in which you can come to create a link between the business ecosystem and the natural ecosystem [35].

Firms, especially those intensive in the use of energy and natural resources (such as the ceramic industry), are intended to think of new products, production, and sales systems capable of integrating more agents of the value chain in the task of maintaining the reverse circulation of resources for their less deterioration [36]. This, in turn, requires them to have effective and reliable information systems that allow them to make appropriate decisions within this new competitive framework. This means being able to quantify the sustainability of the various possible options in terms of environmental, financial, and social acceptability.

The life cycle sustainability assessment framework, expressed as LCSA = LCA + LCC + SLCA [37], is one of the most used tools to measure the sustainability of products and processes. At present, (life cycle assessment (LCA) [38] and life cycle costing LCC) [39] are being performed together [40] in an attempt to broaden the concept of LCSA [41]. In this regard, both approaches contribute to the documentation of product-related business processes, serves as instruments of control business facilitating decision process and making companies be aware of economic and ecological impacts. Furthermore, they are system modeling, so they help to set systems boundaries and relevant data collection. However, there is still a lack of holistic studies reporting the effective use of these tools. Hence, more conceptualization and methodological foundation are needed in order to properly define the sustainability problem and connect the different methods and models [42]. In fact, today's economy is demanding new ways of achieving sustainability, i.e., on the triple-bottom-line, beyond the separate valuation of environmental, social, and economic aspects [43]. Furthermore, the LCSA framework falls short of analysis of the added value of business models [44]. It is precisely in this aspect where the circular economy approach can contribute most, whose main innovation lies in reflecting on the ways of capturing value from what would be considered waste in a linear value generation approach [45]. Whereas LCA is already a standardized method (ISO 14044, 2006) [46] accepted across various industries [47] and widely used to investigate the potential environmental impacts of products and processes [48], LCC and social life cycle assessment (S-LCA) are lacking consensus and definition and thus broad practical implementation [49,50].

A recent report on the state of the art in LCC published by the ICLEI (Local Governments for Sustainability, European Secretariat, 2018) [51] stated that, although LCC is a top strategy in Sustainability Public Procurement in Europe, there is still a clear trend of non-application of its methods into procurement procedures. Among the most important challenges that this report highlights when using the LCC as a sustainability assessment tool are the complexity of environmental issues and the selection dilemma between environmental versus cost-effective alternatives. The LCC technique is designed to present decision options according to the different stages of a life cycle and for different cost estimates. Therefore, LCC focuses on costs at every stage of the life cycle and should answer the questions: How much the process cost? What economic impacts it has? [52]. The different possibilities of defining a productive system, categorizing costs and identifying the agents that support them determine different modes of calculation and aggregation [53]. Therefore, interpretations of the results and alignment with other complementary analysis techniques also depend on these three aspects [54]. Nonetheless, beyond the different methods of cost calculation, LCC is a powerful management technique to make effective decisions about costs [55].

Key sustainability literature differentiates two to three types of LCC [56]. First, conventional LCC (C-LCC) incorporates private costs; in other words, it is based on a purely economic assessment that considers the costs of the different phases of the life cycle incurred only by the company. External costs or costs not directly incurred by the producer are not considered [57]. On the other hand, the environmental LCC (E-LCC) considers the lifecycle costs of a product incurred by the actors involved, including externalities that are expected to be internalized [58]. For example, if it is expected in the future that a new tax on CO_2 will be enforced or a subsidy granted for engaging unskilled people within the next two years, the LCC will reflect these costs and benefits in its calculations [59]. Finally, the societal LCC (S-LCC) internalizes externalities by assigning an economic value to environmental and social externalities determined by LCA and S-LCA analyses, respectively, and transforming those impacts into monetary units [60]. In this way, the societal LCC supports decision-making at the social level, both for companies and public institutions [61].

It is, therefore, clear that these approaches are mainly complementary to the environmental analysis of LCA. In order to operationalize this technique, it should be estimated the economic cost of polluting emissions based, for example, on the willingness to pay (WTP) of the responsible company, to avoid a worsening of the situation created or to remedy damage caused, attributing an economic value to the damage (according to the selected categories of damage, for example, human health, ecosystem production capacity, abiotic stock resource, biodiversity). It should be taken into consideration that the LCC objective to collect all the costs and impacts of the lifecycle environmental aspects implies significant risks of double-counting when environmental damages are monetized in LCC, which would be counted in the environmental domain, as well as cost in the economic domain [62,63].

Based on the above, it could be said that LCC techniques are useful to determine the costs derived from the production of a functional unit in a particular system. However, LCC (conventional and environmental) has important limitations related to the unclear system boundary definition and the unresolved internalization approach [64]. Thus, a need arises to establish a consistent definition of the production system or identify the system's boundaries (quantitative description of all flows of materials and energy through the system, both incoming and outgoing (ISO 14044, 2006)). Following ISO 15686:5 (2017) [65], LCC attempts to capture all costs across the life cycle, in other words, from the beginning until the disposal, end-of-life/status change (also called from the cradle to the grave). Therefore, LCC is based on a linear process that sees the use of raw materials and the generation of production waste that is thrown away (take-make-dispose). Thus, it does not consider other costs besides disposal or end of life [65,66], such as renewable and recyclable resources or the recovery of waste from internal processes and from other players in the ceramic industry, which are consistent with the sustainability principles of the circular economy.

3. Aim and Research Methodology

The aim of this research is to overcome the above-mentioned LCC limits offering a new approach to the economic dimension of sustainability, starting from the ceramic tile-manufacturing context [36]. To this end, a three-stage exploratory research methodology was used:

1. Descriptive analysis based on a survey questionnaire conducted with the contribution of experts belonging to a manufacturing company representative of the Italian ceramic tile industry;
2. Design of the new extended LCC framework;
3. Quantitative validation of the models with production data and industrial costs of the sector.

The first step was based on an in-depth analysis of business processes carried out through sets of semi-structured interviews selecting twenty-one top positions in the board of directors and top management of the company following the protocol adopted by García-Muiña et al. [67] with the same company but in the context of another research. With this approach, different scenarios of LCC applications were simulated following the guidelines of the different ISO standards; then, through abductive inference, a new cost evaluation framework was devised. The same exploratory, interpretive approach with abductive inference has already been successfully applied in other research in the field of sustainability [68].

As a second research step, we built our proposal, using the ISO 15686:5 (2017) guidelines [65] as a reference method. We then started from an internal cost-oriented perspective (conventional LCC) and then incorporated the full cost philosophy. These standards represent an important tool to help establish a clear terminology and a common methodology for lifecycle costing, to enable its practicality, to help to improve decision-making and evaluation processes, and to provide the framework for consistent LCC predictions and performance assessment, among others. However, this framework is particularly aimed at predicting and assessing the cost performance of buildings and constructed assets. With this in mind, it was adapted to the sector through the breakdown of the costs according to the different steps of the production process from a supply chain perspective. Moreover, aiming at strengthening the sustainable dimension of this technique, some costs related to circular economy practices were identified in order to foster changes to circular business models.

Finally, as a third step, the model was empirically validated at meso (sectoral) level, using production data and manufacturing costs of the Italian ceramic industry [69], taking as reference the typology of porcelain stoneware produced in the year 2019 [70]. The perspective of analysis was changed from the micro (firm-level survey) to the meso (industry-level) level in the empirical validation of the model. The reason is that industrial costs are sensitive data for the individual firm and, therefore, cannot be published. On the contrary, the sectorial industrial costs are aggregate data, therefore, not sensitive, periodically supplied from the center studies of the association of the manufacturers' ceramics. The use of sector data offers the opportunity to build a benchmark, useful for individual companies to compare their performance in terms of economic sustainability with that of the industry to which they belong.

4. Descriptive Analysis

4.1. Data Collection

In this phase of the research, the exploratory analysis of the quantitative data collected through a survey carried out with direct interviews with the top and middle managers of the company taken as a case study was conducted. The interviews were then checked and digitally transcribed for subsequent evaluation of the results. Table 1 shows the framework for carrying out the interviews and the questions asked to the sampled company's managers in order to capture the different awareness on the issue of economic sustainability and the possibilities of assessing it.

Table 1. Framework for carrying out the interviews (modified based on [67]).

<table>
<tr><th>Business Function</th><th>Job Position</th><th>Survey Questionnaire</th></tr>
<tr><td>Board of Directors</td><td>Chief Executive Officer</td><td rowspan="3">1. Are you familiar with sustainability assessment tools?
2. Have you heard of economic sustainability?
3. If there is, what is it?
4. Do you think there is a relationship between environmental and economic sustainability?
5. Do you think it is important to extend industrial accounting beyond the company boundary?
6. Do you know life cycle costing?
7. Do you think externalities should be included in industrial accounting?
8. If you believe they should be included, how should this be done?
9. In your opinion, does adopting a circular economy approach represent a cost or a source of competitiveness?
10. How should the effect of circularity practices be included in industrial accounting?</td></tr>
<tr><td>Top Management (C-Level)</td><td>Chief Financial Officer
B2B Sales Director
B2C Sales Director
Procurement Director
Technical Director</td></tr>
<tr><td>Management (B-Level)</td><td>Innovation Manager
Marketing Manager
Administrative Manager
Controller Manager
HR Manager
IT Manager
Credit Manager
Sourcing Manager
Logistic Manager
Security Manager
Quality Manager
R&D Manager
Plant Manager 1
Plant Manager 2
Plant Manager 3</td></tr>
</table>

4.2. Data Analysis

Below are the results of the analysis of the responses provided by the experts, categorized by each question.

- Q1—Are you familiar with sustainability assessment tools? The majority of experts said they were aware, albeit vaguely, of the existence of tools for assessing sustainability, especially those used to obtain environmental certifications.
- Q2—Have you heard of economic sustainability? The economic dimension of sustainability is a concept known primarily to managers in the areas of control, research and development and innovation. On the contrary, experts in the area of operations and sales associate the term sustainability exclusively with the environmental dimension.

- Q3—If there is, what is it? Those who said they were familiar with the concept unanimously believe that a product or process is economically sustainable if it is first able to generate value for the firm and its stakeholders.
- Q4—Do you think there is a relationship between environmental and economic sustainability? Managers already familiar with economic sustainability believe it is closely related to the environmental dimension. The other interviewees are also in line with this conclusion, but only after having taken note of the existence of economic sustainability as well.
- Q5—Do you think it is important to extend industrial accounting beyond the company boundary? Unexpectedly, managers in the accounting and administration area do not think it is particularly important to expand company accounting outside the firm's gates. By contrast, managers in sales, R&D, innovation and quality consider it important because they appreciate the lifecycle perspective of the product.
- Q6—Do you know life cycle costing? The only experts familiar with life cycle costing are those in R&D, innovation and quality.
- Q7—Do you think externalities should be included in industrial accounting? Except for managers in R&D, innovation and quality, everyone else had to explain the meaning of externalities. After doing so, all interviewees agree that externalities should be considered in industrial accounting.
- Q8—If you believe they should be included, how should this be done? None of the interviewees were able to provide convincing solutions to determine and include externalities in business accounting.
- Q9—In your opinion, does adopting a circular economy approach represent a cost or a source of competitiveness? All managers agreed that implementing circular economy strategies could be a source of competitive advantage for the firm.
- Q10—How should the effect of circularity practices be included in industrial accounting? None of the interviewees were able to indicate ways to include circularity practices in corporate accounting; however, all agreed that implementing it would be an important transparency factor in addressing stakeholder expectations.

4.3. Interviews Findings

The survey results show very clearly how economic sustainability is still a little-known concept within companies, even among executives with important management positions in the organization. The economic dimension of sustainability plays a secondary and subordinate role to the environmental one, both because of a greater social awareness of environmental issues and because of the greater diffusion and knowledge of assessment tools used above all to obtain certifications. In spite of this, the survey highlights an important element: from the perspective of transparent communication with stakeholders, managers believe that determining the economic impact of processes and products, as well as circularity practices, would be relevant as a factor of competitiveness and, therefore, should be included in company accounts.

5. Designing the New Framework

Based on the findings of the descriptive analysis outlined in the previous section, a new life cycle costing framework was developed to capture the ideas that emerged from the survey with experts.

5.1. System Boundary

When assessing economic impacts, it is worthwhile considering what is implicit in a final product cost; in other words, along the full production chain relating LCC to the supply chain may help to distinguish the components of the final LCC [63]. For this reason, an inventory analysis to identify the input and output flows in the life cycle of the ceramic process is needed. On the other hand, from a circular approach, the limits of the system a product must be established from its conception, extraction of materials, manufacture, use and end of its useful life until the recovery and putting in a new process return circulation so that the greater quantity of materials is recovered, reproduced, reused or recycled.

The model displayed in Figure 1 shows all the phases of the life cycle of the ceramic product and its relations. It allows determining the inputs and outputs, forwards and backward, from a circularity approach (cradle-to-cradle). It also represents the potential relationships with other agents, which the company may be linked to close the loops in a possible cradle-to-cradle model. The manufacturing process begins with the reception and storage of the raw materials that are used to prepare the ceramic mixture. Before this phase, it is essential to study the strategic alternatives to procurement and transport in order to reduce environmental impacts. For this purpose, collaboration with mining industries is fundamental, for example, through the sharing of storage capacities or by evaluating the different qualities of materials and transport alternatives. In this phase, the options of materials recovery, although desirable, are, in fact, very reduced, so efforts should focus on the reduction of waste and the application of measures for the recovery of soils or ecosystems.

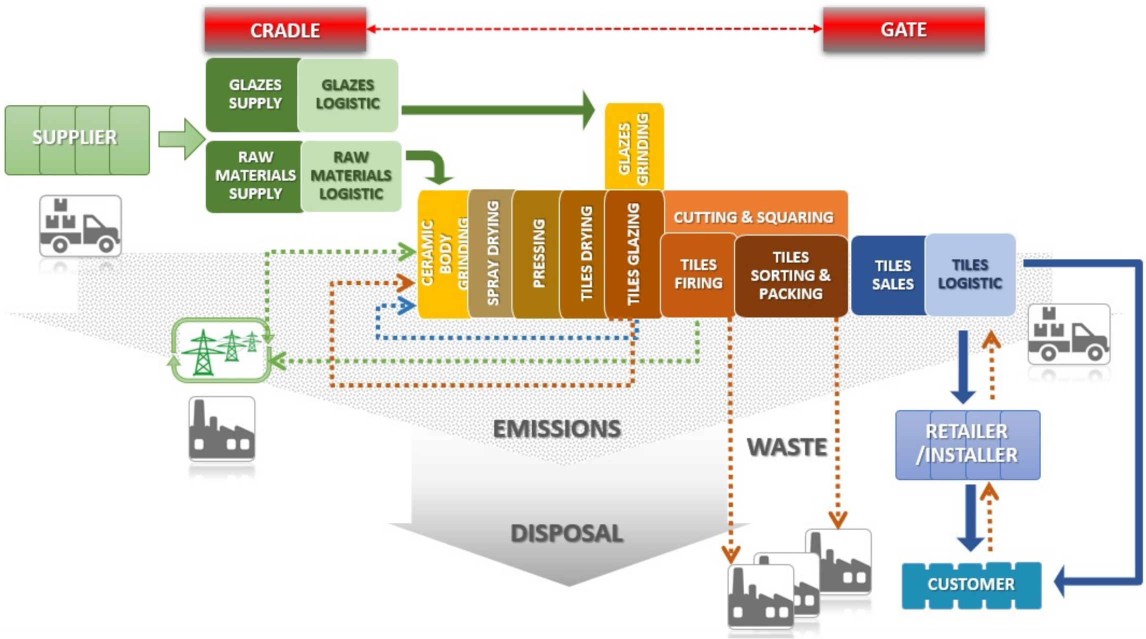

Figure 1. Ceramic production circular process flow (source: our elaboration).

After storage, the raw materials are mixed (with the compositions of the ceramic body of production) and ground with water in continuous rotary mills until a solid/liquid suspension called slip is obtained. This is then stored underground and subsequently nebulized and dried at high temperatures achieving a very fine and homogeneous powder that is subsequently pressed to achieve a format (square or rectangular) the desired size. During these phases, which are continuous, the design and production form alternatives are directed not only to avoid the greater volume of emissions to the atmosphere or to the waters, but also to achieve the greater volumes of reuse, not of the intermediate products (broken unfired tiles), but especially of resources, such as heat, convertible into electrical energy or of the reuse of wastewater. Subsequently, the tiles are then covered with a layer of glaze and digitally decorated with special inks to obtain the required graphic design, making them available to be fired at very high temperatures in cycles of different times. In these phases, the possibilities of reincorporation of flows to the manufacturing system are reduced due to the special characteristics of the products that are already glazed.

The recovery of energy and the search for quality and production alternatives (lean management) that reduce the losses of fired tiles to a minimum are still of special importance. Here, as in the next phase, other companies outside the ceramic value system become important. Either because they can incorporate these materials as raw material for their production processes (reducing the consumption and waste of raw materials and natural environments) or because they are specialists in waste treatment. Next, the tiles coming out of the kiln can follow two paths: they can go directly to the packaging department of the finished product, or they can be sent for further processing, which can include informed cutting of smaller and more modular tiles and/or lapping of the surface to obtain a brilliant effect, such as stone materials (marble and granite). In these phases, the minimization of tile losses is once again essential, but the choice and possibilities of recycling and recovery of packaging materials through appropriate supplier companies also become important. In the end, the finished tiles are routed to the different final agents. In these stages, the selling of the product must be thought of in terms of possible alternatives to reduce the impact (transport and storage) and the cost of using the final product. Equally important are the possibilities of systems for repurchasing, recovering or treating waste from the end-user or from the retailer.

In all production stages, reliability in production and control systems is essential to reduce product and time losses. They do not only involve a higher cost but also a greater environmental impact. In addition, the availability of tools to make sensitivity analysis of the possible alternatives of investment and design of product and production is crucial. The possible symbiosis relationships that are essential for a true circularity of the system and that are already being investigated, especially in the ceramic sector, are also highlighted [71].

5.2. Identifying Costs: The Scope of the LCC Analysis

The scope of the LCC methodology is referred to the type of cost to consider in the analysis. In this regard, in order to identify and allocate those costs, it is important to keep in mind that the LCC analysis is aimed at quantifying the life cycle cost of a product to serve as input information for a decision-making process. The set of costs to be considered in an LCC analysis goes beyond a mere definition of the most direct consumptions related to the life cycle of a product since it is also necessary to take into account other indirect costs and those associated with compliance with national or international regulations or tax systems.

This is reflected in the international reference standard (ISO 15686:5; 2017), which proposes a classification of costs that should be included in a standard analysis for the construction sector, as shown in Figure 2.

This standard (ISO 15686:5; 2017) distinguishes between life cycle cost (conventional LCC) and whole lifecycle costing (WLCC). The first one only collects those costs that are directly related to production and considering this process is long in time. According to this scheme, to know if a product (building) will be sustainable from an economic point of view, all those costs linked to its production (construction), operation, maintenance and disposal at the end of its useful life must be included. Thus, when considering the LCC calculation system of a product, it is not possible to identify those cost savings related to a lower use or a greater recovery of resources, which, however, could be true measures of environmental sustainability. Only those costs related to compliance with norms and standards about, for example, pollution or environmental protection are considered and always if they are monetized in terms of taxes or subsidies (environmental costs). Therefore, it does not include any valuation of other externalities as a consequence of production.

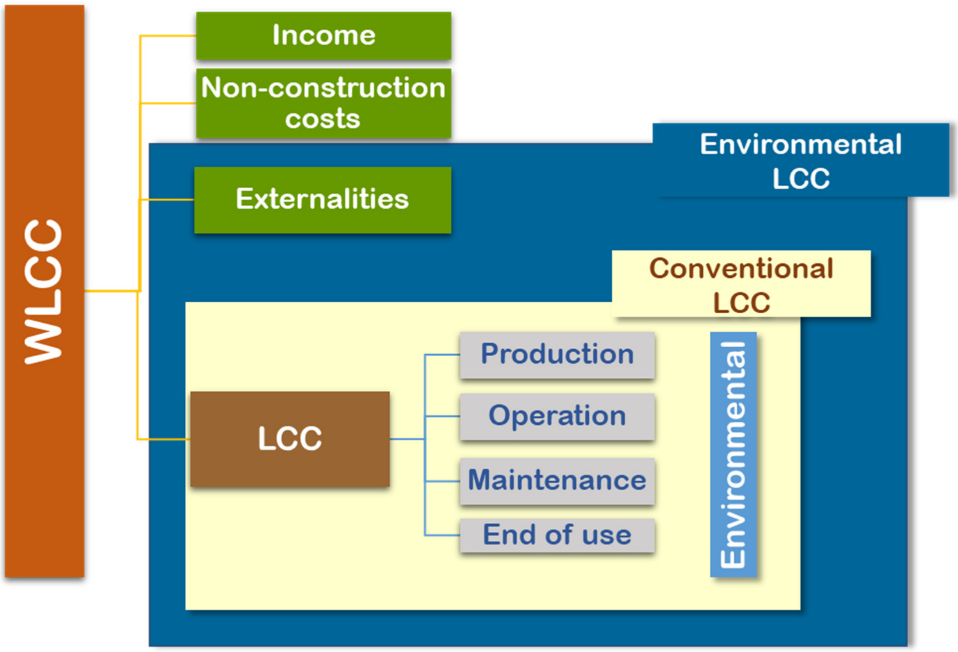

Figure 2. WLCC and LCC elements based on ISO 15686:5; 2017 (source: our elaboration).

In order to be able to collect these externalities, the standard proposes the full cost method. This calculation would include the economic valuation of costs or cost savings that may occur throughout the life of the product due to impacts on the environment or on society. In this respect, the standard makes it clear that only those that are likely to be internalized in the future in the form of taxes, fees or subsidies should be included. That is to say; it explicitly recommends not to monetize those externalities whose future influence on the product cost is unknown. This recommendation is important if we consider costing from an accounting approach since increasing the costs of goods can influence their viability from a purely economic perspective. However, to assess sustainability from a broader point of view, the monetary quantification of externalities should be included regardless of whether or not they were to be internalized in the future. After all, these impacts can be considered as real losses of the value of a good (being more polluting) or greater value of that good (polluting less). In addition, their monetary valuation, for example, based on an LCA analysis, may be more accurate and complete than simply incorporating a current tax, rate or bonus.

One of the pitfalls facing the practical application of this methodology in a ceramic tile industry is the fitting of this cost structure to the reality of a continuous production process. In the ceramic process, some of the costs related to the life cycle of the product are borne by agents other than the company. For example, we can assume that a large part of the costs (economic and environmental) of the tile-laying activity should fall at least partly on the installer rather than solely on the ceramic producer. Similarly, we can assume that the maintenance costs of the product could be covered by the end customer, or even that the costs of dismantling a ceramic flooring could be paid by the customer, the reseller or even the installer.

Therefore, knowing who bears the cost of a certain basic activity related to the life cycle of a product is a key point in determining the real cost of its sustainability. Thus, if a ceramic company launched on the market a new tile design aimed at reducing the consumption of polishing or cleaning products (to be supported by the customer), it would not only be reducing the monetary cost of maintenance to the customer, but it would also be delivering a more sustainable product on the market. An adequate system of sustainability analysis to make these decisions should be able to include these costs regardless of the agent that bears them.

Identifying the costs related to each agent in the value system is not only important for the economic quantification of sustainability but can also be a critical issue to undertake circular economy principles. The analysis might involve reverse logistics actions, waste reuse policies or search for alternative uses of materials throughout the useful life of the product. For example, in order to assess the feasibility of offering retailer or customer programs for the repurchase of materials, it would be necessary to make an economic assessment of the costs associated with the required investments, as well as the environmental impacts that might occur.

5.3. A More Comprehensive LCC Tool

Starting from the ceramic tile-manufacturing context and the ISO 15685:6 (2017) as the reference model, the LCC's new comprehensive tool was built in two sequential models (Figure 3).

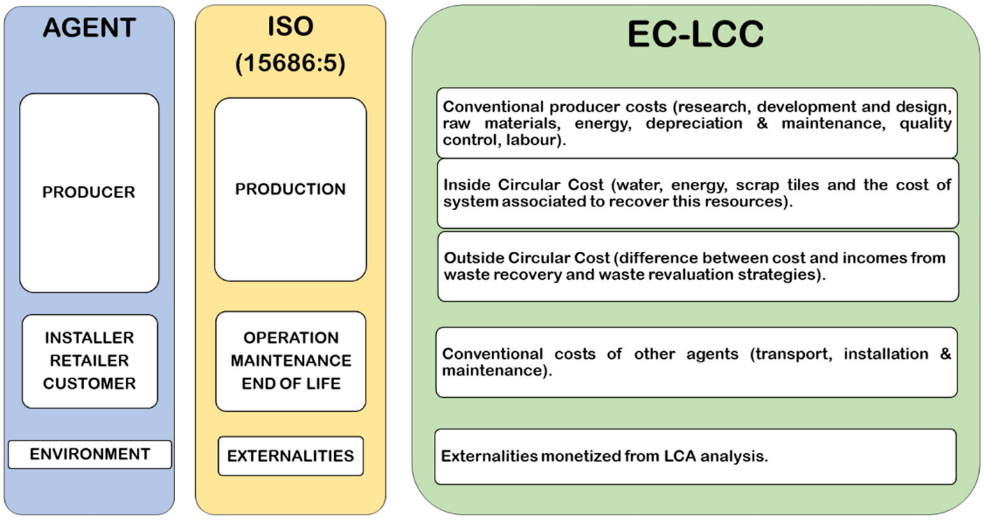

Figure 3. EC-LCC scheme (source: our elaboration).

First, an aggregation scheme was explored from a circular flow approach, which is closer to the reality of a continuous production process. With this first scheme EC-LCC (environmental and circular LCC), the calculation is intended to identify the most relevant circular economy practices in the production process. It also tries to respect the concept of the life cycle in the terms in which it is expressed in the international standard, and it is intended to be calculated in periods of one year or less. In this sense, identification of costs based on three criteria is proposed, considering: conventional costs directly associated with the life of the product, the eco-circularity cost associated with circular economy practices or principles and externalities obtained from the monetary valuation of impact from emissions and non-recoverable waste.

Product lifetime costs are identified without considering the full cost, but only those linked to production, installation, maintenance and end-of-life. In other words, the costs directly associated with design and quality control, the acquisition of materials, labor costs, energy costs and the depreciation, maintenance and repair of productive investments are considered. All this regardless of the agent that bears the costs. Reasonable estimates should be made of the installation, transport and maintenance costs that, due to the characteristics of the product (These costs should not be considered total installation or maintenance costs that would be borne by the installer or the customer as these will depend on other factors not directly related to the product's qualities of functionality, durability, weight, fragility, etc., but on the practices or characteristics of those other agents.), are borne by other agents throughout the entire life cycle.

An eco-cost is a measure to express the amount of environmental burden of a product based on prevention of that burden: the costs, which should be made to reduce the environmental pollution and materials depletion in our world to a level, which is in line with the carrying capacity of our earth (the "no effect level") [44,72].

In this line of thought, the so-called eco-circularity costs would be all costs generated by investments aimed at developing any of the principles of the circular economy (Ellen MacArthur Foundation, 2017) [73]: design out waste and pollution, keep products and materials in use and regenerate the natural system. Two cost types are proposed for assessing this. Inside circularity costs, i.e., the costs of resources reused and the systems to do it inside the production process water, pieces of pressed tiles and the recovery of thermal energy in the form of electrical energy, for example,). Outside circularity costs, i.e., from practices involving other actors and involving reverse logistics. For example, repurchase policies, recovery of packaging or final product from retailers, installers or customers, sale of recovered materials to companies in other sectors, such as cement mortars [74] or concrete production [75]. The calculation of these costs should also consider the potential incomes arising from the recovery of waste of recovered materials that are difficult to remanufacture. These costs must be obtained separately from conventional ones to avoid double counting. In the case of externalities, the tool would be fed by the information from the LCA analysis. Thus, both LCA and LCC need to use a consistent and shared definition of the production system in order to represent all the actors involved [66]. Following Ferrari et al. [9], in order to overcome some of the problems of integrating LCA and LCC, a difference must be done between production phases that generate costs to the producer and others incurred by other agents within the value system: distributor, installer and user. Keeping the same system boundary definition for LCA y LCC analysis, the environmental externalities could be monetized separately, avoiding, to some extent, double counting.

The second scheme is the whole environmental and circular lifecycle costing (WEC-LCC) aggregation model. Despite the implementation of the whole life cycle cost of the ISO is not good for this type of productive process—investments and costs are mixed (multiannual investment)—the general principles and cost breakdown system of ISO 15686-5: 2017 have been followed with reasonable adaptations for the ceramic tiles production process. To do this, two templates of the Society of Chartered Surveyors Ireland (SCSI) working group on LCC [76] have been considered. For this reason, the costs have been included according to the type of asset (investment) associated with the ISO 15686:5 cost structure keeping a reasonable coherence with the cost classification of the first structure. A full cost model (or total cost of ownership) involves including other incomes and costs not directly related to production but necessary for the business' development. These link the company to its administrative and financial activity and to the tax/legal system. These costs have not been included in the first scheme, which is just related to the production process [44,72].

In this model, the strict application of ISO implies considering each ceramic product as an investment project, including assets and incomes, as well as production (operational) costs, which makes it necessary to take into account a time horizon of more than one year. The guide to life cycle costing of the working group on sustainability and LCC of the SCSI was followed to take into account a possible escalation effect for costs and the discount rates to calculate present values. However, statistical methods, such as Monte Carlo analyses, would be recommended when uncertainty about future costs arises. A representation of the proposed model with the two previous schemes is exhibited in Figure 4.

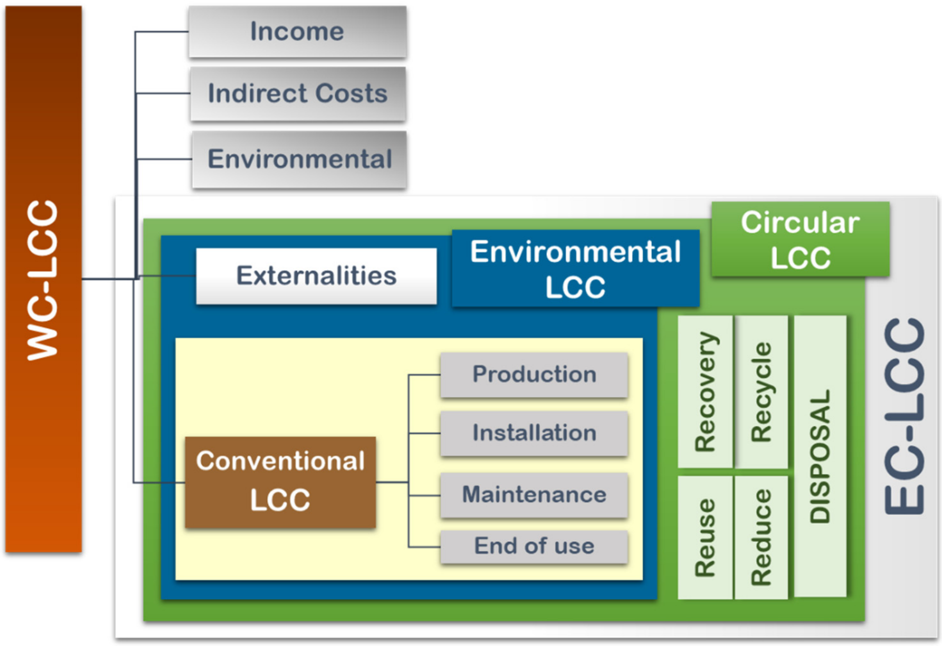

Figure 4. New economic approach, WEC-LCC elements (source: our elaboration).

6. Case Study and Empirical Validation

The Italian ceramic industry is one of the most vibrant manufacturing sectors in the country. In 2019, this industry produced about 401 million square meters of tiles, billing 6.5 billion euros with 27,500 direct employees [70]. The Italian ceramics sector comprises approximately 135 firms organized in an industrial district located in the area of the city of Sassuolo in the Emilia Romagna region in the north of the country. This industry has always been characterized by a strong orientation towards process and product innovation, making factories more efficient and companies more effective, also through the rapid adoption of the latest Industry 4.0 technologies [36].

Considering the sectorial context, it was decided to move away from theoretical models and develop an economic sustainability analysis focused on the production process. The analysis started from an initial assessment of the industrial costs sustained by the ceramic companies belonging to the sector. The level of analysis is that of the conventional-LCC represented above in Figure 4. Table 2, on the other hand, shows the main production costs of the sector expressed in euros related to 355 million square meters of porcelain tiles produced by the sector during the year 2019 [70]. Porcelain tile is the leading type among ceramic tiles, both in terms of volumes produced and sales, which is why the cost analysis focused on this product. The manufacture of the ceramic product requires the preliminary preparation of a semi-finished product, called the ceramic body, which, in the form of powder with controlled grain size, is subsequently formed through a uniaxial pressing process to obtain the ceramic support. This pressed substrate is then glazed and digitally decorated with inks to impart esthetic surface attributes. The glazed and decorated supports are then fired in kilns with cycles of 40–50 min at a maximum temperature of 1220–1225 °C, thus obtaining the ceramic tiles ready for packaging [69]. To manufacture one square meter of ceramic tiles, about 18–22 kg/m^2 of the ceramic body is needed. Hence, considering an average of 20 kg/m^2, the Italian ceramic industry required the following amount of raw materials in 2019 to produce the porcelain tile type:

$$\frac{355 \text{ million m}^2}{20 \text{ kg/m}^2} = 7,100,000 \text{ ton (raw materials)}$$

Table 2. Conventional LCC analysis (industrial costs).

Conventional LCC		
Cost Category	**€/m^2 of Tile**	**Production Cost**
Body raw materials	1.62 €	575,100,000 €
Inks, glazes, grits	0.53 €	188,150,000 €
Water	0.04 €	14,200,000 €
Electrical energy	0.37 €	131,350,000 €
Thermal energy	0.65 €	230,750,000 €
Consumables	0.77 €	273,350,000 €
Packaging material	0.31 €	110,050,000 €
Human resources	1.67 €	592,850,000 €
Total Costs	5.96 €	2,115,800,000 €

From the volumes involved, it is, therefore, clear that the raw material sourcing phase is the most critical from both an environmental and economic point of view, so its cost item, along with that of chemicals (glazes and inks), are the most significant in the C-LCC analysis. The sources of supply of raw materials for the Italian ceramic industry are mines located both in Italy, Europe and outside Europe. The delivery system, from the mine to the factory, is a decisive factor in assessing both the environmental impact and the cost of the raw material [38]. In this study, sourcing costs were estimated by considering an average ceramic body composition containing significant amounts of raw materials imported from non-EU countries, in particular from Turkey (sodium feldspars) and Ukraine (ball clays) [13].

Other relevant cost categories are the cost of natural gas and electricity and the cost of consumables (e.g., ceramic milling spheres and pebbles). Another significant cost is that of human resources worth 1.67 € per square meter, one of the highest costs besides raw materials. Finally, the least relevant costs in terms of euros per square meter are the cost of packaging material and the cost of water.

Once the main industrial costs were clarified, the analysis continues with an economic quantification of environmental externalities. The externalities represent the cost that society must incur from environmental damage. The evaluation method applied in this study is EPS 2015dx [77], which identifies the "willingness to pay" to compensate for environmental damage in monetary terms. The unit of measurement is the environmental load unit (ELU), and 1 ELU (=1 Pt) is equal to 1 €. Starting from an LCA study, we assessed the economic impact in euro per square meter of the externalities produced in the district by combining an industrial cost analysis (conventional LCC) with an environmental LCC analysis. Next, the impact per square foot is multiplied by the industry's 2019 production of 355 million square meters of ceramic tiles.

Table 3 shows the result of the assessment of externalities on the same items of the conventional LCC analysis. The simulation in Table 3 refers to a context in which a totally linear approach is adopted and in which circularity is entirely absent.

Table 3. Environmental LCC analysis (EPS method)—non-sustainable scenario.

Environmental LCC		
Cost Category	**Impact on EPS (€/m^2)**	**Externality Produced**
Body raw materials	3.37 €	1,196,350,000 €
Inks, glazes, grits	0.42 €	149,100,000 €
Water	0.04 €	12,780,000 €
Electrical energy	0.86 €	305,300,000 €
Thermal energy	0.37 €	131,350,000 €
Consumables	0.08 €	28,400,000 €
Packaging material	0.41 €	145,550,000 €
Total Costs	5.55 €	1,968,830,000 €

The costs represented in Table 4 are the environmental costs in euros (production and transport) resulting from the procurement of the cost category inputs. As the Table shows, the major costs in terms of externalities are clearly those arising from raw materials. In this linear scenario, the environmental cost of raw materials is significantly affected by transportation from non-EU countries (more than 65% of the total raw materials). Other important impacts, in addition to the environmental costs of glazes and inks, are those of electricity purchased entirely from the grid and natural gas. Finally, another significant cost is packaging due to the large quantities of cardboard and pallets used to pack the tiles for shipment.

Table 4. Circular LCC analysis (EPS method)—sustainable scenario.

Circular LCC			
Cost Category	**Impact on EPS (€/m^2)**	**Externality Produced**	**Δ**
Body raw materials	2.51 €	891,050,000 €	−26%
Inks, glazes, grits	0.42 €	149,100,000 €	0
Water	0.04 €	12,780,000 €	0
Electrical energy	0.21 €	74,550,000 €	−76%
Thermal energy	0.29 €	102,950,000 €	−22%
Consumables	0.08 €	28,400,000 €	0
Packaging material	0.37 €	131,350,000 €	−10%
Total Costs	3.92 €	1,390,180,000 €	−29%

The next stage (Table 4) consists of a second E-LCC simulation in which circularity and sustainability practices are introduced. The main practices under analysis in this scenario are the following:

- Sustainable raw materials;
- Electricity from cogeneration;
- Use of recycled cardboard and reuse of pallets.

These practices are in part already adopted by companies in the ceramic district, and they are, therefore, feasible in operational terms. In this second scenario, a ceramic body is evaluated with a high content of sustainable domestic raw materials (>40%) as well as European raw materials supplied by more environmentally friendly means of transport, such as rail. Regarding natural gas and electricity, the scenario assesses the effect of, including, for each company in the sector, a cogeneration plant that exploits the heat lost during production by transforming it into electricity. The scenario estimates a percentage of self-generated energy through cogeneration of around 50%. Finally, the scenario assumes the use of cardboard from 100% recycled paper and reuse of at least 5 times of the same pallet in the packing and delivery phases.

The results in Table 4 illustrate the impact of circularity in reducing environmental externalities, where Δ stands for the percentage difference between environmental LCC and circular LCC costs. The use of a sustainable ceramic body drastically reduces the cost per square meter of externalities from 3.37 € to 2.51 € per square meter. As mentioned above, the reduction in externalities results from the proximity of mines to production facilities and the use of more environmentally friendly means of transport. In addition, cogeneration reduces the externality cost of natural gas and electricity. Self-generated electricity reduces the impacts of grid electricity, even considering the environmental impact of building a complex facility, such as a cogeneration system. In conclusion, the use of recycled cardboard and the reuse of pallets has a slightly lower impact (−10%) on externalities in the packaging phase.

The total cost results reveal a clear reduction of the cost in terms of externalities from 5.55 euro per square meter to 3.92 euro per square meter (−29% in total costs). At this point of the analysis, the industrial costs (conventional LCC) should be added to the costs of externalities (environmental LCC or circular LCC if circularity is considered) to obtain a total cost of production of the Italian ceramics sector. This passage is not correct, however, because the two perspectives of analysis are different: industrial costs refer to the gate-to-gate manufacturing process of the companies, while the costs of externalities consider the environmental impact of the cost categories from extraction and supply to the gate, in a cradle-to-gate perspective. In addition, the difficult allocation of environmental damage between supply chain actors and the difficulties in quantifying damage already internalized (e.g., through taxation) by companies renders the sum of costs a worthless figure.

7. Discussion: Adaptive Life Cycle Costing Modeling, and Open Innovation

Innovation represents a fundamental asset to guarantee to the enterprises a competitive position on the market, assuring their growth as well as that of the territories where they operate. The reduction of the life cycle of the products, the increase of the costs of search and development, the dynamism of the economies [78] and the processes of globalization of the supply chain prevent the enterprises from exclusively innovating basing themselves on the competencies generated internally to the organization. This closed model of innovation development has been countered by the paradigm of open innovation [79], which instead embraces the philosophy of collaboration, expanding company boundaries and making them permeable to the increasing availability of external resources that can be integrated into business processes, thanks also to the inter-firm linkages that are created in the ecosystem [80]. This change in perspective requires companies to adopt an open business model, which allows ideas and technologies to flow from the outside to the inside of the company and from the inside to the outside environment. Innovating the business model means changing the way of creating, capturing and sharing value, and these aims are increasingly correlated with sustainability issues, particularly in its environmental dimension. For this reason, in recent times, the traditional concept of open innovation as part of the more general innovation management system [81] is being joined by issues related to sustainability [82]. The central point of open innovation, i.e., the paradigm of collaboration outside the company boundaries [83], is conceptually similar to the life cycle approach and consequently to the life cycle sustainability assessment framework (LCSA) that represents its operational tool.

7.1. Adaptive Life Cycle Cost Modeling

Life cycle costing, as an integral part of LCSA, can be seen as a multiphasic adaptive process aimed at obtaining a prospective evaluation of the evolution of costs with respect to the context in which the organization operates. The analysis of the results obtained with the LCC allows one to rethink both the strategic choices and the technical-managerial ones, but also to decide where it is convenient to concentrate the attention on those phases of the life cycle of the product that results more relevant both in a positive and negative sense. For example, those phases of the process that generate greater externalities should be investigated in order to implement corrective actions or to identify circularity actions that generate environmental and economic benefits. In other words, it helps the company to conduct its innovation efforts along the value chain, taking into account economic and environmental objectives [84]. This analytical process is iterative, and the optimal solution is obtained by applying the LCC calculation procedure several times with successive approximations and greater levels of detail.

7.2. Adaptive Life Cycle Cost Modeling with Open Innovation Dynamics

The adaptive characteristic of LCC is even better carried out in the framework of open innovation, where companies open themselves to the outside world to innovate by creating a real culture of open innovation [85]. Considering the product lifecycle and, therefore, the supply chain as a whole, i.e., the ecosystem that provides inputs to manufacture a product and distribution channels to deliver it to consumers, suppliers and distributors become partners to create and manage innovation [86]. In the medium to long-term, open innovation ensures the economic sustainability of the innovation generated in the supply chain, thanks to the sharing within the ecosystem of tangible resources, such as production factors and intangible resources, such as knowledge.

Cost modeling with LCC in an open innovation framework represents a great advantage for the ecosystem players because it ensures accurate control of economic sustainability in the development paths of new products, promoting economies of scale, scope and knowledge. As part of life cycle management, LCC allows revealing those stages where major improvements can be achieved [87], especially those where the involvement of knowledge from the outside of the organization may be necessary. Therefore, the adaptive attribute of LCC, as a management accounting instrument, if applied in an open innovation ecosystem, can articulate the value proposition chosen to meet the competitive context's changes [88]. Setting the conditions to obtain economic benefits for all partners involved, creating more value than a traditional model of closed innovation.

8. Conclusions

8.1. Theoretical and Practical Implications

Companies undertaking a value creation process in line with a corporate sustainability approach must necessarily consider an evaluation of economic sustainability [89]. This observation is particularly relevant in manufacturing contexts, where companies should assess the environmental and economic sustainability of the circularity practices they intend to introduce. This approach is also relevant in the life cycle perspective when it is important to predict supply chain business performance [90].

Starting from the ceramics sector, we conducted an exploratory analysis of business processes carried out through sets of semi-structured interviews, selecting twenty-one top positions in the board of directors and top management of a ceramic tile company. The results of the interviews revealed that economic sustainability is currently considered subordinate to environmental sustainability. Increased awareness of environmental issues and greater knowledge of assessment and certification tools makes environmental sustainability more recognized within companies. Despite this, the survey showed a strong interest in determining the economic impact of processes and products in order to achieve transparent communication with stakeholders. The same interest was demonstrated in circularity practices, which are considered as a possible competitiveness factor.

Based on the conclusions of the descriptive analysis, this paper proposed two conceptual models for the assessment of economic sustainability through the life cycle costing tool. In this regard, the two schemes approached have different objectives, but they are complementary.

In the first of them (Figure 3), the total cost, considered as an investment evaluation technique, is not considered. However, the model allows to obtain the true value of a product because it is based on the measurement of the consumed resources, the recovered resources and the effects of the process on external parties (externalities) Throughout, not only the life cycle of a product, but also its circular value chain. This scheme for calculating the cost of a product is closer to the way in which LCA sets the system boundaries for calculating environmental externalities. With this scheme, if environmental impacts (externalities) could be monetized for each part of the value system that generates them, then it would be possible to better understand the origin of value gains or losses, avoiding to some extent double-counting throughout the product life cycle. This would allow for a better assessment of the economic sustainability of the product. Furthermore, by also, including an identification of the costs generated by efficiency systems that reduce waste (eco-circularity cost), we contribute to the identification of efficiency measures aimed at reducing the waste load and waste generated, thus highlighting one of the principles of the circular economy. Especially when it is relevant to identify those positive externalities that increase the value generated, for example, more eco-friendly or recovered materials, better designs, more or better recycling or remanufacturing practices or even cooperation agreements with other companies for waste recovery.

The second approach (Figure 4), building as a combination between the standard LCC model (Figure 2) and the first scheme, would allow making a present valuation of the future costs arising from environmentally responsible investments focused on the circular economy. This model considers the indirect cost from the structure of one company (the ceramic producer) and the cost from the legal system in which it is embedded (general and environmental taxes). In many cases, companies implement sustainability actions that are not reflected in their information systems and, therefore, are not being considered in decision-making. Being able to have relevant information on the economic valuation of the harmful effects of production, as well as investments directed towards more circular production models, allows the company to create different decision scenarios truly focused on sustainability. At the same time, growth proposals and/or the incorporation of more or better relationships with other agents that allow more symbiotic models and fewer resource consumers can be taken into consideration (meso-macro approach). As well as better eco-design decisions. The implementation of this new comprehensive tool could help companies to better understand the sustainability of their products to:

(a) Make business decisions regarding, which products to produce, which decisions of circular economy take and how much of pollutant (or little sustainable) is their products;
(b) Be able to inform reliably and to be comparable externally (depending on the standardization of the methodology) to fulfill the real objectives of transparency and consistency. Normally related to intangible returns for the company.

In the last phase, the theoretical models were validated with a case study referring to the ceramic tile sector of Sassuolo, on a production of 355 million porcelain stoneware tiles for the year 2019. The case study focused on the sourcing and manufacturing process and tried to quantify the main industrial costs and environmental externalities produced by the sector on a group of seven cost categories. Once the industrial costs were quantified, two scenarios were illustrated, the first assuming a totally linear production process and the second assuming the introduction of circularity and sustainability practices for all companies in the sector. The results in Tables 2 and 3 show how the introduction of circularity and sustainability significantly reduces the environmental cost of the ceramic production process. Some of these practices are already implemented in companies in the district, which are increasingly focused on the theme of sustainability. While the sector results are encouraging, at the micro level, economic sustainability analysis is always needed to assess whether the introduction of circularity has brought benefits in terms of reduced externalities.

Finally, the discussion highlighted the importance of LCC in an open innovation framework. The collaborative approach of open innovation increases the value and reliability of an economic sustainability assessment, generating benefits for all partners involved. For [84], one of the logical evolution processes in the implementation of open innovation is the search for new decision tools. Those that provide managers with the identification of where to innovate and the key factors for doing so. It is precisely an operational tool, such as the LCC developed in this paper, which can meet this need. In fact, according to the literature, the LCC should address the economic and environmental costs of all phases of the product life cycle. In this regard, considering managerial implications, it is, therefore, important to underline how the involvement of stakeholders from the first steps of an economic sustainability analysis allows to widen the boundaries of the assessment and to implement cohesive corrective actions.

8.2. Limits and Future Research Topics

Despite the contributions that these two proposals can offer, further work is still needed. In particular, models allow companies to calculate their contribution to improving the sustainability of a product. In this sense, we believe that one of the main problems that lie in the difficulty of integrating economic sustainability from the LCC with environmental sustainability (LCA) is that the former is based on the sum of the value generated/recovered by each agent involved in the value chain of a product. Whereas the latter is calculated taking into account the entire life cycle and not partially aggregating the externalities generated by each agent involved in the life cycle of a product.

Although the case study is extremely interesting, there are some limitations that need to be highlighted. First, the case study proposes two scenarios (a linear one in Table 2 and a circular one in Table 3) in which it is assumed that all companies adopt circularity and sustainability practices at the same level. Although this is a simplification, the transition to circularity is indeed occurring, and many companies in the sector have already successfully invested in circular production processes. Second, the case study does not consider the multiyear investment perspective developed in the second theoretical model of WEC-LCC and focuses only on the manufacturing phase, omitting relevant phases, such as use and end-of-life. To achieve this level of analysis, it would be essential to analyze the primary data of other actors in the supply chain, such as sourcing and distribution.

In conclusion, this paper is proposed as a useful benchmark for companies in the ceramics sector to start addressing the issue of economic sustainability. The models, although tailored to a specific sector, could also be adapted to other manufacturing industries. From a research perspective, the theoretical models are proposed as a first attempt to overcome the limitations of the LCC methodology in assessing economic sustainability. In this regard, questions such as the uncertainty associated with the assessment of future impacts or the evolution of prices and risks must continue to be studied in order to improve decision-making tools. In the same way, dealing in-depth with the valuation of income or intangibles, both company and of third parties (social cost) is another of the issues that will allow us to build more sustainable models on more realistic and complete decision bases. Finally, as mentioned at the end of the case study, once the externalities were quantified in economic terms, a criterion for sharing the damage between the actors involved in the supply chain should be investigated. In addition, some of the damage is already internalized by companies, e.g., through taxation through which governments partly mitigate the environmental damage of local production processes. All these issues will be the subject of future research already planned.

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