# Lifecycle-oriented design of ceramic tiles in sustainable supply chains (SSCs)

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## Abstract

**Purpose** – The purpose of this paper is to analyse the production cycle of glazed porcelain stoneware, from the extraction of raw materials to the packaging of the finished product, with the aim of verifying the effects of integrating an environmental impact assessment into the decision-making process for managing the life cycle, to make it economically and ecologically sustainable, in a holistic approach along the supply-chain.

**Design/methodology/approach** – The research is performed using the life cycle assessment and life cycle costing methodologies, to identify environmental impacts and costs, that occur during extraction of raw materials, transportation, ceramic tiles production, material handling, distribution and end-of-life stages within a cradle to grave perspective.

**Findings** – Through the use of a comprehensive analysis of the environmental impact assessment and related externalities, three possible strategic options to improve the environmental performance and costs of ceramic tile production were formulated, leveraging sustainability as a competitive advantage.



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**Research limitations/implications** – This exploratory research opens future lines of investigation, the first of which is to confirm the technological feasibility and market responsiveness to the three strategic solutions hypothesised thanks to the use of an innovative eco-design technique.

**Originality/value** – The research has allowed testing and validating the tools of environmental impact assessment (life cycle assessment) and economic impact assessment (life cycle costing as structured methodologies in a life cycle management framework, to help companies implement competitive strategies based on sustainability.

**Keywords** Life cycle management, Impact assessment, Life cycle assessment, Life cycle costing, Sustainable supply chain, Italian ceramic industry

**Paper type** Case study

## 1. Introduction

The concept of supply-chain (SC) is becoming increasingly important in companies after years of dominating the financial aspects, relevant for shareholders, but that if not used as a resource in business processes, are poorly effective in creating value (Beamon, 1998; Stadtler, 2015). The competitive tensions that affect all industrial sectors and the development of network technologies have led companies to develop a special focus on managing the interrelations between different business processes (Zerbini and Castaldo, 2007; Arora *et al.*, 2016; Kwon and Kim, 2018). This implies an accurate analysis of the SC as a fundamental tool to dynamically assess whether and to what extent competitive advantage is achieved, maintained and defended (Li *et al.*, 2006; Mellat-Parast and Spillan, 2014). Therefore, the traditional idea that identifies logistics as an internal function of companies is superseded by a broader, but also more complex, concept, which defines logistics as a technical and organisational infrastructure that manages the physical and informational connections of the plurality of companies that participate in the SC (Closs *et al.*, 1996; Ralston *et al.*, 2015). This becomes even more important in view of the production models of the industrial district, geographical areas where there are concentrated companies that produce the same type of product, strongly linked to the territory and its history (Albino *et al.*, 2007; Ortega-Colomer *et al.*, 2016). A new phenomenon has emerged in recent years: pressure from stakeholders, shareholders, consumers and not-for-profit organisations to integrate sustainability into SC (Seuring and Müller, 2008; Beske and Seuring, 2014). If companies can manage and improve social, economic and environmental performance in their SC, they can also avoid waste, optimise processes, discover new product innovations, reduce costs, increase productivity and promote true business values (Markley and Davis, 2007; Mota *et al.*, 2015). From these assumptions, it follows the need to consider *extended* management models able to reduce overall impacts through the engagement of all actors in the chain, creating sustainable value for stakeholders and minimising inefficiencies and risks. Therefore, the main aim of this paper is to test the approach of life cycle management (LCM; Labuschagne and Brent, 2005; Bey, 2018) to attribute to environmental damage an economic value both at company and supply chain level and, for this purpose, have been used jointly the life cycle assessment (LCA; Klöpffer, 1997; Hauschild *et al.*, 2018) and the life cycle costing (LCC; Norman, 1990; Heidrich *et al.*, 2017), respectively, as tools for environmental and economic impact assessment (Auer *et al.*, 2017).

## 2. Theoretical framework

SC has been defined as the set of actors that aim to complete a customer's request, including suppliers, transporters, warehouses, resellers and customers themselves (Carter *et al.*, 2015). It is, therefore, an end-to-end process that allows products and/or services to be produced and distributed to customers by moving goods from suppliers to producers, distributors, retailers and finally to customers with the aim of maximising the performance and efficiency of the entire chain (Sithole, *et al.*, 2016). This process is very articulated and complex and starts with the raw materials, continues with the realisation of the finished product and its warehouse management, and ends with the supply of the final product to the customer. The entire process is divided into several steps, and, in each step, are involved different professional figures. Supply-Chain Management (SMC) is, therefore, the coordination of the various stages that help to create the supply chain of an entity or a company to improve the performance and efficiency of the entire flow of supply and storage of resources finished products (Stevens and Johnson, 2016). In other words, we can speak of the management of the different logistical activities of a company.

The concept of Green Supply-Chain Management (GSCM) defines a management approach that aims to minimise the environmental impact of a product or service throughout its life cycle (Fahimnia *et al.*, 2015). In this definition, the life cycle concept of a product and process shifts the focus of attention from the company itself to the entire system of relationships and actors that contribute, together with it, to the creation of value, opportunities and minimisation of environmental impacts (Bag *et al.*, 2017). Until now, most companies have considered their relationship with the environment as a problem substantially limited to its physical boundaries, which can be managed through the environmental compatibility of their processes and products and the adoption of management models aimed at limiting the negative impacts of the production site (Barile *et al.*, 2014). However, such an approach is limited in reality to the extent that the environmental impacts of a product, when brought back to and related to its entire life cycle, accumulate throughout the relationships between different customers and suppliers in the form of waste, emissions and consumption generated along the value chain, from the extraction of raw material to the end of the product's life (Genovese *et al.*, 2017). If you leave a model where the company is responsible and able to act exclusively on the impacts generated by its internal operations (in the production process), you will notice that a significant part of the negative externalities is generated in the nodes and connections that make up the SC (Ding *et al.*, 2015).

The "one-to-one" management of one's own business is above all unthinkable for the companies inserted in districts where the systemic logic constitutes the essence and the competitiveness of a specific organisational model and where the companies are placed in relation to the finality to reach and the behaviour of each one is subjected to determined constraints and rules (De Marchi *et al.*, 2017). The economic and business literature shows how the district's logic is closely linked to the concept of network: network of social relations, skills and knowledge. A network of resources and distribution points that performs the functions of procurement of materials, processing into intermediate and finished products, distribution and delivery to customers and is composed of independent companies that share common goals (Carbonara, 2018). By reason of these distinctive elements, the actors of the industrial district are operators inextricably conditioned by the competitiveness of the SC in which they are located (Park and Shin, 2017). Companies within a SC find it difficult to improve the sustainability of their organisations because the problem remains to identify the right parameters to measure to ensure that sustainability objectives are met (Vigneau *et al.*, 2015). Among the reasons, there is the lack of culture on the part of SC's economic agents on the topic and the unavailability of information and data on which to build a strategy of corporate social responsibility.

Among the tools of environmental monitoring at the company level is quite well known the LCA method that allows you to assess the environmental loads associated with a system (product, process and service), through the analysis of energy and materials consumed, waste generated, logistics and transport, as well as waste and emissions released into the environment, all throughout the life cycle. The analysis must include an entire system with all its processes, from the extraction of raw materials to the disposal of products at the end of their life: it is the so-called from cradle to grave approach, a path that follows all the steps from the cradle to the grave. Or even better, in a perspective of eco-sustainability, from the cradle to a new cradle: recovery, reuse and recycling of materials at the time of their first end of life (Heijungs and Guineév, 2012). Instead, to implement a sustainable supply chain, companies need to adopt a holistic systems-based approach where all supply chain partners' activities are integrated throughout the entire product lifecycle: from raw materials to the end customer (Brandenburg *et al.*, 2014). The implementation of sustainable SC is hampered by the number of companies involved and the complexity of the relationships between them. Moreover, each actor in the value chain will most likely have different interpretations of the key factors for promoting sustainability (Tran and Von Korflesch, 2016). Recently, economic (Ciroth *et al.*, 2016) and social (Petti *et al.*, 2018) impacts are also being addressed in life cycles and SC, leading to the definition of LCC and Social Life Cycle Assessment (SLCA), respectively.

Whatever monitoring system is chosen, companies that are central to the SC cannot afford to be the last to respond to the problems that arise in their SC. There is a risk of negative repercussions not only in terms of growth potential, but also on reputation and image, without underestimating the danger of losing the ability to rapidly align with industry regulations. Normally, the relations between the different economic agents operating within the same SC are strictly commercial (the companies buy from their suppliers and sell to their customers), regulated by the quality–price ratio of the product exchanged. To include environmental aspects in product attributes, it is necessary to integrate internal industrial costs with external costs that quantify in monetary terms the environmental damage produced (Sánchez *et al.*, 2004). The assessment of the environmental impact of an industrial activity (LCA) and the assessment of the resulting economic damage (LCC) can be carried out in parallel (Akbar and Mokhtar, 2017) and can be integrated in a single management accounting tool called Life Cycle Management (LCM). Traditional approaches to managing the environmental effects of business operations have always focused on local optimisation of process parameters, such as energy consumption or the level of certain polluting emissions. With the introduction of the LCM concept, the horizons of process and/or product planning are broadened to cover the entire supply chain, from raw material supplier to final distribution (Blass and Corbett, 2018).

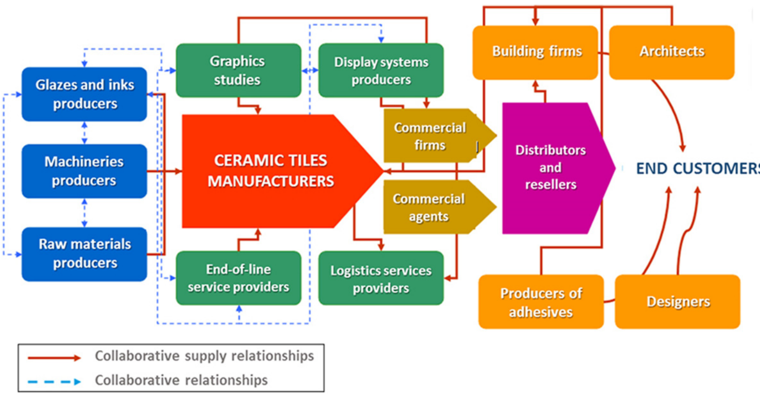
The main objective of this work is, therefore, to use the environmental impact assessment (LCA) and economic impact assessment (LCC) tools integrated in a LCM context to eco-design alternative technological solutions to improve the environmental performance of ceramic tile production as new product innovation (Han and Park, 2017).

## 3. Case study and methodology

A strong integration between SC's economic agents takes place in the industrial districts (ID) typical of the labour-intensive sectors (Carbonara *et al.*, 2002), where the localisation of the enterprises follows, first of all, a logic of cost advantage, whereby the companies tend to settle close to the organisations upstream and downstream of the SC. In Italy, the Sassuolo ceramic district, located in the foothills between the provinces of Modena and Reggio Emilia, is a paradigm for this. In the 1950s, the local factors that have favoured the development of an agglomeration economy in this specific geographical area are the large availability of raw material (red clay, with a high level in iron oxide content), the ease of finding labour from neighbouring agricultural areas and the important initial financial support provided by local banks in favour of indigenous entrepreneurs who have invested the accumulated capital in the agricultural sector (Bursi and Nardin, 2008). Now, the district consists of a network of 79 companies, which in 2016 produced 341 million square meters of ceramic tiles, generating a turnover of 5.4 billion euros and employing approximately 19,000 people (Confindustria Ceramica, 2016).

The ceramic industry SC is a complex network of economic agents, in which supply relationships intertwine and overlap with collaborative ones (Figure 1). In a central position, we find the companies that produce ceramic tiles, which supply themselves with materials (producers of raw materials and glazes and inks) and technologies (manufacturers of machinery and equipment). Ceramic manufacturers also avail themselves of the collaboration of numerous service companies: to develop the graphics with which the tiles are decorated (graphic studios); to finish the final product with cuts, grinding and lapping (suppliers of end-of-line processing); to have display systems for the exhibition rooms and the sales points (display systems producers) and for the logistical management of the finished product (suppliers of logistical services). The ceramic product is delivered through the distribution channel either through the direct sales network of the ceramic manufacturer (commercial agents), or through the intermediation of commercial companies that deal only with sales to distributors. Distributors and retailers work with construction companies, suppliers of glues and adhesives for tile laying, architects and designers to meet the expectations of end customers. By looking at the flow of materials in their path of transformation into ceramic tiles, we can see this network of economic agents as an efficient supply chain that can also create value for the end customer. In fact, each operator belonging to the supply chain creates value in the network thanks to the collaborative relationships between technology and material suppliers and tile manufacturers in an open innovation environment that increases the competitiveness of individual companies and the entire ceramic sector.

As a general scheme, the production process of ceramic tiles can be traced back to seven main phases (Figure 2): delivery and storage of materials; grinding of the mix of raw materials in mills with water and subsequent drying (spray drying) of the suspension of the ceramic body slurry to obtain a powder with a residual humidity of 7-8 per cent; pressing of the spray dried powder to obtain the support to be glazed; drying of the support to eliminate




**Source:** Our elaboration

**Figure 1.**
Supply chain of the tiles ceramic industry

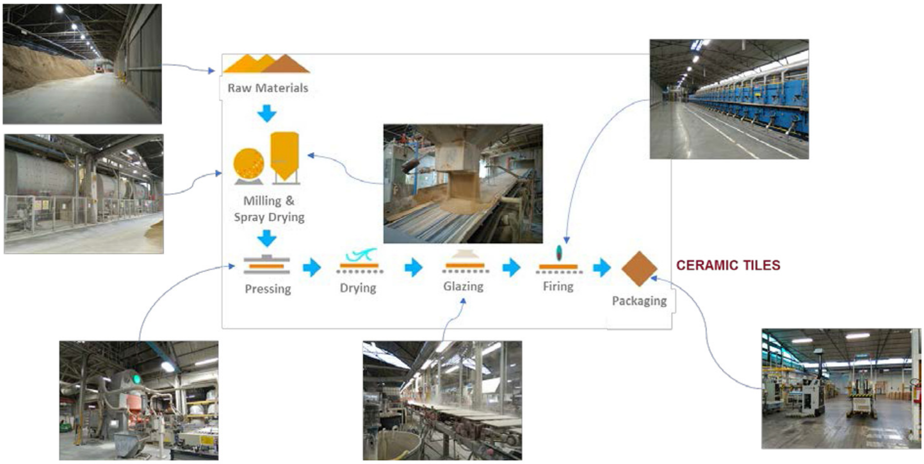



**Figure 2.** Ceramic tile manufacturing process

**Source:** Our elaboration based on the scheme proposed by Mezquita *et al.* (2012)

the residual humidity; glazing and decoration of the dried support; firing of the decorated support in kilns with cycles of 30-45 minutes at a maximum temperature of 1,200-1,230°C; and finally selecting and packaging of the finished product.

The main type of production in the Sassuolo district today is glazed porcelain stoneware (Confindustria Ceramica, 2016). The term porcelain stoneware identifies a particular class of ceramic tiles for floors and walls. The term stoneware refers to ceramic materials with a compact structure, characterised by the simultaneous presence of both the vitreous and crystalline phases, while the second term porcelain refers to the technical characteristics of the product, which make it similar to those of porcelain. Porcelain stoneware is essentially a ceramic product that is obtained from inorganic raw materials and, by means of a heat treatment (firing), has particular mechanical resistance. In fact, it is a product capable of combining pleasant aesthetic properties, especially when glazed, with excellent technical characteristics, the main of which are water absorption of less than 0.1 per cent and high mechanical strength.

Italian ceramic companies mainly use imported raw materials to produce porcelain stoneware, which come from mineral deposits located far away: Germany (15-25 per cent), Ukraine (20-30 per cent) and Turkey (30-40 per cent). Only 10-20 per cent of raw materials come from national mines. Different combined transport is used:

- road + sea + road (Turkey);
- road + rail + road (Germany);
- rail + sea + road (Ukraine); and
- only road (national).

These transport solutions, using different carriers, will have different impacts on the environment depending on the mix used, and these impacts will extend throughout the entire SC.

Historically, to analyse and reduce an impact on the environment, attention has been focused on monitoring and punctual intervention towards what made an impact evident in an "end of pipe" logic: chimneys, exhaust pipes, landfills, water drains and so on. This analysis is, therefore, limited to “environmental loads” at the end of the production and/or consumption chain. This approach did not serve to solving the nature of the problem itself but only to reducing the final impact without solving the systemic causes. On the other hand, the environmental impacts of a complex system such as an industrial product are distributed throughout its entire life cycle and can therefore only be fully assessed by analysing and weighting all the phases that make it up. The LCA methodology is used to take a complete overview of a system: of all inputs (materials, electricity, water and various fuels used) and outputs (emissions of all kinds) without forgetting any environmental impact from the extraction of raw materials to the end of their life (disposal or recycling). An LCA analysis is based (Figure 3) on the study of the so-called functional unit and is divided into four consequential phases: definition of goals and scopes, inventory analysis (i.e. data collection), evaluation of impacts and interpretation of results (in accordance with international standards ISO 14040:2006 and ISO 14044:2006).

Conducted in parallel and with the same phases of the LCA, the LCC analysis aims to quantify the externalities that are expected to be internalised in the industrial cost. The method follows the international standard ISO 15686-5:2017, which provides requirements and guidelines for performing it. The impact assessment and externalities were obtained with IMPACT 2002+ method using SimaPro Software as it is the most widely used for this kind of analysis and covers the broadest range of indicators.

The information to carry out this study was collected through a direct inventory analysis, i.e. measuring the consumption of natural resources (raw materials), energy (electricity and methane) and emissions into the atmosphere of each stage of the current manufacturing process of the company being studied. The alternative scenarios, on the other hand, have been defined through the eco-design approach, i.e. by mathematically simulating variations in the supply mix of resources and estimating, therefore, the environmental and economic impacts.

## 4. Environmental impact assessment

This study presents a comparison between the environmental impact of the current production of a major Italian ceramic producer (Gruppo Ceramiche Gresmalt) and three different strategic production scenarios obtained by varying the mix of procurement of raw materials. In the three scenarios, we have progressively reduced the use of raw materials from mines far from the production unit and with a complex transport mix to the advantage

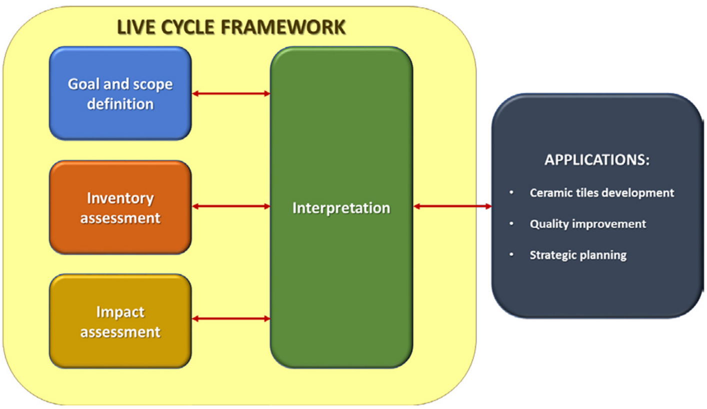



**Figure 3.** Conceptual framework of LCA (our elaboration)

of raw materials of national origin (Table I). These scenarios were defined thanks to the potential for eco-design offered by the impact assessment tools (LCA and LCC). Compared to current production, the simulation was carried out by modifying the transport mix (sea, rail and road) and the distances from the raw material extraction point and the production factory but keeping all other process parameters constant. The tools were then able to quantify, through a new calculation, the influence of the type of transport system on the environmental and economic impact of the manufacturer and the entire supply chain. The analysis was carried out on the condition that the technological and aesthetic properties of the design alternatives complied with current legislation and company quality standards.

### *4.1 Goal and scope definition*

The objective of the analysis is to assess the environmental damage and the economic cost of the life cycle of glazed porcelain stoneware produced by Gruppo Ceramiche Gresmalt of Sassuolo (Italy). The function of the system, i.e. the use of ceramic products, is the use as flooring and walling (inside and outside) of buildings. The functional unit (i.e. the reference unit against which all the data making up the environmental balance of the system under examination will be standardised) is 1 $m^2$ of glazed porcelain stoneware produced by the company.

The boundaries of the system range from the collection of raw materials to the packaging of the final product, ready for marketing. Within these boundaries are covered the structures and machinery used for the extraction of raw materials, transport and the production process, meaning by what the use of machinery and infrastructure and, thus, the consumption of raw materials and energy and the emissions of pollutants associated with their production, maintenance and end of life have been included in the study.

### *4.2 Inventory assessment*

The company has provided data on the stages of the production processes that take place at its plants. The data were collected using a series of sensors, meters and instruments (Wei *et al.*, 2017), located in each of the seven phases described above. The information collected digitally was transmitted through a manufacturing execution system, (MES; Tao *et al.*, 2017) to the enterprise resource planning (ERP; Hong *et al.*, 2016; Chofreh *et al.*, 2018) for subsequent data processing. The life cycle tools (LCA and LCC) used the company data processed by the ERP and stored in the database for environmental and economic impact assessment. The construction characteristics and cost of the main equipment included in the study were provided by the machinery manufacturers. For the raw material processes, data on mining and transport activities were provided directly by the mining companies. Information on the sea leg of the sea trips of some of the raw materials concerned has been collected from the Ravenna Port Authority (Italy). To represent the remaining processes, such as the use of electricity and thermal energy, production and processing of plant materials (such as metals, cement and refractory bricks) and plant end-of-life processes, processes from the SimaPro calculation software libraries were used.

**Table I.**
Composition of the current supply mix (production) and four alternative scenarios (expressed in percentage)

| Sources of raw material supply | Production | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| Germany | 25 | 25 | 30 | 30 |
| Ukraine | 25 | 20 | 0 | 0 |
| Turkey | 40 | 30 | 20 | 10 |
| Italy | 10 | 25 | 50 | 60 |

*4.3 Impact assessment*

The inventory data were collected by monitoring the entire process, from raw materials extraction through to finished product packaging. For each stage, the consumption of energy and materials and emissions of polluting substances into the air, water and soil were measured. The IMPACT 2002+ environmental assessment method, on the other hand, makes it possible to quantify environmental impacts according to midpoint-oriented (based on impact categories) and damage-oriented (based on assessment by damage categories) approaches. The results of the inventory analyses can be expressed both in 13 impact categories and in 4 damage categories, such as human health, ecosystem quality, climate change and resources (Table II). The evaluation of environmental impacts by category of damage is expressed in eco-points (Pt) for individual impact categories. The value of 1 Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant. It is calculated by dividing the total environmental load in Europe by the number of inhabitants and multiplying it with 1,000.

The weak point in all environmental impact analyses is the inability to translate environmental damage into economic damage in terms of values. All production activities consume environmental goods in the same that they consume raw materials for production but do not incur any cost owing to this collateral effect. This phenomenon of using environmental goods without paying to consume them is referred to in economic terminology as external costs or environmental externalities. Given that it quantifies environmental impact, the LCA is the most effective tool for estimating environmental externalities that would otherwise be impossible to calculate. Although there is no shared standard, external costs can be estimated by adopting suitable coefficients for conversion, from the units of measurement of the damage to monetary units.

In this LCC study, the following empirical formula was used to quantify the economic value of current production and the assumed scenarios:

$$LCC_{TOT} = \text{Production Costs} + \text{Utilization Costs} + \text{Externalities}$$

The results of the calculation are shown in Table III, which indicates the real cost per square meter of glazed porcelain tile if the producer company were to "internalise" its externalities – in other words, if it were to pay for the environmental damage it has caused. In addition, considering the company's annual production volume (20,000,000 $m^2$ of ceramic tiles), it was possible to quantify the effective cost (including externalities) of the finished product.

*4.4 Interpretation*

As shown by the histograms in Figure 4, the environmental impact of glazed porcelain tile production over its entire life cycle is attributable mainly to consumption of non-renewable resources, especially fossil fuels, during the processes of firing and to a transport. The harmful effects on human health are likewise attributable to these processes and are mainly owing to emissions of NOx (nitrogen oxide) associated with transportation of raw materials from the extraction site to the place of production. On this baseline, the alternatives assumed, which foresee a reduction in transport owing to the increasing use of national raw materials (Scenarios 1 to 3), show a clear reduction of the environmental impact by 22, 35 and 43 per cent, respectively. The preference for the use of national raw materials clearly does not have an autarkic value but, rather, means significantly reducing the distance between the mine and the factory. As it has been demonstrated that transport is one of the main sources of environmental impact, reducing the distance minimises the contribution of this factor to the overall impact of the system.

**Table II.**
LCA analysis of current production and the four alternative scenarios (expressed in Pt)

| Damage categories | Impact categories | Production | | Scenario 1 | | Scenario 2 | | Scenario 3 | |
|---|---|---|---|---|---|---|---|---|---|
| Human health | Carcinogenic agents | 3,40E−05 | *1,00E−03* | 2,50E−05 | *7,73E−04* | 1,80E−05 | *7,30E−04* | 1,50E−05 | *5,54E−04* |
| | Non-carcinogenic agents | 5,60E−05 | | 4,70E−05 | | 4,10E−05 | | 3,80E−05 | |
| | Respiratory inorganic | 9,10E−04 | | 7,00E−04 | | 6,70E−04 | | 5,00E−04 | |
| | Respiratory organic | 1,80E−06 | | 1,40E−06 | | 1,20E−06 | | 1,00E−06 | |
| Ecosystem quality | Ozone depletion | 4,50E−07 | *1,11E−04* | 3,50E−07 | *9,86E−05* | 2,80E−07 | *9,68E−05* | 2,40E−07 | *8,50E−05* |
| | Aquatic ecotoxicity | 1,00E−05 | | 8,20E−06 | | 7,60E−06 | | 6,50E−06 | |
| | Terrestrial ecotoxicity | 8,10E−05 | | 7,40E−05 | | 7,30E−05 | | 6,50E−05 | |
| | Aquatic acidification | 0,00E+00 | | 0,00E+00 | | 0,00E+00 | | 0,00E+00 | |
| | Soil acidification | 1,42E−05 | | 1,20E−05 | | 1,20E−05 | | 9,80E−06 | |
| | Land occupation | 5,10E−06 | | 4,00E−06 | | 3,90E−06 | | 3,50E−06 | |
| Climate change | Global warming | 1,41E−03 | *1,41E−03* | 1,10E−03 | *1,10E−03* | 8,50E−04 | *8,50E−04* | 8,40E−04 | *8,40E−04* |
| Resources | Non-renewable energy | 1,52E−03 | *1,52E−03* | 1,20E−03 | *1,20E−03* | 9,40E−04 | *9,43E−04* | 8,10E−04 | *8,13E−04* |
| | Mineral extraction | 3,62E−06 | | 3,20E−06 | | 2,70E−06 | | 2,50E−06 | |
| *Total* | | | *4,05E−03* | | *3,18E−03* | | *2,62E−03* | | *2,29E−03* |

Figure 5 shows the variation of the environmental costs of the scenarios considered compared to the current production in the form of histograms. The reduction in the distances covered by raw materials to the factory reduces externalities by up to 33 per cent compared to the current state of the art and, to a lesser extent, but always significantly (26 per cent), production costs, because of savings in transport costs and a lower incidence of the costs of raw materials. Indeed, domestic materials have a lower market price than imported materials because they are considered less valuable.

Therefore, the LCM framework allows to design the supply chain in an innovative way and consistent with the principles of sustainability. The quantification of the environmental impact related to the manufacturing process and the transport system of raw materials offers the possibility to quantify in economic terms such damage as externalities. The innovative aspect is twofold: on the one hand it is possible to predict alternative procurement scenarios with the eco-design function to support decision-making processes at company level; on the other hand, the company can internalise its externalities (environmental damage) but not only. The entire SC could be required to internalise the damage produced in the different phases of transport. In this manner, the environmental issue is not only limited to the perimeter of the company but also extended to all economic agents that compose it. The result is that the environmental benefit for the territory can increase significantly compared to what is obtained with the "environmentally virtuous behaviour" of the individual company.

| Life cycle costing | Production | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| Production Costs (€/m$^2$) | 8,50 | 7,80 | 7,25 | 6,32 |
| Utilisation costs (€/m$^2$) | 9,88 | 9,01 | 8,50 | 7,87 |
| Externalities (€/m$^2$) | 0,97 | 0,85 | 0,71 | 0,65 |
| *Total* | *19,35* | *17,66* | *16,46* | *14,84* |
| *Total over 20,000,000 m$^2$/y* | *€387,000,000* | *€353,200,000* | *€329,200,000* | *€296,800,000* |

**Table III.** Economic evaluation of externalities expressed in euro/m$^2$

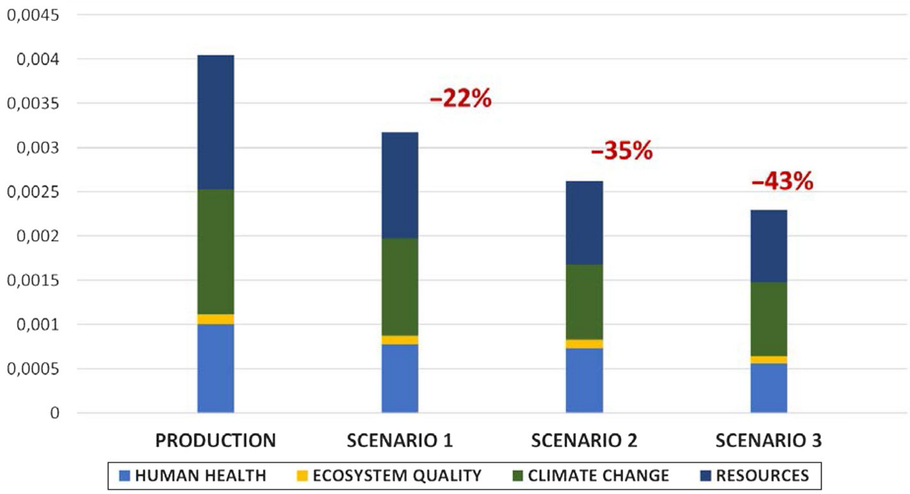



**Figure 4.** Graphical representation of environmental impacts (expressed in Pt)

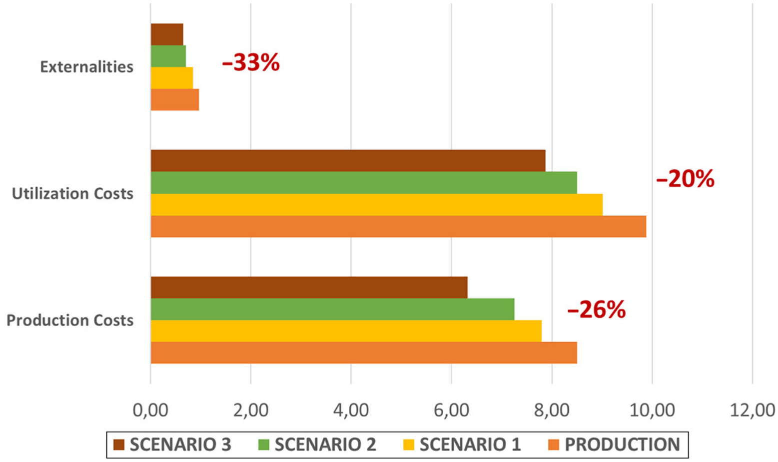



**Figure 5.** Graphical representation of environmental costs (expressed in €/m$^2$)

## 5. Evaluation of results and conclusions

In this research, we aimed to test the potential of the LCM framework to interpret the environmental analysis in terms of economic–financial consequences at company and SC level. The joint use of LCA and LCC has made it possible to combine the estimation of environmental impact with industrial cost (producer perspective), including not only environmental externalities but also the phases of use and disposal of the ceramic product (consumer perspective). On the basis of the analysis, we can suggest two possible areas for improvement: reducing energy consumption and reducing the average distance travelled by transport vehicles for sourcing raw materials (supplier perspective). The first solution is very difficult to achieve as ceramic technology is highly standardised. It appears more realistic to concentrate on optimising logistics, particularly inbound. The analysis focused on the Italian ceramic district where a large portion of the bodies for tile production consist of raw materials sourced from abroad. This involves a considerable consumption of fuel for transport (especially diesel fuel) resulting in the emission of NOx. For this reason, our study made a comparison between four porcelain tile bodies: one with a traditional composition, typically used by glazed porcelain tile manufacturers, and another three formulated based on a standard composition with the addition of Italian raw materials in place of imported materials.

The scenarios assumed have shown that as the use of national raw materials increases, owing to the simplification of transport, the environmental impact decreases significantly compared to current production. Moreover, from a strategic point of view, the reduction of transport costs would allow the company to incorporate environmental costs into production costs, transforming externalities into internalities, without, however, burdening industrial costs.

Therefore, the manufacture of products that are technologically less resource-intensive and have a low environmental impact is a valuable factor of competition for advanced companies, which can offer lasting comparative advantages in multinational markets. In fact, even potentially more expensive products initially (for the transformation of externalities into internalities), but with less impact on the environment, are of considerable interest to a many customers, who intelligently look for social product attributes and lasting operational savings in the purchased goods. The analysis conducted, extended upstream of the SC (to raw material suppliers), has shown that sustainability becomes a factor of competitiveness not only when it is functional to create value not only for the final consumer, but also for the industrial customer within the sustainable SC.

This exploratory study represents the first step towards other research objectives, which are already planned: first, to integrate the third pillar of sustainability in the study with an analysis of the social impact that integrates the environmental and economic ones; second, the assessment of the impacts must also be carried out downstream of the ceramic manufacturer, to involve the operators in the distribution of the finished product.

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