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Department of Engineering “Enzo Ferrari”
PhD "Enzo Ferrari" in Industrial and Environmental Engineering
XXXVI cycle

From sustainable technologies to technological sustainability: a new method for analysing and designing products and processes

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Academic Year 2022-2023

ABSTRACT

Nowadays, a key driver of change in the market is the focus on sustainability, which is increasingly important for business strategies and competitiveness. Technological progress, especially in manufacturing, is essential for businesses to reduce their environmental impact and contribute positively to the communities they serve. Using technology as a tool to promote sustainable practices highlights the expanding connection between innovation and sustainability.

This connection, generally studied in terms of the sustainability of technological solutions, is instead addressed in this thesis with the aim of building a theoretical basis for technological sustainability seen as a possible fourth dimension of sustainable development.

For this purpose, the thesis presents three interrelated studies that address the following research questions:

1 How can Industry 4.0 technologies be leveraged to develop and apply circular eco-design models in manufacturing?
2 How can technological sustainability be conceptualized and integrated into sustainable development frameworks?
3 How can technological sustainability be quantitatively assessed in manufacturing operations?

In order to answer these RQs, the study was developed in 3 phases:

1 Proposition of a circular eco-design model that integrates Industry 4.0 technologies, smart data, Life Cycle Assessment methodology, and material analysis techniques. The model is applied to the Italian ceramic tile manufacturing industry, demonstrating the feasibility of re-engineering ceramic products to align with circular economy principles.
2 Development of a theoretical framework for technological sustainability, defining it as the ability of technology to support the long-term sustainability of manufacturing operations.
3 Validation of the conceptual model in an operational context, demonstrating its ability to quantitatively assess technological sustainability and identify areas for improvement. The framework considers the environmental, social, and economic impacts of technology, emphasizing its role in enhancing the sustainability of products and processes.

The findings of these studies contribute to a broader understanding of technological sustainability in manufacturing, providing insights into its role in circular economy practices, sustainable product and process development, and the transition towards Industry 5.0. The research also offers practical guidance for manufacturing companies seeking to integrate technological sustainability into their operations.

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1 INTRODUCTION

In the contemporary economic and industrial landscape, sustainability emerges as an unavoidable imperative. The growing awareness of environmental, social, and economic challenges has led sustainability to become a crucial element in corporate strategies and a determining factor in market competition. This paradigm shift not only implies a reorientation of business practices towards greater environmental and social responsibility but also places technological innovation at the center of a radical transformation.

Technological progress, especially in the manufacturing sector, is essential for reducing the environmental impact of businesses and contributing constructively to the communities in which they operate. Technology, employed as a tool to promote sustainable practices, highlights a growing link between innovation and sustainability.

This interconnection, traditionally explored in terms of the sustainability of technological solutions, is examined in this thesis with an innovative approach. The goal is to build a theoretical foundation for technological sustainability, proposing it as a possible fourth dimension of sustainable development, alongside the traditionally recognized environmental, social, and economic dimensions. This expanded perspective on sustainable development underscores the crucial importance of technologies, not only as means to achieve sustainable outcomes but also as intrinsic elements of a sustainable ecosystem.

Technological sustainability thus becomes a key concept for understanding and addressing changes in the industrial landscape, where emerging technologies like those related to Industry 4.0 are seen not only as tools for efficiency and innovation but also as vehicles for a more sustainable future. In this context, the thesis aims to explore and define the role and potential of technological sustainability, addressing crucial issues related to the integration of sustainable practices into technological innovation and the reconfiguration of production processes in a sustainable manner. Through this approach, the work aims to provide a contribution to academic literature and practical insights for manufacturing companies seeking to integrate technological sustainability into their operations, outlining a path toward a responsible and sustainable industrial future.

1.1 RESEARCH OBJECTIVES

The research presented in this thesis is guided by a series of broad and multifaceted objectives aimed at exploring and defining the role of technological sustainability in the context of modern manufacturing. The objectives are formulated to address complex questions and contribute to the understanding and implementation of sustainable practices in the manufacturing sector. The research revolves around the following main objectives:

1. **Exploitation of Industry 4.0 Technologies for Circular Eco-Design**: The first objective is to explore how advanced technologies, particularly those related to Industry 4.0, can be used to develop and apply circular eco-design models in the manufacturing sector. This involves the integration of intelligent data, life cycle assessment, and materials analysis techniques to create products that adhere to the principles of the circular economy and are efficient and environmentally sustainable.

2. **Conceptualization and Integration of Technological Sustainability**: A second crucial objective is to formulate a clear and operational definition of technological sustainability and study how it can be effectively integrated into existing frameworks of sustainable development. This entails the analysis of the interactions between technology and sustainability and the exploration of how technological innovations can contribute to promoting long-term sustainable practices, not only in production processes but also in the broader social and economic context.
3. **Quantitative Assessment of Technological Sustainability in Manufacturing Operations**: The final objective is to develop a model for the quantitative assessment of technological sustainability in manufacturing operations. This includes the creation of metrics and indices to measure the effectiveness of technologies in achieving sustainable goals, allowing such assessments to be integrated with analyses of the environmental, social and economic impact of the technologies employed. The aim is to provide a framework for manufacturing companies to continuously evaluate and improve their sustainable practices, guiding strategic and operational decisions.

In summary, the research aims to make a contribution to the existing literature on technological sustainability, providing new perspectives and tools for manufacturing companies. These objectives reflect a commitment to deepening the understanding of the relationship between technology and sustainability and guiding the manufacturing sector towards a more sustainable and responsible future, in line with emerging trends and challenges of our time.

1.2 OVERVIEW OF CHAPTERS

The thesis is divided into three main chapters, each addressing different aspects of technological sustainability in the manufacturing sector, providing a comprehensive and in-depth view of the subject.

- **Chapter 2 - Industry 4.0 and smart data as enablers of the circular economy in manufacturing: product re-engineering with circular eco-design**: This chapter explores the crucial role of Industry 4.0 technologies and smart data as facilitators of the circular economy in the manufacturing sector. The focus is on innovation in product design processes, particularly on how the principles of circular eco-design can be integrated into manufacturing through the use of these advanced technologies. The chapter provides a detailed analysis of the redesign of specific products, in this case in the Italian ceramics sector, demonstrating how the principles of the circular economy can be practically applied to improve the sustainability of products and processes.
- **Chapter 3 - Technological Sustainability or sustainable technology? Towards a multidimensional vision of sustainability in manufacturing:** The third chapter deepens the understanding of technological sustainability, asking fundamental questions about its nature and role in the manufacturing sector. A theoretical framework is developed to define and understand technological sustainability, examining how it can be effectively integrated into production practices. The chapter focuses on the development of a technological sustainability assessment model (Technological Sustainability Assessment, TSA).

- **Chapter 4 - Driving manufacturing companies towards industry 5.0: a strategic framework for Process Technological Sustainability Assessment (P-TSA):** Chapter four further extends the discussion on Technological Sustainability, introducing a strategic framework for the evaluation of Technological Sustainability of processes (Process Technological Sustainability Assessment, P-TSA). This chapter emphasizes the strategic implications of technological sustainability, exploring how it can act as a catalyst to guide companies towards Industry 5.0. It discusses in detail the development of a model for strategic evaluation of technological sustainability, examining how this model can be used to steer business decisions towards more sustainable practices.

2 INDUSTRY 4.0 AND SMART DATA AS ENABLERS OF THE CIRCULAR ECONOMY IN MANUFACTURING: PRODUCT RE-ENGINEERING WITH CIRCULAR ECO-DESIGN

The content of this chapter is the subject of a scientific publication:

Vacchi, M.; Siligardi, C.; Cedillo-González, E.I.; Ferrari, A.M.; Settembre-Blundo, D. Industry 4.0 and Smart Data as Enablers of the Circular Economy in Manufacturing: Product Re-Engineering with Circular Eco-Design. Sustainability 2021, 13, 10366. https://doi.org/10.3390/su131810366

2.1 ABSTRACT

The digital transformation of manufacturing firms, in addition to making operations more efficient, offers important opportunities both to promote the transition to a circular economy and to experiment with new techniques for designing smarter and greener products. This study integrates Industry 4.0 technologies, smart data, Life Cycle Assessment methodology, and material microstructural analysis techniques to develop and apply a circular eco-design model that has been implemented in the Italian ceramic tile manufacturing industry. The model has been initially adopted in a simulation environment to define five different scenarios of raw material supply, alternative to the current production one. The scenarios were then validated operationally at laboratory scale and in a pilot environment, demonstrating that a proper selection of raw material transport systems significantly improves the environmental performance of the ceramic product. Both the results of the laboratory tests and of the pre-industrial experiments have demonstrated the technological feasibility of the solutions identified with circular eco-design, enabling the re-engineering of the ceramic product as the fifth of the 6Rs of the circular economy.

2.2 INTRODUCTION

The manufacturing world has now taken up the challenge of the fourth industrial revolution, or Industry 4.0 [1], which is based on two foundations: automation [2] and data [3]. The new manufacturing paradigm of smart factories [4] is able to create environments that can adapt processes in real time to current needs through the elaboration of information based on the digital technologies of the Internet of Things [5]. Industry 4.0 pushes manufacturing industries to make their processes minimize waste: this transition to efficiency links Industry 4.0 with the goals of the circular economy [6]. This relationship becomes increasingly evident as companies define new strategies to achieve more ambitious environmental sustainability goals [7]. In fact, Industry 4.0 has a high potential to promote environmental sustainability because, unlike previous industrial revolutions, it is not accompanied by increased emissions or waste generation [8], but rather by increased operational efficiency [9] and organizational resilience [10]. To ensure successful optimization of manufacturing operations and improve production efficiency, an integrated MES (Manufacturing Execution System), ERP (Enterprise Resource Planning), and PLC (programmable logic controller) system was implemented. Thanks to these digital systems, it is possible to manage, monitor, and coordinate the execution of real-time physical processes providing feedback on process performance. In addition, to follow the environmental aspects into product and process development, the insertion of intelligent and interconnected sensors and PLCs in the production lines enables automated data collection for dynamic life cycle assessment (LCA) analysis [11]. The integration of simulation modelling with LCA increases predictive capacity in terms of environmental sustainability and circular eco-design, drastically reducing the reaction time of the company and its operational efficiency. Environmental impact assessment can also be combined with economic [12], social [13], or technological [14] impact assessment for a more complete view of the degree of sustainability. Alternatively, LCA, LCC, and S-LCA can be integrated with each other in a holistic methodological approach called Life Cycle Sustainability Assessment (LCSA) [15].

This efficiency can not only be determined in real time, but thanks to simulation environments where the physical and virtual worlds come together, it is possible to predict the behavior of production systems by anticipating errors and improving decision-making processes [16]. Thus, the simulation environment can improve efficiency in the exploitation of natural resources, energy, and other inputs, as well as in the development of closed-loop processes within the supply chain [17]. From an organizational point of view, Industry 4.0 leads to the transformation of the traditional factory into an effective smart factory [18] that, due to its intrinsic characteristics, is more efficient and therefore potentially more sustainable and able to implement the characteristic aspects of the circular economy [19], i.e., the so-called 6Rs: reduce, reuse, recycle, recover, redesign, and remanufacture [20]. To implement this change in corporate culture, however, it is necessary to innovate not only technologies, but also organizational paradigms and, therefore, business models [21]. Among these, circular business models [22] involve the development of products as service models [23], for which servitization becomes the way to extend their life cycle [24]. Extending the life cycle of products means keeping their value, and the resources used to manufacture them as long as possible within the economic loop [25]. Therefore, the impact level on the environment, economy, and society will be lower.

In a technologically advanced production framework, as smart factories are [26], the efficient use of production factors is already a given. Implementing at least four of the six R actions (reduce, reuse, recycle, recover) that characterize the circular economy is, therefore, easier. The real challenge for manufacturing companies is instead the redesign of products [27] and, therefore, of the entire value chain [28]. Eco-design [29], a methodology for product design in which sustainability issues (environmental, but also socio-economic) are considered during the product development process as an additional factor to those traditionally used for decision-making, can help manufacturing companies [30]. Eco-design simultaneously considers all the fundamental elements that make a product marketable, from its aesthetic characteristics to its functional performance, also evaluating all the phases of its production and distribution chain, in addition to the socio-economic and commercial factors [31,32]. In this life cycle approach (understood as the set of stages in the useful life of a product up to the final management of its waste), the product is not the final destination but a temporary state of matter and energy that can provide the consumer with a use and service benefit [33]. Therefore, from a circular economy perspective, eco-design is one of the main ways to re-engineer products so that they are high quality as well as ecological and socially responsible.

As previously pointed out, the literature evidences the benefits that manufacturing firms can reap from the synergistic relationship between digital technologies and the re-engineering of products [34], processes [35], and entire supply chains [36] in a circular economy perspective

[37]. However, having the right technologies is not always a sufficient and necessary condition to change the operational paradigm. In this regard, Zheng et al. [38] point out that there is still a lack of comprehensive research on the applications of Industry 4.0 enabling technologies in manufacturing life cycle processes. The digital transformation of industrial sectors also leads companies to address a new reality in which physical and virtual resources are integrated into a single production system. Among virtual resources, data are an important raw material able to produce organizational knowledge if manufacturing firms can turn Big Data (collected in an Industry 4.0 environment) into Smart Data (able to generate value). Lacam and Salvetat [39] argue that Smart Data cannot replace Big Data, but both domains work in a synergistic relationship through a virtuous cycle of data exploitation. These authors also emphasize that it is not necessary to mine a large amount of data to extract value from it. Even how to capture and exploit a smaller volume of useful data for a specific purpose has not yet been adequately explored in the literature. The latest literature explores the barriers to the circular economy and sustainability implementation in an Industry 4.0 environment [40]. However, empirical studies with quantitative approaches are lacking, and most studies are conceptual or qualitative [41].

This study, therefore, aims to fill the literature gap regarding the role played by smart manufacturing techniques in the adoption of circular economy practices [42], and how to transform part of Big Data into Smart Data [39], focusing on the re-engineering of the product and input sourcing system in an operational environment with a quantitative approach [41]. To achieve this goal, the study analyzes the manufacturing process of ceramic tiles for construction in Italy, a resource-intensive industry [43] with a complex input sourcing system [44], a high level of adoption of Industry 4.0 digital technologies [45,46], and characterized by the implementation of internationally recognized environmental best practices [11]. From the environmental point of view, the Italian ceramic industry, thanks to continuous investments, can count on more sustainable technologies with pollution levels well below the legal limits and on the Best Available Techniques (BATs) [47].

Based on what is stressed above, we can formulate the following Research Question:

RQ: Is it possible to validate through a feasibility study the hypothesis that Industry 4.0 digital technologies can work as an enabling operating environment for the Circular Economy?

The chapter is structured as follows. Section 2.3 outlines the research methodology with a statement of the techniques applied. In Section 2.4, the experimental part is explained, namely the circular eco-design in a simulation environment, the tests at laboratory scale, and finally, the experimentation in the industrial environment. In addition, the potential of the obtained results is also discussed. Finally, conclusions are drawn in Section 2.5.

2.3 MATERIALS AND METHODS

2.3.1 Industrial Background and Methodological Design

The ceramic tile manufacturing industry is a sector that requires significant amounts of natural resources (raw materials) and energy (methane gas and electricity) [11]. Italian companies use, on average, about 20 kg of a mix of raw materials called ceramic body to manufacture 1 square meter of tiles [48]. In 2020, the Italian ceramic industry produced 344.3 million square meters of tiles [49], so the natural raw material requirement was:

$$344.3 \text{ million m}^2 \times 20 \text{ kg/m}^2 = 6.886 \text{ million tons} \quad (1)$$

The main material supply sources of the Italian ceramic industry are located in Turkey (sodium feldspar), Ukraine (ball clays), Germany (ball clays), and, to a lesser extent, in Italy (potassium feldspar, kaolinitic volcanic clays, and sands) [44]. Recent studies carried out in the same industry have shown that the environmental impact of the finished product is attributable not only to the production process in the strict sense but also to the raw material sourcing system. Thus, sourcing logistics offers significant opportunities for improving environmental criticality [11].

This research was conducted with the methodological approach of the single in-depth case study [50] considered appropriate to draw inductive inferences to gain a better understanding of the re-engineering potential phenomenon [51]. Moreover, this methodological approach is the one most widely employed in the literature in studies related to the operating environment of Industry 4.0 [52–57]. As a case study, a company was selected among the TOP 10 Italian producers of ceramics and among the TOP 5 for economic performance, which produces the tile type of porcelain stoneware [58]. The same company has already been successfully engaged as a case study in research in the field of sustainability management [46,59,60].

In this study, the raw material sourcing system is optimized by re-engineering processes and materials supported by eco-design to achieve circular economy goals and improve the environmental performance of the ceramic product. In particular, the activity is directed to reduce the distances between the factory and mines and consider more ecological transport systems. The aim is to minimize the environmental impact while respecting the constraint of technological feasibility through the reformulation of the compositions of ceramic bodies by maximizing the amount of local or European raw materials to the detriment of non-EU ones. The digital technologies of Industry 4.0 enable this development. Thanks to the process data collected in real-time in the factories, it is possible to build a predictive model of alternative scenarios’ environmental and technological performance.

2.3.2 Environmental Assessment and Eco-Design

According to Directive 2009/125/EC [61], eco-design integrates environmental aspects into product design to improve the product’s environmental performance during its life cycle. The key methodology of eco-design is the Life Cycle Assessment [62], a tool that investigates and evaluates the environmental impacts of a product or service during all phases of its existence: extraction, production, distribution, use, and end of life. The framework documents for conducting a Life Cycle Assessment are the international standards ISO 14040 (principles and framework for LCA) and ISO 14044 (requirements and guidelines for LCA) [63]. In this study, eco-design, based on LCA, consists of performing consecutive studies on the current composition of ceramic body by making variations in resource inputs and estimating the different environmental impacts until the formula with the most negligible impact is identified. However, unlike the traditional LCA approach that is based on the analysis of historical data—for example, considering the previous year than the time when the study is conducted—in this research, we will exploit the potential of Industry 4.0 for the collection of process data in real time. This means that a dynamic, and not static, eco-design will be conducted, based on information about consumption and emissions collected at the very moment they are realized thanks to digital technologies. In this way, it is possible to give the modeling carried out with eco-design an even more prospective vision from the present to the future, which overturns the traditional approach of eco-design that is based instead on the scheme from the past to the present.

2.3.3 Sample Preparation

Table 1 shows the six different ceramic body compositions, where C1 was used as starting composition.

Table 1 - Raw materials [64,65] *(wt.%) composition of the ceramic body mixtures.*

Raw materials (wt.%)	C1	C2	C3	C4	C5	C6
Ukraine Clay	30	25	20	15	10	/
German Clay	15	20	20	25	25	30
Turkish Na-Feldspar	37	35	30	25	20	20
Italian Clay	/	/	10	15	20	30
Italian K-Feldspar	10	10	10	10	15	15
Italian Feldspar Sand	/	/	10	10	10	5
Italian Quartz Sand	8	10	/	/	/	/
Extra-EU raw materials (wt.%)	67	60	50	40	30	20

The sample preparation route for laboratory samples can be summarized as follows: dry raw materials, pre-grinded by a dry route to a particle size <100 µm, were carefully weighted (Bel Engineering M120A Model Analytical balance, ±0.0001 g) and wet-milled in a porcelain jar (500 g of dry powder mixture and 270 g of deionized water) using alumina balls (500 g, mixture of sizes with diameters in the range 9–18 mm) as grinding media. Tripolyphosphate (0.75 g in 500 g of dry powder mixture) was added as a deflocculant. Following milling, the slip was dried at 110 °C, and the resulting powder cake was disaggregated and moisturized (6 wt.%). Disc-shaped ceramic bodies with a diameter of ca. 50 mm were obtained by dry-pressing of the moist powder (40 MPa). The samples of ceramic bodies prepared in this way were dried at 110 °C and then fired in a roller kiln at a maximum temperature of 1220 °C with a 40 min cycle.

2.3.4 Sample Characterization

Chemical analyses of the mixtures of the raw materials were performed by X-ray Fluorescence Spectroscopy (XRF) on fused glass discs using a ARL 9400 XP instrument. Before sample fusion, the Loss on Ignition (LOI) was determined gravimetrically following roasting at 1050 °C for 2 h.

Quantitative phase analyses of raw materials mixtures and fired ceramic bodies were performed using X-ray powder diffraction (XRPD) data. Data were collected using a θ/θ diffractometer (PANalytical, CuKα radiation) equipped with a fast real-time multiple strip detector (step scan of 0.0167°2θ). Divergence and anti-scattering slits of 0.5° were included in the incident beam optics with 0.04 rad soller slits and a beam mask of 15 mm. The diffracted beam passed through an anti-scatter blade, a 0.04 rad soller slit and a Ni-filter. The wet-grinded and moisturized powder mixtures used to prepare ceramic bodies were analyzed following equilibrating with ambient conditions. Instead, fired bodies were first ball-milled in an agate jar for 20 min followed by drying (110 °C, >2 h). The dry powder was subsequently mixed with a standard (10 wt.% NIST 676a) before data collection. The addition of an internal standard allowed us to perform a full quantitative phase analysis, including the amorphous fraction, using the Rietveld method and rescaling following a previously described procedure [66]. The refinements were accomplished with the GSAS-EXPGUI package [67,68]. The use of an internal standard with certified unit cell also abled the determination of absolute unit cell parameters of the phases.

Particle sizing of the mixtures of the raw materials was performed by laser diffraction using a Mastersizer 2000 (Malvern Instruments) equipped with a system for measuring in a liquid (Hydro 2000S). Water was used as a carrier fluid for these analyses. Sintering of the ceramic bodies was followed in situ using Optical dilatometry (Misura ODHT-HSM instrument, model 1600-80, Expert System Solutions) in the temperature range 25–1400 °C using a heating rate of 10 °/min. The measurement output was the dimensional variation of a parallelepiped (15 × 5 × 5 mm^3), carved from the disc-shaped dry ceramic body, as a function of temperature.

Thermogravimetry in conjunction with Differential Scanning Calorimetry (TG/DSC) was performed using a Netzsch STA 429 instrument. Data were recorded in an air atmosphere in the temperature range 25–1400 °C using a heating rate of 10°/min.

2.4 RESULTS AND DISCUSSION

2.4.1 Circular Eco-design

Within the 6R methodology, the ceramic industry is characterized by very efficient production processes despite the need to use significant amounts of raw materials and energy resources. The result obtained by these industries is already oriented to rationalizing production resources, completely reusing both processing waste and industrial water. With this starting base, already performing well from the environmental point of view, as also highlighted in the literature [11,47], as an area of improvement and in a circular economy perspective, this research focused on the R of the redesign of the ceramic product to make it even more environmentally performing. In this case, the redesign has been executed as re-engineering, i.e., applying the digital technologies of the smart factory to make the ceramic product even more sustainable.

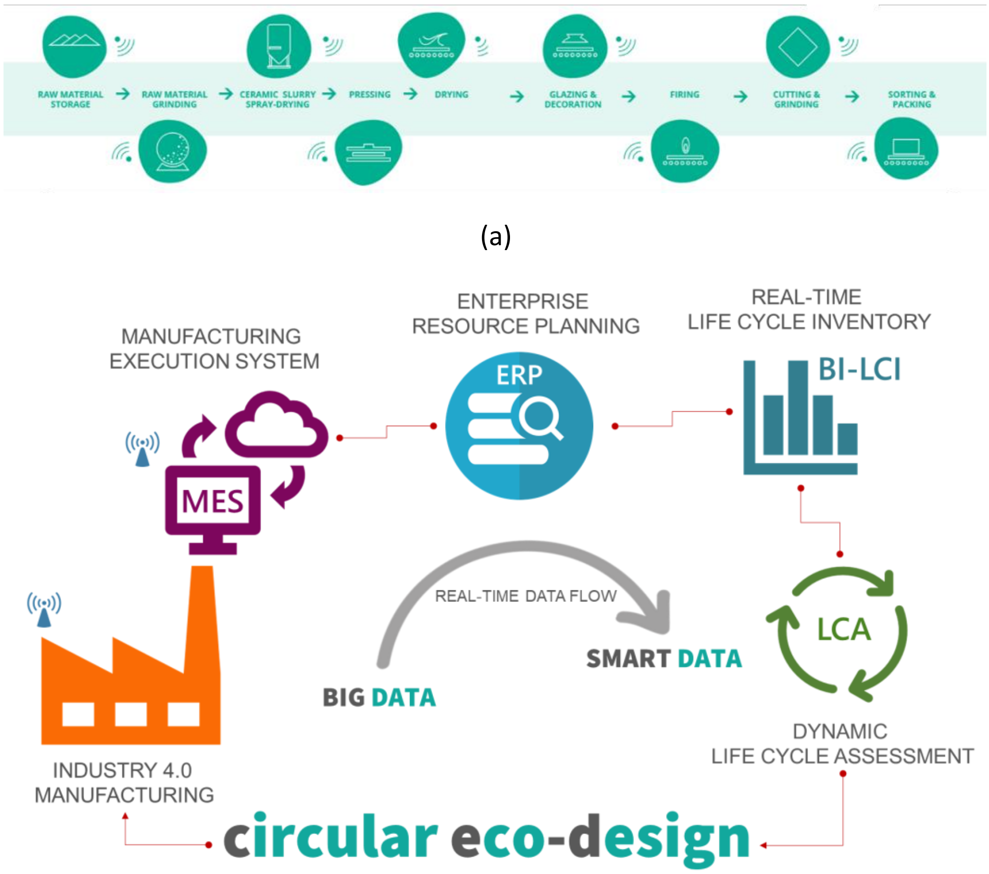
A ceramic porcelain stoneware body is mainly made up of three main categories of raw materials that give the product different technological properties: clays (plasticity during pressing) [65], feldspars (glass formation and fusibility during firing) [69], and sands and feldspathic sands (formation of crystalline structure during firing) [70]. The eco-design phase began with the production composition labeled C1 in Table 1 to formulate replacement compositions. The eco-design in the simulation environment foresaw a progressive decrease in Ukrainian clay and Turkish sodium feldspar, to the advantage of German clay and other domestic raw materials that are closer at the production plant. In fact, the transportation system is different depending on the origin of raw materials:

- Ukrainian clay: train + ship + truck;
- Turkish feldspar: truck + ship + truck;
- German clay: truck + train + truck;
- Domestic raw materials: truck only.

From an environmental point of view, German clay has an advantage because its transportation is mostly by train that is a lower impact transport system than truck [71], and the distance covered is shorter than the Ukrainian clay, while domestic raw materials benefit from the shorter distance between mine and factory.

In order to confirm these hypotheses, the Dynamic Life Cycle Assessment system already developed by Ferrari et al. [72] and based on the real-time collection of process data thanks to the IoT technologies of Industry 4.0 was used.

The ceramic tile manufacturing process consists of several steps that are illustrated in Figure 1a. Raw materials from the mines are stored in the warehouse waiting to be mixed according to the composition of the body. The mixture is introduced in a cylindrical mill containing silica pebbles as grinding bodies and water as grinding vehicle in a solid/liquid ratio of 66%/33%. The milled mixture, in the form of a solid/liquid suspension called slurry, is dried and converted into a granular powder through a vertical spray dryer. The powder is then pressed to form ceramic tiles which, after drying to remove residual moisture, are glazed and digitally decorated with special inks. The glazed and decorated products are then transferred to the roller kiln for firing, after which the products can be cutting and possibly lapped as a final finishing step. Finally, the tiles are selected on the basis of their geometric and aesthetic conformity and packaged to be sent to distributors. Each of the described phases has a system of sensors connected to each other through cabling and/or Wi-Fi network, which collect process data to send them to the factory Manufacturing Execution System (MES). The new circular eco-design model depicted in Figure 1b leverages the vast amount of process-related data (Big Data) and collected through line sensors connected to the MES that links the factory with Enterprise Resource Planning (ERP). A Business Intelligence (BI) application selects only those data contained in the ERP that are critical (Smart Data) to carry out the real-time Life Cycle Inventory (BI-LCI). The LCI is the basis for performing environmental impact assessment with Dynamic Life Cycle Assessment (LCA).



(a)

(b)

Figure 1 - (a) Ceramic tile manufacturing process phases and (b) integration of Industry 4.0, Smart Data and Dynamic LCA in the new circular eco-design model (modified from the model proposed by [65]*).*

The functioning of the dynamic environmental assessment system is shown in Figure 1. The different design scenarios, corresponding to the compositions from C1 to C6 shown in Table 1, were tested in a simulation environment using process data collected in real time at the factory. In other words, it was simulated to produce a batch of 100,000 m2 of tiles for each type of ceramic body, keeping the other process parameters fixed. Thanks to the Dynamic Life Cycle Assessment, the environmental impact was predicted for each composition. This phase of the study was enabled by the digital technologies of Industry 4.0 which allow us not only to collect processed data, but also to process it, in real time. Therefore, the manufacturing model of Industry 4.0 enables the smart exploitation of the large amount of production data to perform a dynamic inventory analysis and environmental assessment in the sourcing and manufacturing phases of the product life cycle.

The results of the Dynamic Life Cycle Assessment are detailed in Table 2.

Table 2 - Environmental impacts of 1 m^2 of ceramic tiles (19.9 kg/m^2).

Product Life Cycle Stages	Composition	GWP	ODP	AP	EP	POCP	ADPE	ADPF	TOTAL DAMAGE
		[kg CO2 eq.]	[kg CFC-11 eq]	[kg SO2 eq.]	[kg (PO4) 3- eq.]	[kg C2H4 eq.]	[kg Sb eq.]	[MJ]	[kPt]
Raw materials and chemicals sourcing (Modules A1–A2)	C1	3.49	1.91 × 1015	1.95 × 10-2	5.51 × 10-3	6.23 × 10-4	6.84 × 10-5	4.49 × 101	1.50 × 10-6
	C2	3.32	4.95 × 10-7	1.85 × 10-2	5.25 × 10-3	6.09 × 10-4	6.56 × 10-5	4.26 × 101	1.43 × 10-6
	C3	3.05	4.62 × 10-7	1.65 × 10-2	4.74 × 10-3	5.63 × 10-3	6.37 × 10-5	3.95 × 101	1.32 × 10-6
	C4	2.81	4.25 × 10-7	1.50 × 10-2	4.35 × 10-3	5.39 × 10-4	6.08 × 10-5	3.64 × 101	1.22 × 10-6
	C5	2.59	3.94 × 10-7	1.33 × 10-2	3.89 × 10-3	5.09 × 10-5	5.88 × 10-5	3.38 × 101	1.12 × 10-6
	C6	2.32	3.53 × 10-7	1.15 × 10-2	3.41 × 10-3	4.80 × 10-4	5.60 × 10-5	3.05 × 101	1.01 × 10-6
Tiles manufacturing (Modules A3)	C1–C6	7.21	2.07 × 1015	8.34 × 10-3	1.71 × 10-3	6.68 × 10-4	1.03 × 10-5	1.10 × 102	2.01 × 10-6
Tiles transport and installation Modules (A4–A5)	C1–C6	5.75	5.48 × 1014	2.13 × 10-2	4.91 × 10-3	1.03 × 10-3	7.79 × 10-5	5.45 × 101	1.93 × 10-6
Tiles use (Modules B1–B7)	C1–C6	1.51	7.59 × 1014	7.57 × 10-3	5.81 × 10-3	8.08 × 10-4	4.47 × 10-5	1.80 × 101	2.10 × 10-6
Tiles end-of-life	C1–C6	0.04	1.39E × 1013	4.44 × 10-4	7.37 × 10-5	1.53 × 10-5	1.85 × 10-6	9.25 × 10-1	3.37 × 10-8

As shown in Figure 2, the environmental results of the different Product Life Cycle Stages are the same for the considered compositions except for raw materials and chemical sourcing because of the influence of the different scenarios of raw materials supply.

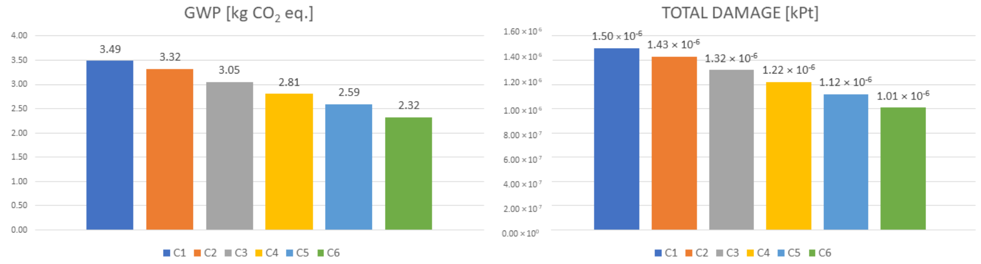
The Dynamic Life Cycle Assessment is a model based on the Ecoinvent 3.6 database [73] within the Simapro 9.1.1 [74] calculation code, which integrates a detailed midpoint analysis with an aggregated endpoint analysis. The impacts assessment was conducted using the CML-IA baseline [75] method for midpoint indicators and the IMPACT 2002+ method [76], to evaluate the aggregate endpoint indicator "Total Damage". The midpoint analysis uses the following impact categories: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Abiotic Depletion Potential for Non-fossil Resources (ADPE), and Abiotic Depletion Potential for Fossil Resources (ADPF). The total damage indicator is calculated by normalizing and weighting the results obtained for each damage category (Human Health, Climate Change, Resources, and Ecosystem Quality), which allows us, through a single value expressed in environmental points (kPt), to compare the different scenarios.

In accordance with ISO 14040 and ISO 14044, 1 m^2 of porcelain ceramic tiles was chosen as the functional unit to conduct the impact assessment. At the same time, the system boundaries were set from cradle-to-grave. The mass of the functional unit is 19.9 kg/m^2. Table 2 shows the results obtained for each ceramic body composition by stage of the life cycle. In detail, the phase of extraction of raw materials and production of chemical compounds and their transport to the ceramic tile factory is followed by the manufacturing phase (body grinding and spray-drying; pressing and drying; glaze grinding, glazing and decoration; firing; finishing; sorting and packaging) and then the transport to the building with installation, use, and end of life that closes the cycle.

Following the new standard EN 15804:2012+A2:2019 [77] that regulates the development of Environmental Product Declarations (EPDs) for the construction sector, the table shows the mandatory modules for each phase of the life cycle: the production processes of energy and natural resources (A1); the transport of resources to the factory (A2); the production process of the tiles (A3); the transport of the ceramic product from the production plant to the building site (A4); the installation phases of the tiles (A5); the period of use (B1), maintenance cleaning

(B2); repair, replacement and refurbishment of the product (B3, B4, B5); finally, the use of energy (B6) and water (B7) for the operation of the building. Similarly to what occurs in EPD documents, in Table 2, the modules are aggregated to represent the main phases of the ceramic product life cycle.

The different scenarios considered in this study change how the raw materials that make up the ceramic body are sourced, so these changes' effect on environmental impact is only evident in modules A1–A2. Therefore, the other phases of the life cycle and the corresponding modules remain unchanged as basic assumptions for eco-design. Figure 2 presents the trends of the midpoint indicator GWP and the endpoint indicator Total Damage for the supply modules (A1–A2).



(a) (b)

Figure 2 - Variation of the indicators Global Warming Potential (a) and Total Damage (b) related to modules A1–A2 of different compositions of ceramic bodies.

GWP is a crucial indicator because it is closely related to the use of fossil fuels in transport systems, while Total Damage, as an endpoint indicator, provides a holistic estimate of environmental damage. The values assumed by all midpoint indicators in modules A1–A2 predict that the progressive change in the supply system towards the use of raw materials closer to the manufacturing unit or employing a more ecological transport system such as the train significantly reduces environmental impact. This is well evidenced by the endpoint indicator (Total Damage, Figure 2b), which decreases progressively from composition C1 to C6. In this forecast, the GWP drops by 33.6% and the Total Damage by 32.4% when switching from the old production composition (C1) to the new (C6) with potentially eco-friendly raw materials. These predictive results provided by dynamic eco-design, using production data collected in real time with Industry 4.0 technologies, show that a different way of selecting raw materials significantly improves the environmental performance of the ceramic product. The results obtained provide the environmental validation to carry out the re-engineering of the raw material sourcing system. However, to implement the real re-engineering of the process, empirical verification is needed to show how much the different compositional solutions are technologically feasible.

2.4.2 Ceramic Bodies Testing

Mixtures of the different green ceramic bodies corresponding to the compositions shown in Table 1 were screened for mineralogical and chemical characterization. Tables 3 and 4 show the mineralogical and chemical compositions of the raw materials and ceramic bodies, respectively.

Table 3 - Mineralogical composition of the green ceramic bodies.

Body Composition	Main Mineralogical Phases (wt.%)					
	Quartz	Kaolinite	Illite/Mica	Plagioclase	K-Feldspar	Calcite
C1	27.4 ± 0.2	19.1 ± 0.4	11.0 ± 0.5	38.8 ± 0.3	3.2 ± 0.4	0.4 ± 0.1
C2	30.9 ± 0.2	21.9 ± 0.3	7.1 ± 0.3	36.0 ± 0.3	3.7 ± 0.7	0.4 ± 0.1
C3	36.7 ± 0.2	13.1 ± 0.4	10.3 ± 0.3	38.5 ± 0.3	1.4 ± 0.2	-
C4	32.3 ± 0.2	13.1 ± 0.5	16.0 ± 0.6	30.8 ± 0.3	6.9 ± 0.4	0.8 ± 0.1
C5	38.9 ± 0.2	13.1 ± 0.4	12.1 ± 0.4	26.1 ± 0.3	8.9 ± 0.2	0.9 ± 0.1
C6	33.4 ± 0.2	12.8 ± 0.3	16.5 ± 0.3	28.4 ± 0.2	8.4 ± 0.2	0.5 ± 0.1

The clay fraction is composed of kaolinite and illite, whereas the melt minerals are plagioclase with minor amounts of K-feldspars. Quartz is present in various amounts, ranging from ca. 27–39 wt.%. The good thermal stability of quartz during the firing cycle, with only partial melting, renders this mineral suitable as a ceramic backbone [78]. The successive replacement of extra-EU raw materials with raw materials coming from within the European Union leads to an increased quartz content, a more illitic character of the clay fraction, and a decreased plagioclase/K-feldspar ratio (Table 3) [78].

These mineralogical variations are reflected in the chemical compositions (Table 4). The various amounts of K-bearing minerals, i.e., illite/mica and K-felspars, present in the bodies determine important variations mainly in the concentration of alkali metal oxides.

Table 4 - Chemical composition of the ceramic bodies.

Oxide (wt.%)	Body Composition					
	C1	C2	C3	C4	C5	C6
SiO_2	66.68	67.27	67.74	68.24	69.11	69.79
Al_2O_3	20.56	20.05	19.51	19.00	18.16	17.35
Fe_2O_3	0.83	0.86	0.90	0.98	1.02	1.09
TiO_2	0.77	0.76	0.69	0.68	0.61	0.56
MgO	0.46	0.45	0.44	0.43	0.41	0.38
CaO	0.90	0.94	0.62	0.58	0.62	0.61
Na_2O	4.00	3.81	3.49	3.05	2.60	2.60
K_2O	1.95	1.93	2.58	2.75	3.14	3.22
LOI	3.93	4.00	4.12	4.35	4.36	4.36

Compared to the production composition (C1), which presents a Na_2O/K_2O ratio strongly unbalanced towards sodium (Na_2O/K_2O = 2.05), the alternative scenarios move towards a rebalancing of this ratio due to the reduction in imported sodium feldspar in the compositions (Na2O/K2O is 1.97, 1.35, 1.11, 0.83, and 0.81 for C2, C3, C4, C5, and C6 compositions, respectively). Technological tests will have to demonstrate the feasibility of this change in terms of sintering level, i.e., it will have to be verified that the porosity of the ceramic body complies with the requirements set by current standards. The SiO_2/Al2O_3 ratio (SiO_2/Al2O_3 = 3.24 for C1) also increases progressively in C2–C6 compositions (SiO_2/Al_2O_3 is 3.36, 3.47, 3.59, 3.81, and 4.02 for C2, C3, C4, C5, and C6 compositions, respectively) and this could have repercussions on linear shrinkage during the firing phase of the tiles. Likewise in this case, the technological tests must ascertain the feasibility of these variations.

The six compositions (C1–C6) were then milled as described in Section 2.3.3, and particle size analyses were conducted on the powders obtained.

Figure 3 shows the grain size distributions of the ceramic body mixtures.

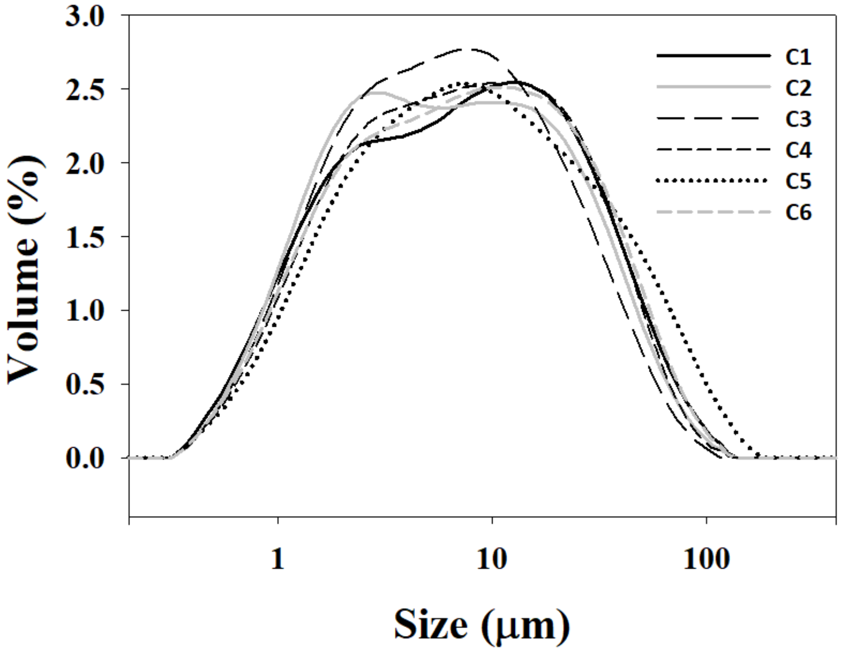


Figure 3 - Grain size distributions of the ceramic body C1-C6 mixtures measured by laser diffraction.

The distributions are rather similar, indicating comparable grindabilities. The ranges are broad, going from the lower detection limit of the laser diffraction instrument (0.01 µm) up to ca. 100 µm with values of D(90), D(50), and D(10) being in the ranges 1.3–1.5 µm, 6.4–8.2 µm, and 29–47 µm, respectively. These results are in line with those generally found for wet-grinded ceramic powders for the manufacturing of porcelain stoneware tiles [79].

2.4.3 In Situ Thermal Analyses

Thermal expansion tests were then performed on the same powders as the milled bodies. Figure 4 shows expansion (%) as a function of temperature obtained by dilatometry experiment of the dry bodies.

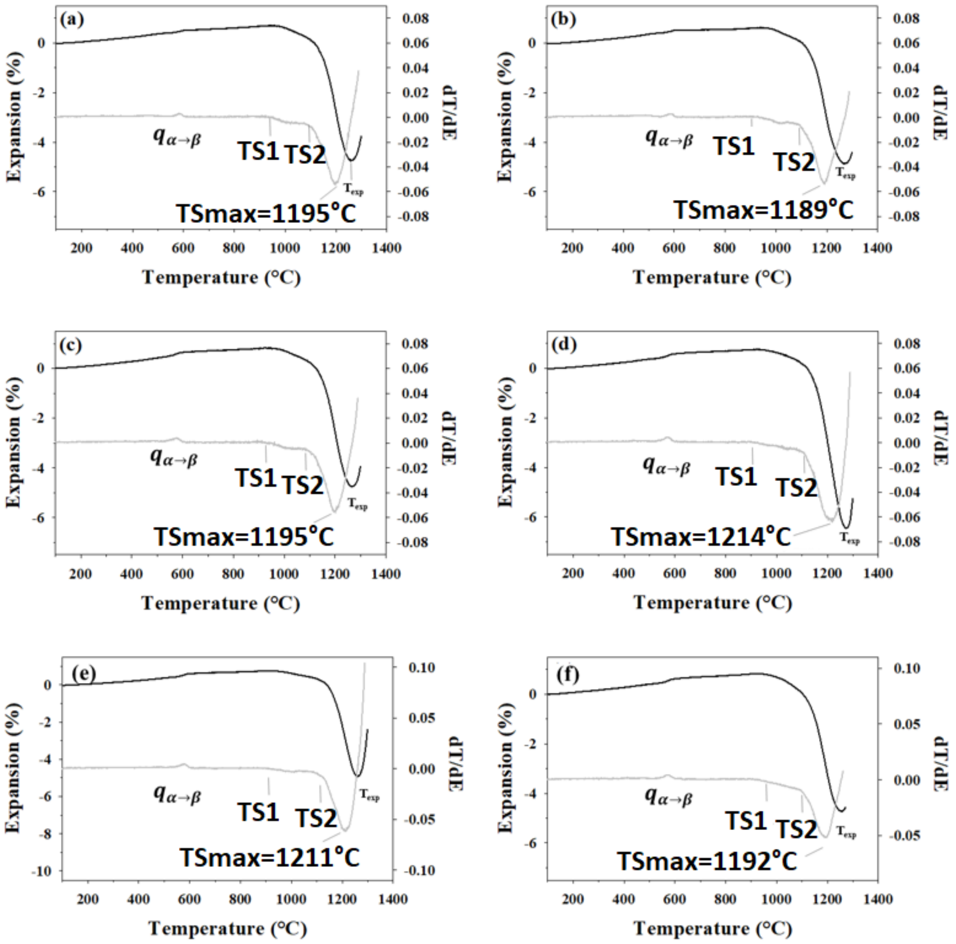


Figure 4 - Expansion (%) (black curves) and dT/dE (gray curves) as functions of temperature obtained by dilatometry experiment of the dry-pressed ceramic bodies. Curves (a)-(f) correspond to Expansion and dT/dE curves of body compositions C1-C6, respectively.

For comparison, the first derivative curves are also depicted. Apart from the sudden expansion in the transition range of quartz (α→β) around 573 °C, a positive linear trend is observed up to about 950 °C followed by a first small contraction step (TS1 in Figure 4). The main contractions step (TS2) starts at ca. 1100 °C and is assigned mainly to viscous sintering triggered by the melting of the feldspars. The maximum sintering rate, indicated by the minimum point of the first derivative curve, is found at a temperature of ca. 1200 °C. In order to shed light on these events, TG/DSC measurements were performed; for example, the results for composition C4 are shown in Figure 5.

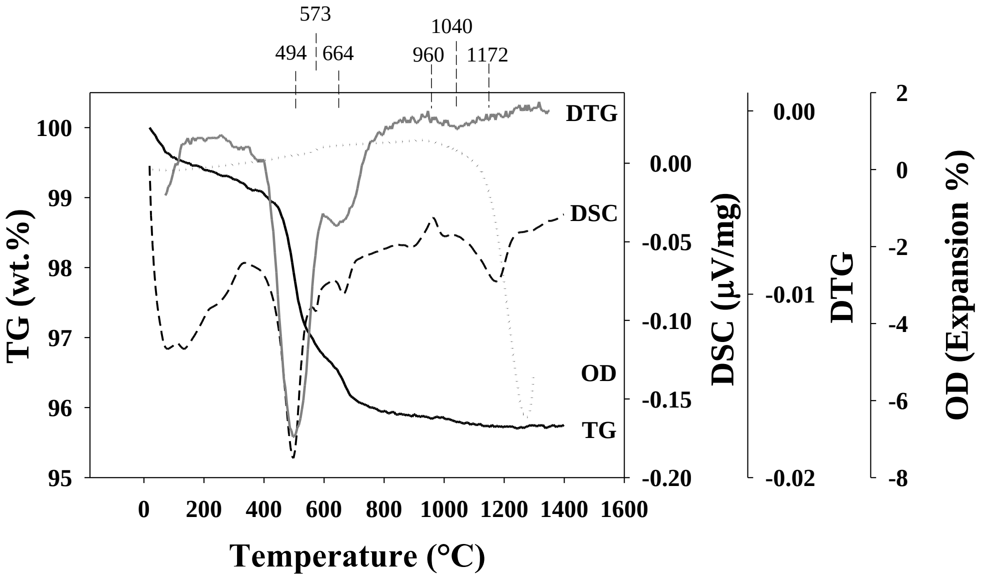


Figure 5 - TG/DSC results for composition C4. For comparison, the expansion curve obtained from dilatometry measurements (also shown in Figure 4d) is also displayed.

For comparison, the expansion curve obtained from optical dilatometry is also displayed. The following dehydration and possibly also decomposition of organic matter naturally present in the raw materials and/or added to the slip as dispersant (endothermic band at T< ca. 340 °C), two important endothermic events are observed at 494 °C and 665 °C which are assigned to dehydroxylation of kaolinite and illite, respectively [80]. The α→β transition of quartz is also evident at 573 °C. An exothermic peak is observed at 960 °C and is assigned to the crystallization of primary mullite from the dehydroxylated clay minerals. The endothermic peak at 1176 °C is assigned to the melting of feldspars. The TG/DTA curves show a minor weight loss in the range 960–1170 °C. A trace amount (<1%) of calcite is present in the starting compositions (see Table 3) but is expected to decompose at a lower temperature (<900 °C). Instead, this event is assigned to dehydroxylation of mica, structurally similar to illite but known to display considerably higher dehydroxylation temperature. Rodriguez-Navarro et al. [81] studied the temperature-induced breakdown of muscovite and found that temperatures higher than 900 °C triggered dehydroxylation followed by partial melting and crystallization of mullite. The authors observed bubbles of trapped water molecules (TEM analyses) due to overlapping of dehydroxylation and melting, only developing under fast-firing conditions such ceramic firing. The phase transitions/transformations observed by TG/DTA are reflected in the dilatometry curve (see Figure 4). The volume expansion due to the phase transition of quartz is evident. The first contraction step (i.e., TS1 in Figure 4) is in concomitance with the crystallization of primary mullite and possibly also to the dehydroxylation of mica (see Figure 5). The endothermic peak assigned to feldspar melting perfectly matches the major contraction in the optical dilatometry curve due to viscous sintering. It is interesting to observe that the high-temperature weight loss assigned to dehydroxylation of mica overlaps with the formation of a viscous melt (Figure 5). This should further contribute to the formation of closed porosity triggered by water molecules entrapped in the viscous melt.

2.4.4 Microstructural Properties of the Fired Ceramic Bodies

The in situ sintered samples, after thermal analysis, were submitted to microstructural analysis to highlight the effect of thermic treatment on the ceramic bodies. Figure 6 shows the quantitative phase analyses (XRPD and Rietveld-RIR) of the fired ceramic bodies.

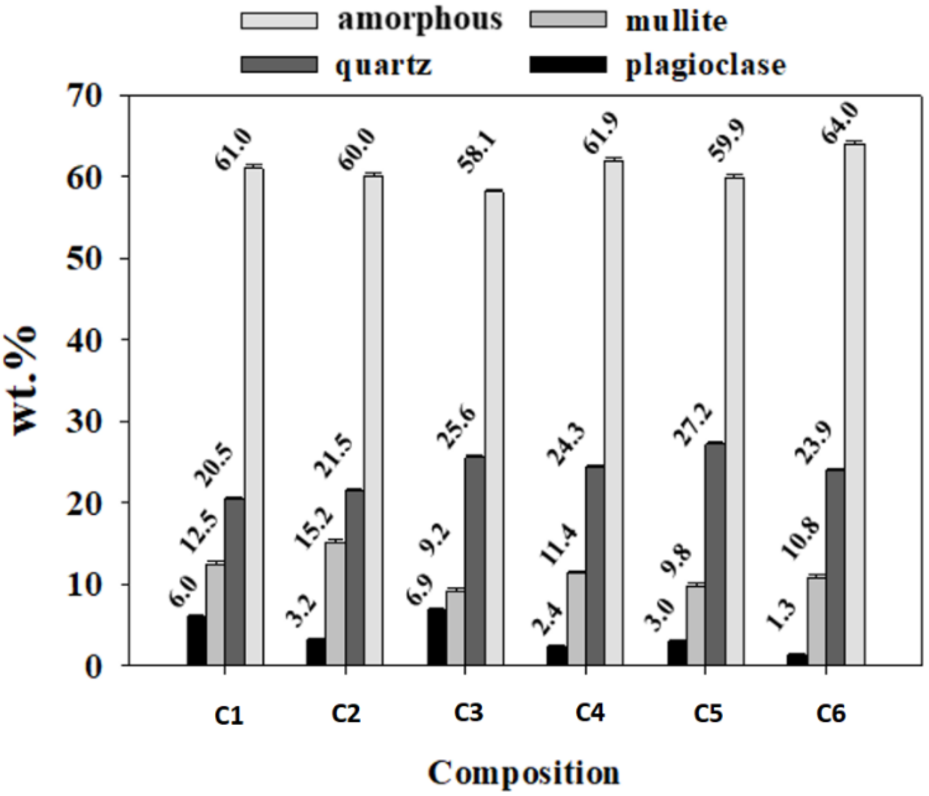


Figure 6 - Results from full quantitative phase analyses (XRPD and Rietveld-RIR) of the fired ceramic bodies.

The Rietveld refinement output of the fired ceramic body obtained from composition C6 is shown in Figure 7 for demonstrative purpose.

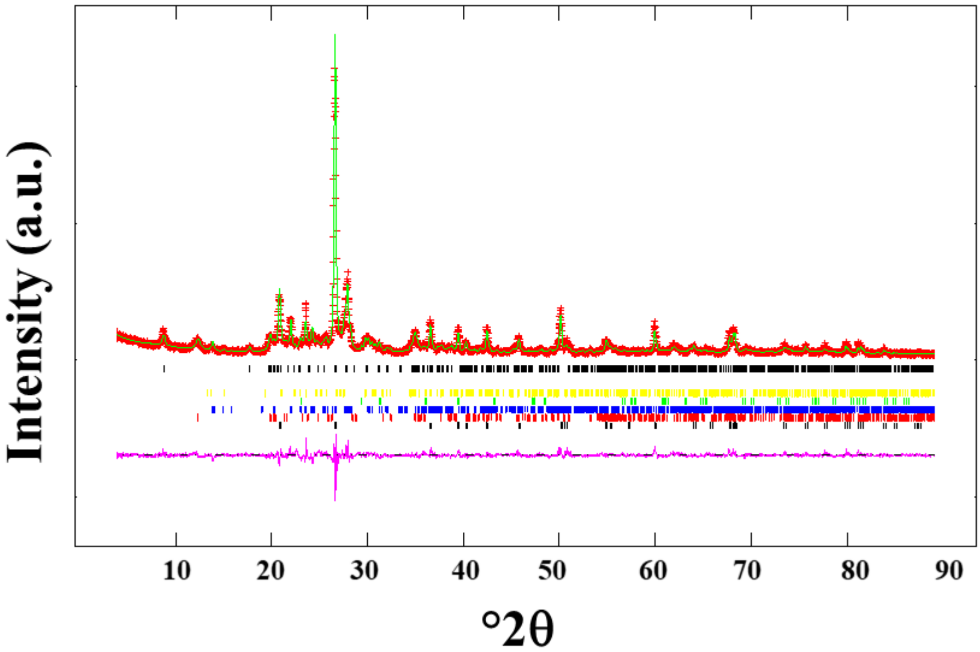


Figure 7 - Rietveld refinement output for composition C6. The observed, calculated (red, above), and difference (pink, down) curves are depicted. Starting from the top, the following phases are indicated with tick marks: illite/mica; K-feldspar; calcite; plagioclase; kaolinite; quartz. "a.u" identifies the number of photons counted by the detector of the XRD, "°2ϑ" stands for the angle between the detector and the electron beam [82].

As shown in Figure 6, the vitreous phase is by far the most abundant phase ranging from 60–64 wt.%. The amount of residual quartz (20–27 wt.%) is linearly proportional with the quantity present in the starting mixtures, although about 30 wt.% lower due to partial melting during firing. The presence of mullite (9–15 wt.%) is correlated to the amount of kaolinite and illite/mica in the starting compositions. Some residual feldspars (1–7 wt.%) are also detected. Zanelli et al. [78] performed full quantitative phase analyses of 40 industrial tiles from various manufacturers in addition to 53 tailored compositions processed in a pilot plant. The authors found that the amorphous content lies in the range 40–75 wt.%, whereas the contents of quartz, mullite, and feldspars are in the ranges 11–31 wt.%, 2–15 wt.%, and 0–15 wt.%, respectively. Taking these values as references, we can thus conclude that the phase compositions of the ceramic bodies investigated here are typical for porcelain stoneware.

The chemical composition and the phase composition of the fired ceramic bodies were used to determine the vitreous phase's chemical composition by subtracting the crystalline phases' contribution from the overall chemical composition. The results are shown in Table 5.

Table 5 - Chemical composition amorphous fraction.

Oxide (wt.%)	C1	C2	C3	C4	C5	C6
SiO_2	70.8	71.7	70.0	70.1	70.1	71.2
Al_2O_3	17.3	16.2	17.5	15.8	16.0	15.4
Fe_2O_3	0.8	1.1	0.9	1.9	1.4	1.7
TiO_2	0.8	1.1	1.0	1.0	1.0	0.8
MgO	0.4	0.6	0.4	0.7	1.0	0.6
CaO	1.2	1.2	0.7	1.6	1.9	1.0
Na_2O	5.8	5.7	6.5	4.0	3.9	3.8
K_2O	3.0	2.4	3.0	4.9	4.6	5.5

For these calculations, the chemical compositions of residual feldspars were assumed to be that of pure Na-feldspar ($NaAlSi_3O_8$) and K-feldspar ($KAlSi_3O_8$). Instead, the stoichiometry of mullite was determined to be $3Al_2O_3 \cdot 2SiO_2$ by using the refined a-axis length and its relation to the mol% Al_2O_3 [83]. The resulting chemical composition of the glassy phase was subsequently used to calculated the shear viscosity as a function of temperature using the model proposed by Giordano et al. [84]. The applicability of this model was recently verified by Conte et al. [85].

Figure 8 shows the resulting curves as well as the specific values at maximum firing temperature. The trends observed for the different compositions are similar, with values at maximum firing temperature ranging from 4.87–5.06 log10 Pas. Conte et al. [85] reported that viscous sintering in porcelain stoneware tiles is accomplished with a glassy phase with a viscosity of about 4.5–5.4 log10 Pas, which is perfectly in line with our observations. The trend of melt viscosity as a function of temperature was obtained by applying the model described by Giordano et al. [84]. The calculated viscosity at the maximum firing temperature is inserted for comparison. Although these are complex mixtures of oxides, it is possible to provide a qualitative explanation for the viscosity values obtained by correlating them with the composition of the six formulations. C2 and C6, which have the highest viscosity values, contain a greater amount of silicon, behaving as a glass former. The higher amount of sodium present in C3, on the other hand, returns a more open and weak structure, thus behaving as a glass modifier and lowering the viscosity of the system.

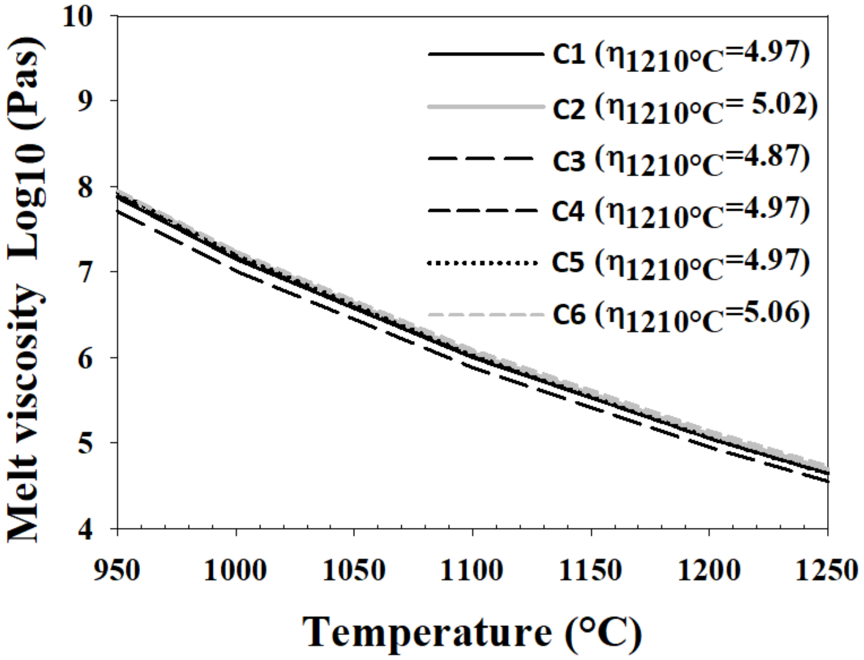


Figure 8 - Melt viscosity of the ceramic bodies.

2.4.5 Technological Properties of Fired Ceramic Bodies

In order to test the technological feasibility of the studied compositions of mixture, prototypes of tiles have been realized in a pilot environment. For this reason, the six body compositions were milled in an industrial mill. The slips obtained were spray-dried to obtain powders pressed with a pilot hydraulic press at a pressure of 40 MPa, thus repeating the same operating conditions of the laboratory tests. The 646 × 646 mm tiles were then dried to remove residual humidity and fired in an industrial roller kiln at a maximum temperature of 220 °C with a 40 min cycle.

Technological performance indicators are shown in Table 6, namely, dimensional conformity, which is measured by comparing the effective length with the nominal length (ISO 10545-2) (the measurements were performed with CNE100 1000 mm fiftiethsimal caliper, ±0.02); water absorption conformity which is measured under vacuum according to ISO 10545-3 [86] (the measurements were performed with Bel Engineering M6202Di Model Precision balance, ±0.01 g); and flexural strength according to ISO 10545-4 [87] (the measurements were performed with Gabbrielli Technology Flexi 1000 LX-650, ±100 g). Linear shrinkage of fired tiles was determined as the difference between the length of unfired and fired samples [88]. Finally, the table also shows the content of extra-European raw materials to show the evolution of the body compositions concerning the sourcing alternatives.

Table 6 - Technological performance of the ceramic bodies.

TECHNOLOGICAL PROPERTIES	Composition of Ceramic Bodies					
	C1	C2	C3	C4	C5	C6
Extra-EU raw materials (wt.%)	63	57	52	42	26	20
Length (nominal N = 604 mm)	603.7 ± 0.1	601.3 ± 0.1	604.6 ± 0.1	608.1 ± 0.1	605.1 ± 0.1	603.2 ± 0.1
Linear shrinkage (%)	6.55 ± 0.02	6.92 ± 0.02	6.41 ± 0.02	5.87 ± 0.02	6.33 ± 0.02	6.63 ± 0.02
Dimensional conformity (ISO 10545-2)	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm
Water absorption (%)	0.39 ± 0.01	0.18 ± 0.01	0.49 ± 0.01	0.61 ± 0.01	0.52 ± 0.01	0.27 ± 0.01
Water absorption conformity (ISO 10545-3)	≤0.5%	≤0.5%	≤0.5%	≤0.5%	≤0.5%	≤0.5%
Bending strength (N)	1749 ± 1	1592 ± 1	1482 ± 1	1420 ± 1	1510 ± 1	1767 ± 1
Bending strength conformity (ISO 10545-4)	≥1300 N	≥1300 N	≥1300 N	≥1300 N	≥1300 N	≥1300 N

All compositions are compliant with respect to flexural strength. However, compositions C2 and C4 are out of standard, although for different reasons. C2 is too sintered, and this is evidenced by the very low water absorption (0.18%) and small size (601.3 mm) due to the high shrinkage (6.92%). On the contrary, C4 is a very refractory composition. The high absorption (0.61%) determines the high dimensions (608.1 mm) due to the low shrinkage (5.87%). Compositions C3 and C5 are at the limit of acceptability thresholds for high absorption, 0.49% and 0.52%, respectively. Finally, compositions C1 and C6 are similar in terms of technological compliance despite having very different compositions in terms of raw materials: 63% of extra-EU resources against 20%.

The tests conducted in an operational environment on the compositions selected with the dynamic eco-design validate the technological feasibility of the new materials, realizing a substantial product innovation (from composition C1 to C6) made possible by the re-engineering of the raw material supply system of the company, in compliance with R5 of the circular economy.

2.5 CONCLUSIONS

The circular economy represents a new organizational paradigm for manufacturing systems that drives companies to re-engineer activities and processes to make them sustainable, thanks to a conscious and efficient use of resources and production factors. The transition to the circular economy can be enabled by the development of digital technologies related to Industry 4.0, as they facilitate process and product innovation thanks to their high potential for tracking resource consumption and emissions. This study has provided empirical validation in an operational environment of the conceptual assumptions related to the enabling potential of digital technologies for the circular economy. Therefore, the results obtained from this experimentation provide implications of both a theoretical and managerial perspective and identify areas that require further investigation in future lines of research.

2.5.1 Implications for Scholars

This research has shown that the digital technologies of the Industry 4.0 environment really can help companies embark on a path toward circularity, not only based on the increased operational efficiency implicit in smart manufacturing but also by promoting a trajectory of organizational innovation. It is based on integrating two categories of production factors: tangible resources (materials and machinery) and intangible resources (data). Therefore, the enabling factor of circularity and, more generally, of sustainability becomes the ability of the manufacturing firm that is already efficient from an operational point of view to analyze the raw information intelligently collected by the equipment, i.e., to transform data from a simple accumulation of records (Big Data) into high-value assets (Smart Data).

From the large availability of Big Data, helpful information was selected to conduct a predictive assessment of environmental impacts corresponding to different procurement scenarios. This allowed the selection of the best solution from an environmental and technological point of view and, therefore, the re-engineering of the ceramic product. This predictive approach, based on Life Cycle Assessment and microstructural analysis of materials, has been called circular eco-design precisely because it responds to the fifth of the 6Rs of the circular economy: redesign.

Therefore, this empirical validation of the theoretical hypotheses that emerged from the literature fills the knowledge gaps highlighted in the introduction paragraph: the enabling potential of digital technologies for the circular economy and the transformation of Big Data into Smart Data to create value.

2.5.2 Implications for Industry Practitioners

The theoretical contribution of this study has direct consequences from the perspective of practitioners and organizations. Smart Data has made it possible to highlight new circular opportunities, exploiting the full potential of Industry 4.0 to achieve significant environmental benefits. Circular eco-design has highlighted how distances between the source of supply of raw materials and the factory and the type of transport are together key factors for the environmental sustainability of the finished product. Through a life cycle approach and the use of technological characterization techniques of materials, this research has shown how it can change the paradigm of product design. In the case of ceramic materials, the industrial practice has always seen technologists formulating body compositions whose sodium/potassium ratio was strongly unbalanced in favor of sodium. This conviction has led companies to oversaturate with extra-EU sodium feldspar to maintain a high level of sintering of the ceramic body to obtain low porosity. Eco-design and empirical testing in laboratory and pilot environments have challenged this assumption, also demonstrating that with a strong reduction in imported sodium feldspar to the advantage of domestic potassium feldspar, it is possible to obtain a fully sintered and technologically performing ceramic body. With the same logic, the quantity of Ukrainian clay in the composition of the ceramic bodies was progressively reduced in favor of the German clay supplied to the factory by train and of a national clay. Both raw materials benefit from a transport system with low environmental impact.

From the point of view of industry practitioners, a virtuous circle of circular innovation has thus been created:

- Digital technologies have enabled the smart exploitation of Big Data;
- Smart Data has enabled circular eco-design that has led to product innovation;
- Product innovation has favored the re-engineering of the raw material sourcing system;
- The company moved a further step toward transitioning to the circular economy.

2.5.3 Limitation and Future Research

In addition to the theoretical and practitioner contributions, this research also has some limitations that represent suggestions for future research directions listed below.

Empirical validation of the theoretical hypotheses was carried out on a single case study. Although this methodological approach is widely used in the literature, and the company involved is one of the most representative in the ceramic sector, it would be appropriate to test the circular eco-design model with other companies, even in different sectors.

The Italian ceramic sector is certainly exemplary of a resource-intensive industry with a high level of process digitalization and environmental best practices. Therefore, the approach followed in this research should be tested in other manufacturing sectors that are less evolved from an Industry 4.0 and environmental viewpoint.

The circular eco-design model adopted in this study considered only the environmental dimension of sustainability without including the economic and social dimensions. Therefore, the question of the multidimensionality of the circular economy to go beyond only environmental aspects remains open.

The results show a strong link between environmental and technological performance. This relationship, along with that between technological performance and social and economic ones, are to be further investigated.

The interdependence between Na_2O/K_2O and SiO_2/Al_2O_3 ratios and the degree of sintering of a ceramic body that arose from the results of this study require further investigation, as well as the effect of the chemical nature and quantity of the glass phase formed during firing on the degree of sintering of the ceramic body.

3 TECHNOLOGICAL SUSTAINABILITY OR SUSTAINABLE TECHNOLOGY? TOWARDS A MULTIDIMENSIONAL VISION OF SUSTAINABILITY IN MANUFACTURING

The content of this chapter is the subject of a scientific publication:

Vacchi, M.; Siligardi, C.; Demaria, F.; Cedillo-González, E.I.; González-Sánchez, R.; Settembre-Blundo, D. Technological Sustainability or Sustainable Technology? A Multidimensional Vision of Sustainability in Manufacturing. Sustainability 2021, 13, 9942.
https://doi.org/10.3390/su13179942

3.1 ABSTRACT

The topic of sustainability is becoming one of the strongest drivers of change in the marketplace by transforming into an element of competitiveness and an integral part of business strategy. Particularly in the manufacturing sector, a key role is played by technological innovations that allow companies to minimize the impact of their business on the environment and contribute to enhancing the value of the societies in which they operate. Technological process can be a lever to generate sustainable behaviors, confirming how innovation and sustainability constitute an increasingly close pair. However, it emerges that the nature of this relationship is explored by researchers and considered by practitioners almost exclusively in terms of the degree of sustainability of technological solutions. Lacking is an in-depth exploration of how a, product, or process in addition to being environmentally and socio-economically sustainable, must or can also be technologically sustainable. This research therefore aims to build a theoretical foundation for technological sustainability seen as a possible fourth dimension of sustainable development.

3.2 INTRODUCTION

Technology and sustainability should be considered key factors in a company's competitiveness, since without these factors it is more difficult to achieve positive results and keep them over time [89]. Together, technology and sustainability enable companies to achieve higher earnings, reach new markets, expand their customer base, and increase their margins. However, for this to happen, firms need to embed technology and sustainability within their strategies and corporate culture [90], as well as invest in them and take action to address results and continuously monitor performance [91]. Nevertheless, especially in a managerial environment, when talking about sustainability, there is a tendency to consider the environmental, economic, and social dimensions as separate and independent elements [92,93]. What is still missing is an understanding of the strong interconnections that bind the different dimensions of sustainability that are linked together and enabled by technology, which is a fundamental driver of business development [94].

3.2.1 Background

With the growing use of digital platforms, technological innovation, is currently helping manufacturing companies to adopt sustainable processes and practices by making available a series of innovative solutions that can support the path to responsible production [95].

However, for a company to take full advantage of this opportunity, sustainable practices must extend to all stakeholders in the production chain and to all phases of a product's life cycle [72]. Indeed, sustainability requires the adoption of a systemic approach and a holistic vision with the application of 4.0 technologies to the entire production process to enable the reengineering of products, business models and logistics supply chains in a sustainable way [96].

On the other hand, the current concept of sustainability is the result of a growing awareness of its multidimensionality [97,98]. In a seminal work, Osorio [99] defined sustainability as the ability of man to maintain a certain system in a state of equilibrium. At the same time, the concept of development has also changed over time to include multidimensionality as a characterizing factor as well as the multiplicity of objectives [100]. Multidimensionality is expressed by the definition of sustainable development that includes the three pillars or the three dimensions of sustainability [101]: environmental sustainability (ability to protect the environment and preserve the resources offered by the planet); economic sustainability (continuous ability to generate profit, welfare and wealth while respecting what surrounds us) and social sustainability (ability to ensure social welfare to every individual in the world in an equitable manner). According to Braccini and Margherita [57], each of these dimensions is a necessary but not sufficient condition for achieving sustainability because they interact, overlap and sometimes conflict with each other.

The concepts of sustainability and technology are associated together mainly with the meaning of sustainability of technologies, explored primarily in the environmental dimension and more rarely in the economic and social ones [102]. In fact, the environmental approach to sustainability is prevalent and refers to an equilibrium situation that can be maintained over a long period without depleting natural resources or causing serious damage to the environment [103]. When this definition is translated to the domain of technology, it usually means the possibility that companies have to progress through development and innovation, but without forgetting to consider the respect of natural resources [104]. This approach to production is referred to as sustainable manufacturing [105] or even green manufacturing [106] and is an operational model that integrates product and process design with production planning [107]. The aim is then to identify, quantify, assess, and manage material flows, energy and water consumption, air emissions and waste generation, maximizing resource use efficiency and minimizing environmental impact [108]. In this framework, the sustainable manufacturing domain thus covers three areas: production technologies (facilities and equipment), products and their life cycles, and the organizational contexts in which value is created (manufacturing firms and supply chains) [109].

In economics, the term manufacturing is used to indicate the sector that, through production processes, transforms raw materials into manufactured goods, i.e. products that satisfy utility and consumption needs [110]. As part of the development of a product, able to meet the needs of consumption, a crucial role is assumed by the engineering activities. Based on the outputs of the design processes, the engineering activities verify the technical feasibility of the product in terms of raw materials, constituent components as well as processes, ensuring qualitative compliance with reference standards [111]. It follows that there is both product engineering and process engineering integrated and interdependent with each other [112]. The engineering establishes the characteristics of a product by determining the relationship between quality and costs that, by the way, depends on the performance of the process, also expressed by the relationship between quality and costs [113]. Business decision-makers must therefore resolve the technological trade-off (incompatibility) between costs and quality both of the process and of the products looking for the best solution that maximizes the quality and minimizes the costs [114]. The technological trade-off is not the only challenge facing manufacturing companies. Attention to sustainability (especially environmental sustainability) has now become an ever-growing business necessity [115], not only for compliance or reputational reasons, but also because of the widespread presence of ESG (Environmental, Social and Governance) funds [116]. These funds by statute are expected to invest in sustainable companies, as well as those that pay attention to the well-being of employees and collaborators and to the respect of governance rules. For companies, therefore, two additional sustainability trade-offs arise.

- Environmental trade-off [117]: is environmental sustainability economically viable, or is it increasingly difficult to find the resources needed to finance the ecological transition?
- Social trade-off [118]: how consistent is social equity with the goal of economic efficiency?

Even the orientation of European policies, for example with the programming of structural funds 2021-2027 (Next Generation EU), propose a paradigm of development achieved through the integration of economic growth with social inclusion and environmental sustainability [119]. In other words, business and profit goals must go hand in hand with social and environmental responsibility issues, no longer considered as alternatives to be balanced in a difficult equilibrium, but as mutually reinforcing pillars [46]. Reconciliation of conflicts related to environmental and social trade-offs, however, should also consider reconciliation of technological trade-offs [120,121], but not only. From a perspective of effective sustainable manufacturing, conflict reconciliation should take a holistic view and include all three trade-offs (environmental, social and technological) simultaneously [122].

With this approach, economic sustainability, understood as the economic viability of a process or product, becomes the common thread between environmental and social sustainability [123]. Therefore, within the framework of sustainable development, in order to ensure the growth of manufacturing companies and social systems in which they operate, it is appropriate to raise the issue not only of sustainability of technologies [124], but of an effective technological sustainability. In fact, the question of the technological feasibility of a product or a process cannot be separated from its environmental and socio-economic impact [125]. In other words, a process or a product, as well as minimizing the impact on the environment and society and being economically viable, must also be a technically feasible solution and have technological performance that complies with applicable standards.

3.2.2 Gap identification and research aims

The scientific literature shows that the concept of "technological sustainability" is often used as a synonym for "sustainability of technologies" emphasizing mainly their environmental dimension and, to a lesser extent, their social and economic one. Confirming this, it is clear that in the few studies published on "technological sustainability", scholars refer to: sustainable technologies [126], component of economic sustainability [127], environmental sustainability [128], sustainability of technological processes [129], sustainability of (mobile learning) m-learning [130], exergy [131], personal access devices (PDAs) [132], capabilities to reduce ecological impact [133,134], component of sustainable development [135], technological competitiveness [136] , degree of how technology affects other dimensions of sustainability [137] and intellectual infrastructure of technological development [138].

Based on the above statements and at the current state of our best knowledge, we can conclude that there is a gap in the scientific literature regarding the concept of technological sustainability. Scientists do not attribute to this term an unambiguous meaning, but above all there is a lack of vision of technology as an integral part of sustainability on the same level as the other dimensions: environment, economy and society. Given these premises, we address the following research questions.

RQ1: Can a conceptual framework arise from a manufacturing context to ascribe technology as a key dimension of sustainability?

RQ2: Is it also feasible to design a model for assessing technological sustainability?

Therefore, this exploratory study aims to define a conceptual framework for technological sustainability and develop a method for its assessment in manufacturing, both from an organizational and product perspective.

3.3 RESEARCH DESIGN AND METHODOLOGY

The RQs previously stated, call for a methodological approach capable of resolving the uncertainty and complexity of the topic of technological sustainability, which is still under-researched. The constructivist paradigm has been considered more appropriate for the creation of an explanatory model of the real world as it is that of the manufacturing environment. In such a model, the knowledge building is due to the two-way interaction between the researcher's experience and ideas with the sociocultural context in which he/she acts, thus subject and context are interactively linked [139]. Following this constructivist approach, the theoretical framework was built using inductive inference. For this purpose, empirical data from both secondary (literature, best practices, international standards and guidelines) and primary (direct observation of a factory reality) sources were processed simultaneously. The factory reality that was observed as a primary source of data is an important Italian company that produces ceramic tiles for the building industry, already studied by the authors to carry out research on sustainability management [46,72]. Finally, through abductive inference [140], empirical and real-world observations were transformed into an explanatory model for technological sustainability, which is aimed at answering the RQs posed above. The abductive logic has already been applied in the managerial field in those cases where it takes its cue from the existing theory and then develops a new theory to better understand and interpret organizational phenomena [141,142].

3.4 THEORETICAL FRAMEWORK

A general definition of sustainability can be obtained by inductive inference, synthesizing the scientific contribution of other scholars. In this sense, it is possible to consider sustainability as an intrinsic property of a system [143,144], that is the ability of a complex organization structured in processes, to perpetuate itself over time while maintaining its structure and functions unchanged by integrating its economic, social, and environmental dimensions [145,146]. In manufacturing, sustainability [147] is a set of operational best practices [148], enabled by digitization [149], aimed at reaching and maintaining the point of equilibrium [45] where all production factors [150] are consumed at least as intensively as they can be regenerated [151]. Therefore, based on what has been said above, we argue that:

Proposition 1 (P1): The concept of sustainability is related with change to indicate the capability of a natural, economic, and social system to maintain its intrinsic properties, a continuous process where these three fundamental dimensions interact and are interdependent.

Proposition 2 (P2): Sustainable manufacturing is a system that integrates product design, process design, and operating practices while maximizing resource use efficiency.

Sustainability requires an assessment of the environmental [152], social [153] and economic [154] impacts of products, processes, and organizations [155,156]. Currently, the most widely used framework for these assessments is Life Cycle Thinking (LCT) [63], which considers all the phases and processes that contribute to the manufacturing of a product, including the use and end-of-life phases [157], according to the cradle-to-grave approach [158]. The perspective of analysis can be the product [159], the process [160], or the organization [156] that controls manufacturing. The LCT is a tool to support decision-making and to develop regulatory frameworks or industrial strategies [161]. It is enabled by scientific methods such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) used respectively to determine the environmental, economic and social impacts of a product, process or organization [63]. LCA is a methodology standardized by ISO 14040:2021 that defines the principles and framework in which the analysis should be performed [162]. In contrast, LCC does not yet have a recognized standard for products and services; instead, there is the ISO 15686-5 standard for buildings and constructed assets [163]. S-LCA also does not refer to an ISO standard, but to the UNEP guidelines updated in 2020 [164]. The three methods share the same analytical framework defined by ISO 14040 for LCA, namely 4 steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation [165]. Environmental impact assessment can also be combined with economic [12] or social [13] impact assessment to get a more complete view of the degree of sustainability. Alternatively, LCA, LCC and S-LCA can be integrated with each other in a holistic methodological approach called Life Cycle Sustainability Assessment (LCSA) [15]. Consequently, we postulate that:

Proposition 3 (P3): Life Cycle Thinking (LCT) allows the social, economic, and environmental dimensions of the sustainability of a product, process, or organization to be brought into a single relationship by assessing its impacts from a life cycle or supply chain perspective.

In accordance with ISO 14040, one of the most critical steps is the Life Cycle Impact Assessment (LCIA), which establishes the relationships between each life cycle stage and the corresponding sustainability impacts [166]. Especially in the environmental field, there are many database-driven methods available to determine impacts [167]. As they are very different, the choice of database can influence the final results of sustainability studies [168]. In the social domain, on the other hand, the assumption is that any human activity, therefore including manufacturing, has the power to create or destroy value [169]. This occurs through the transformation (process) of inputs (resources) into outputs (products) and outcomes (results) which have a direct or indirect influence on the context of reference [170,171]. The changes induced or caused by the input transformation process are the impacts generated in the general environment in which the organization operates, both in the short and long term [172]. The impacts are therefore that part of the outcomes that is attributed exclusively to the activities carried out by the organization. The causal chain that links inputs to processes, processes to outputs, outputs to outcomes, and outcomes to impacts is known as the Theory of Change (ToC) [173]. We formalize this as follows:

Proposition 4 (P4): In a general perspective of sustainability, impact can be seen as a change or modification of the context in which an organization operates due to anthropogenic activities.

In accordance with [174], in the social sciences the abductive approach becomes central because it allows shifting the focus from the result to the process and from theory to the formulation of innovative hypotheses. Abductive inference begins with an observation or a set of observations that, according to rules we already know, help us to formulate a hypothesis that can explain the result we have observed. The conclusion of this reasoning is a hypothesis, i.e. a possibility that must be verified [175]. In the specific case of this research, the abductive inference from the theoretical framework is the following:

- **Rule:** the sustainability of a natural, economic or social system is the capability to maintain its state unchanged by anthropogenic activities.
- **Observation:** in order to be efficient, a manufacturing system must maintain a balance between the technological performance of process and product.
- **New explanatory hypothesis:** (perhaps) the maintenance of the operational performance of a manufacturing system represents its technological sustainability.

Based on this new explanatory hypothesis, the theoretical framework shows the relationships between the different topics by suggesting the following assumptions:

The degree of technological sustainability of a manufacturing company is dependent on its capability to optimize the production factors, ensuring that the organization will continue to operate in the future, at least in the same way as it does today.

A technological sustainability assessment should also follow the same life-cycle approach as provided by the LCT and the same analysis steps set by ISO 14040. This methodological consistency with the main methods of sustainability assessment can indeed facilitate their integration following a holistic perspective for environment, economy, society and technology.

3.5 TECHNOLOGICAL SUSTAINABILITY ASSESSMENT (TSA)

Following the life cycle approach (LCT) and supply chain perspective, a methodological framework for technology sustainability assessment is proposed in this section, based on the best practices developed in the European Commission-funded project LIFE Force of The Future [176]. The aim is to provide a tool for managing the impact of technology in manufacturing industry that can assist companies' decision-making processes, following the ISO 14040 logic framework.

3.5.1 Definition of the goal and scope of the TSA

The first step of the TSA was to define the objectives of the study, specifying the motivations behind the work and the information expected to be obtained as a result. Similarly to other sustainability assessment tools, two different approaches can be adopted to capture the technological dimension of sustainability: (1) the perspective of the product and the its manufacturing process with which the product is closely associated [177]; (2) the organization that operates the manufacture and sale of the product from a business viewpoint [178].

The unit of analysis in the first approach is the functional unit that defines the product system to be analyzed, while in the second approach is the organization under study. Adapting the activities categories defined by Porter [179] to describe the value chain of a business, as already done in other recent studies [180], the pattern of possible system boundaries (cradle-to-gate and gate-to-grave) was drawn (Figure 1) for the assessment of the technological sustainability of the product-process (P-TSA) or organization (O-TSA).

In the case of P-TSA, the following activities are addressed.

1 Sourcing (cradle-to-gate): supply of the raw materials and the other factors of productions).
2 Inbound Logistics (cradle-to-gate): delivery of raw materials and other inputs to the factory.
3 Operations (gate-to-gate): Processes of physical and/or chemical transformation of production factors (inputs) into finished products (outputs) ready for sale, including packaging.
4 Internal Logistics (gate-to-gate): handling and storage of finished products awaiting shipment.
5 Outbound Logistics (gate-to-grave): processes of picking up products at the manufacturer's warehouse for delivery to the distributor or end customer.
6 Product Usage (gate-to-grave): these are the activities of using the product whether it is industrial assets for other industrial customers (business-to-business market) or consumer goods (business-to-consumer market).
7 Waste Logistics (gate-to-grave): product end-of-life and waste gathering and disposal.

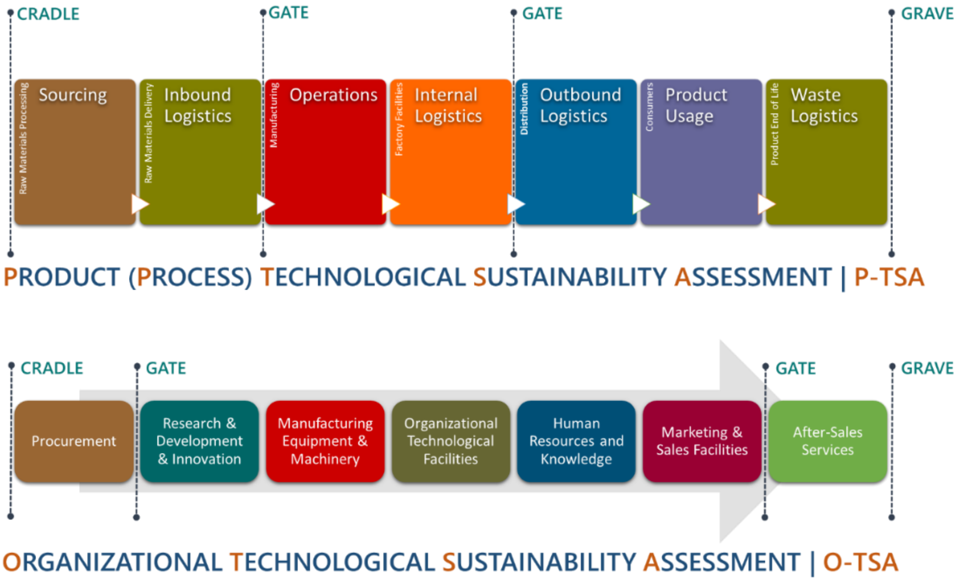


Figure 1 - Life cycle approach to assessing product/process (P-TSA) and organizational (O-TSA) technological sustainability.

In the case of the O-TSA, the perspective of the analysis changes to focus on the organization that controls the technologies to design, manufacture, and market a product. Following the same logic adopted previously, the main activities identified are as follows:

1. Procurement (cradle-to-gate): refers to the function of purchasing technological inputs such as raw materials, semi-finished goods, machinery, equipment, and services used by the organization.
2. Research & Development & Innovation (gate-to-gate): this is a strategic function of the organization that must build and preserve competitive advantage through product and process innovation both enabled by the development of new technologies and knowledge.
3. Manufacturing Equipment & Machinery (gate-to-gate): the endowment of innovative or, on the contrary, outdated manufacturing technologies has a significant impact on the company's competitiveness.
4. Organizational Technological Facilities (gate-to-gate): the relationship between technology and business organization goes beyond manufacturing operations and involves IT infrastructure, management systems such as Enterprise Resource Planning (ERP) and Business Intelligence systems (BI), all of which are essential tools for data collection and information processing.
5. Human Resources & Knowledge (gate-to-gate): human resources, both at the individual and organizational level, play a fundamental role in technological innovation processes. Knowledge represents the intangible component of an organization's technological assets, expressed through culture, skills, interactions between parties, and decision-making heuristics.
6. Marketing & Sales Facilities (gate-to-gate): technologies must be at the service of marketing and commercial strategies to integrate and automate data and information that are collected and processed in other departments (product development, production, management control and administration and finance).
7. After-Sales Services (gate-to-grave): it means the set of assistance activities that a company provides to a customer before, during and after the purchase or use of a consumable product and the technical support services of industrial companies that manufacture durable goods.

3.5.2 Technological inventory analysis

This phase includes all activities aimed at collecting data on all inputs and outputs included in the system boundary and elaborating specific technological metrics related to each category of activity of the product/process system (P-TSA) or organization (O-TSA) considered.

3.5.3 Technological impact assessment

According to ISO 14040, this is the third phase of the assessment aiming to convert the inputs and outputs identified in the inventory analysis phase, into potential contributions to technological life cycle impacts.

3.5.3.1 Selection of technological impact categories

The selection of impact categories for technological sustainability assessment must be consistent with the objective and scope of the study and specify the technological concerns of interest to the organization. Therefore, starting with the explanatory hypothesis that sees technological sustainability as the ability of a production system to maintain its operational performance over time, the following impact categories were selected.

In-/Outputs Availability (IOA): Refers to the potential of the system to provide the necessary inputs and outputs at the appropriate time to ensure continuity of operations. The output of one phase or activity in the life cycle becomes the input of the next.

Operational Performance (OP): Describes the potential of the outputs of a process step or activity to meet the demands and needs of the organization's internal users or end customers, optimizing the ratio of output value to input use.

Technical Quality (TQ): Expresses the set of intrinsic characteristics and functional parameters that the output possesses and that satisfy the expected requirements of users and/or customers in accordance with current regulations.

More generally, the concepts of availability, performance and quality are used to build the OEE (Overall Equipment Effectiveness) index used to monitor the production losses of an equipment or process [181]. In this case, availability measures production losses related to downtime, performance measures losses related to reduced speed, and quality measures losses due to units that are not released [182]. The choice of these parameters as technology impact categories is based on the results of the study by Durán and Durán [183] who, in addition to scaling the analysis from the facility to factory level, employ this approach to determine the systemic impact of each piece of equipment through a sensitivity analysis.

3.5.3.2 Classification

In this phase, the technological metrics selected earlier (section 3.5.2), are associated with the various impact categories according to the effects they may have on the production performance of a manufacturing organization.

3.5.3.3 Characterization

In order to assess the technological sustainability, we create a composite index, namely a combination of individual indicators, which represents a convenient tool to convey information. The first stage of constructing a composite index is the selection of individual indicators.

For each impact category, technological metrics are used to create indicators. These indicators make it possible to quantitatively express the contribution provided by each technological metric to each impact category.

In the case of IOA, average stock and average consumption were selected as the technological metrics to construct the Stock Coverage Rate (SCR) indicator.

Let ‘A’ be the set of organizational activities, so that each activity a ∈ A; and let ‘ia’ represent the input associated with each activity ‘a’: ∀ a ∈ A ∃ ia. The Stock Coverage Rate (SCR) for each input ‘ia’ can be defined as follows:

$$SCR_{i_a}^{t} = \frac{AS_{i_a}^{t}}{AC_{i_a}^{t}} \qquad (1)$$

$SCR_{i_a}^{t}$ = Stock Coverage Rate of input i, in the activity a, at time t.

$AS_{i_a}^{t}$ = Average Stock of input i, in the activity a, at time t.

$AC_{i_a}^{t}$ = Average Consumption of input i, in the activity a, at time t.

As operations management aims to optimize the use of an organization's resources, productivity metrics are key to evaluating operations-related performance. Therefore, in the case of the OP, inputs and outputs have been adopted as technological metrics to construct the Productivity Indicator. Productivity is the ratio between the real output of the production and the resources really employed (input) to generate said output, representing the capability to rationally use resources.

$$PI_a^t = \frac{ROU_a^t}{RIN_a^t} \qquad (2)$$

PI_a^t = Productivity Indicator of the activity a, at time t.

ROU_a^t = Real Output in the activity a, at time t.

RIN_a^t = Real Input in the activity a, at time t.

Finally, in the case of TQ, the technological metrics selected were the quality parameter controlled, and the acceptability threshold of this parameter set by current regulations to assign conformity to the output produced. The ratio between these two metrics represents the Output Conformity Rate (OCR)

Let ‘oa’ be the output generated from each activity ‘a’, the OCR for each output ‘oa’ can be formalized as follows:

$$OCR_{o_a}^t = \frac{QP_{o_a}^t}{AT_{o_a}^t} \qquad (3)$$

$OCR_{o_a}^t$ = Output Conformity Rate of output o, in the activity a, at time t.

$QP_{o_a}^t$ = Quality Parameter of output o, in the activity a, at time t.

$AT_{o_a}^t$ = Acceptability Threshold of output o, in the activity a, at time t.

3.5.3.4 Normalization and aggregation

As individual indicators often have different scales of measurement, normalization is required prior to any aggregation [184]. This process brings indicators onto a common scale, maintaining the relative differences and producing dimensionless scores that allow for comparison.

For the purpose of the study we opted for standardization (z-scores); for each individual indicator the mean (x̄) and the standard deviation (σ) across activities are computed.

Let K be a set of individual indicators K = {km}, m = 1, …, M, standard scores are derived as:

$$z_{ka}^{t} = \frac{x_{ka}^{t} - \bar{x}_{k}^{t}}{\sigma_{k}^{t}} \quad (4)$$

z_{ka}^{t} = standardized score of the indicator k, for activity a, at time t.

x_{ka}^{t} = score of the indicator k, for activity a, at time t.

$\bar{x}_{k}^{t}$ = average score of indicator k, for all activities, at time t.

σ_{k}^{t} = standard deviation of indicator k, for all activities, at time t.

After standardization, data will have a 0 mean and a unit standard deviation.

Next, the results of the impact categories are first multiplied by weighting factors and then added together to obtain a single value, thus allowing the assignment of values to the different impact categories.

Weights reflect the relative importance of each individual indicators to the overall composite index [185]. Given a set of individual indicators K = {km}, we can define the set of indicator weights as W = {wm}, with m = 1, …, M, such that wm ≥ 0 and $\sum_{m=1}^{M} w_m = 1$.

Because of the exploratory nature of the study, adopting the approach already followed in other studies [186], we assume equal weights for all indicators:

$$w_m = \frac{1}{M} \quad (5)$$

wm = weight of indicator km

M = total number of indicators for each activity a in the life cycle

Weighted arithmetic mean, one of the most widely used aggregation methods [187], was used to aggregate normalized indicators and into sub-indexes for each category of technological impact.

$$IOAI^t = \sum_{a \in A} w_m \left(zSCR_{i_a}\right)^t \qquad (6)$$

$$OPI^t = \sum_{a \in A} w_m \left(zPI_a\right)^t \qquad (7)$$

$$TQI^t = \sum_{a \in A} w_m \left(zOCR_{o_a}\right)^t \qquad (8)$$

(IOAI)t = In-/Output Availability Index for the standardized indicator zSCR, at time t.

(OPI)t = Operational Performance Index for the standardized indicator zPI, at time t.

(TQI)t = Technical Quality Index for the standardized indicator zOCR, at time t.

Finally, to build the overall Technological Sustainability Index (TSI), we aggregate the scores obtained from partial indices (IOAI, OPI and TQI), each of them corresponding to an impact category.

In particular, given the set of sub-indexes H = {hj} (j = 1, …, J), we assign to each sub-index 'hj' a weight 'wj ≥ 0', such that $\sum_{j=1}^{J} w_j = 1$. The composite index can be formalized as follows:

$$TSI^t = \sum_{j=1}^{J} w_j \, h_j^t \quad (9)$$

$$TSI^t = \left[w_{IOA}\, IOAI^t\right] + \left[w_{OP}\, OPI^t\right] + \left[w_{TQ}\, TQI^t\right] \quad (10)$$

Also in this case equal weighting scheme was adopted, as the three dimensions have equal status in the composite index. However, weighting factors may be set differently depending on the relevance attributed by the organization to individual indicators.

We can now take into consideration the TSI time series for year t, which can be expressed as:

$$TSI_1^t, TSI_2^t, \dots, TSI_{12}^t \qquad (11)$$

Then, let's consider the TSI time series for the previous year t-1:

$$TSI_1^{t-1}, TSI_2^{t-1}, \dots, TSI_{12}^{t-1} \qquad (12)$$

The use of time series, as demonstrated by other studies [22,188], allows for the analysis of trends in the performance of an index. The trend variance rate of technological sustainability (TSIt-1, t) is then given by the ratio between the index of the month of reference at time ‘t’ and that of the corresponding month at time ‘t-1’, the result is multiplied by 100 and then subtracted 100. For example, considering the month of March for year t and year t-1, the following will occur:

$$\Delta TSI_{t-1,t} = \left(\frac{TSI_3^t}{TSI_3^{t-1}} \cdot 100\right) - 100 \qquad (13)$$

This trend variance rate provides additional information about the effects of technology on process, product, and organization because it includes the time dimension. The performance achieved in transforming inputs into outputs using technology in operational activities can be monitored with the IOA, OP and TQ indexes. While the evaluation of the technology-driven change can be measured as the result (outcome) generated by the product or process (output) and the impact (positive or negative) that the result has induced on the organization in the medium to long term (Figure 2). Outcome and impact, if positive, can be seen as benefits for the consumers of the products and for the organization that has operated the manufacturing process. Or, in other words, as the value generated by the organization for stakeholders when their expectations are met. One way to capture the contribution made by technology to value creation may be to perform a simple arithmetic mean of the monthly trend variance rates to obtain the Technology Improvement Index (TII), (equation 14).

$$TII_{t-1,t} = \frac{\sum_1^{12} \Delta TSI_{t-1,t}}{12} \qquad (14)$$

This index provides an indication of how the organization, in processing resources to obtain products, improves (or worsens) its results and impacts as a result of technology, from one year to the next. The economic and social value created through technological improvement can be quantified by integrating this assessment with the socio-economic and environmental ones.

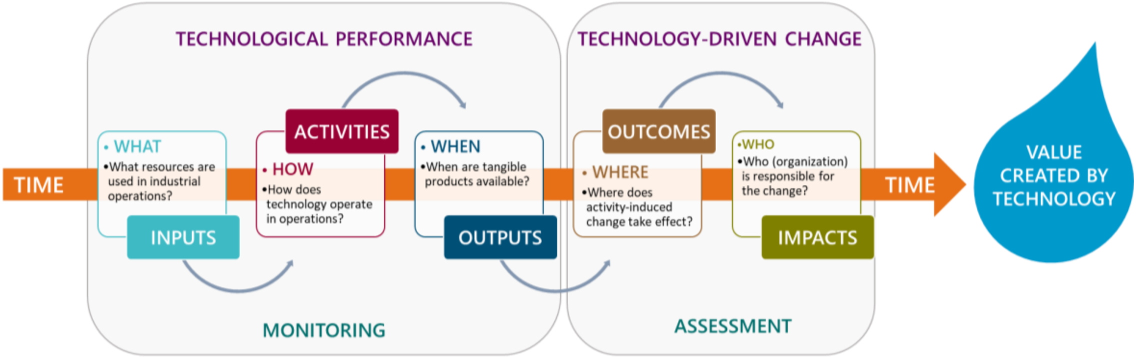


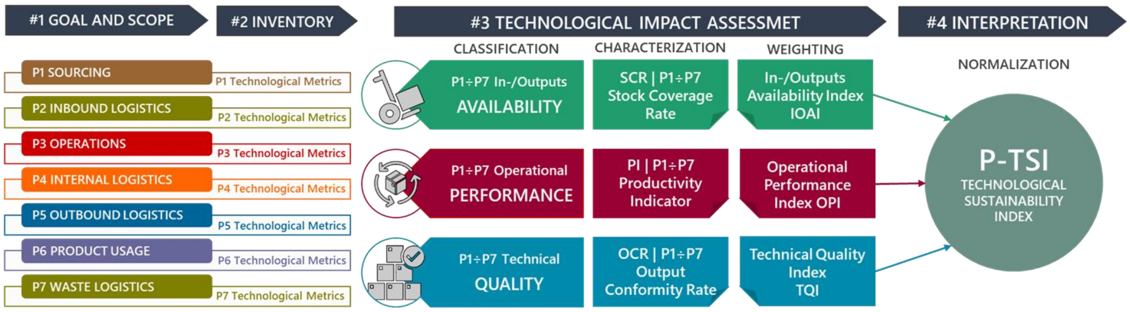
Figure 2 - Causal relationships between inputs, activities, outputs, outcomes and impacts in the chain of change to create value by technology.

3.5.4 Technological interpretation

Whatever output/outcome of the data collection and processing procedures requires the researcher to perform interpretation, i.e., to attribute meaning and technological value to the intermediate or final results of the sustainability assessment. Therefore, interpretation is the stage of the technological sustainability assessment in which the results obtained in the inventory analysis and impact assessment are combined in a manner consistent with the objectives and scope of the study to derive insights and recommendations. Any critical issues identified in the impact assessment can help to modify processes, products, and organizational procedures in an iterative approach to improvement. Interpretation should contain three main activities: (1) identification of significant factors that have the potential to change the final results of the technology assessment; (2) evaluation of the completeness of the inventory and impact assessment, supplemented with sensitivity analysis of key factors for technology impact and checking for consistency of methods and data with the objective and scope; and (3) preparation of a final report that includes the results obtained and the conclusions reached with the study.

This procedure, although subdivided into phases, should be conducted with an overview as schematized in Figure 3 for the P-TSA and O-TSA respectively. In fact, results are not automatically endowed with meaning if the researcher does not combine his expertise in processing technical data, with a technological sensitivity derived from knowledge of the organizational context of application of the results and his interpretive effort. Interpretation requires the rhetorical ability to argue the choices made and to effectively interpret and expose the key findings, thanks to the two-way contamination between technological data and organizational context. The stronger this relationship, the higher the heuristic potential of the final Technology Sustainability Indexes (P-TSI and O-TSI).

PRODUCT (PROCESS) TECHNOLOGICAL SUSTAINABILITY ASSESSMENT | P-TSA



ORGANIZATIONAL TECHNOLOGICAL SUSTAINABILITY ASSESSMENT | O-TSA

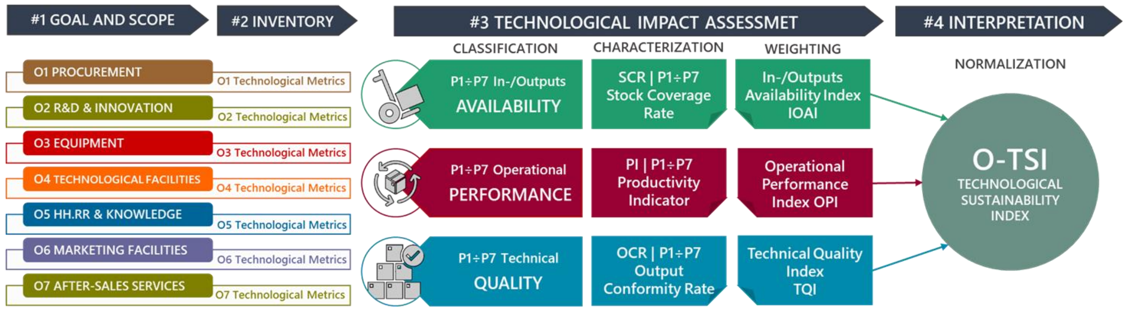


Figure 3 - Holistic interpretive frameworks for the four phases of both product/process (P-TSA) and organizational (O-TSA) technology sustainability assessment. The frameworks differ for the different activities considered in phase #1 and #2.

3.6 DISCUSSION OF RESULTS

Following a theoretical-conceptual perspective, the main result of this research is a methodological framework for Technological Sustainability Assessment (TSA) based on the life cycle approach (LCT) and in line with the operational scheme of ISO 14040. The methodological framework is divided into two application options: one to determine the technological sustainability of a product or process (P-TSA) and the other designed for an whole manufacturing organization (P-TSA). In both cases, to adopt the perspective of the value chain and the life cycle approach (cradle-to-gate and gate-to-grave), seven main activities have been identified against which to conduct the analysis of technological sustainability. In addition, three impact categories necessary to determine the level of technology impact along the value chain were defined for both: In-/Outputs Availability (IOA), Operational Performance (OP), and Technical Quality (TQ).

By combining a set of technology metrics, three general indicators were defined for each impact category: Stock Coverage Rate indicator (SCR), Productivity Indicator (PI), and Output Conformity Rate (OCR). When applying this technology sustainability assessment framework, analysts should appropriately select those specific metrics that best represent the impact of technology on their product/process or organization.

After weighting, the indicators for each impact category can be aggregated into general indices of technological impact: In-/Outputs Availability Index (IOAI), Operational Performance Index

(OPI), and Technical Quality Index (TQI). Finally, a mathematical way to construct the Technological Sustainability Index (TSI) was provided. This index quantitatively describes the degree of technological sustainability associated with the product/process or, more generally, the level of technological sustainability achieved by the organization.

Finally, in order to capture the trend of technological sustainability over time, the methodological framework also proposes to normalize the indices measured at a given time with respect to an internal baseline, obtaining a further index called Technology Improvement Index (TII). This has the advantage of including the dimension of time in the assessment of technological sustainability, showing how technology contributes to improving the performances of a product/process or the outcomes of an organization. The economic and social value created through technological improvement can be quantified by integrating this assessment with the socio-economic and environmental ones.

The results obtained from this conceptual framing provide several implications for both scholars as well as practitioners and businesses.

3.6.1 Implications to academia

This study contributes to fill the gap in the literature regarding the concept of technological sustainability, which is often instead understood as the sustainability of technological solutions. Thus, technology becomes an integral part of sustainability along with environment, economy, and society, providing a multidimensional view of it. To justify this new attribution of meaning, three categories of technological impact have been identified (In-/Outputs Availability; Operational Performance and Technical Quality), all of which are necessary to determine whether a production system is able to maintain its functional capabilities over time. For each impact category, an index is determined by combining specific technology indicators and metrics. This study therefore provides a methodological framework for quantifying, with a general technology sustainability index, the contribution made by technology to the value creation of an organization (O-TSI) through a product or process (P-TSI).

3.6.2 Implications to practitioners

From the perspective of industrial and business practitioners, the framework for assessing sustainability technology provides a promising operational tool for monitoring how technologies really contribute to the effectiveness of production systems. Normally, industrial engineering and operations research specialists focus on analyzing the performance efficiency of a single equipment. In contrast, the technology assessment framework proposed in this study, with its holistic view, shifts the focus of managers from the nano-level of machinery to the micro level of the whole system, up to the meso level of the supply chain, expanding the possibilities for broadening knowledge about the real contribution of processes, products, and organization to value creation.

3.6.3 Limitations and future research directions

Due to its theoretical-conceptual focus, this study has some limitations that nevertheless offer insights for subsequent in-depth research activities. First, the proposed technological sustainability assessment framework will need to be validated through its application in an operational context. In fact, it is necessary to ascertain that the indicators and indices, as well as the technological impact categories, are relevant and suitable for different production environments. Second, if the empirical validation is successful, it will be necessary to reinforce the theoretical construction that, while having a certain degree of detail, needs to be linked to current management theories in order to make the introduction of an additional pillar of sustainability more solid. Finally, it is necessary to explore the relationships between technological sustainability, introduced in this study, and environmental, social, and economic sustainability, in order to build an integrated framework of sustainable development.

3.7 CONCLUSIONS

The capability to equilibrate social, economic and environmental sustainability is the essence of the concept of sustainable development, which has also become a key issue for manufacturing companies. This process ensures a balance between the economic growth of a given industry, care for the environment and the well-being of the society in which it is integrated. Cross-cutting each of these concepts is technology as a fundamental element both in industrial processes and in every aspect of people's lives. In every era of human history, technological innovations have arisen that can optimize processes and advance societies, so it is necessary to think of technology as an enabler for sustainability.

In this study, the aim was to investigate the transversal character of technology with respect to the environmental, economic and social dimensions of sustainability in order to highlight its relevance for preserving the equilibrium between the three pillars of sustainable development. The theoretical construction was grounded on the definitions of sustainability and sustainable production and on the methodological approach of Life Cycle Thinking (LCT). Under conceptual abstraction, and applying an abductive inference, it was assumed the existence of technological sustainability understood as the capability of a production system to maintain its operational performance.

Thanks to these theoretical backgrounds, it was possible to answer positively the RQ1 stated in the introduction, that is, technology can be seen as a key dimension of sustainability along with environment, economy, and society. Then, following the holistic view of Life Cycle Thinking and the methodological scheme of ISO 14040, a framework was proposed to carry out the assessment of the technological sustainability of an organization (O-TSA) and of a product or process (P-TSA). This provided a positive response to RQ2.

This research represents an initial conceptual and exploratory contribution aimed at providing an operational framework to help manufacturing companies to consider the technological dimension within the broader framework of the sustainability of a product/process and an organization.

4 DRIVING MANUFACTURING COMPANIES TOWARDS INDUSTRY 5.0: A STRATEGIC FRAMEWORK FOR PROCESS TECHNOLOGICAL SUSTAINABILITY ASSESSMENT (P-TSA)

The content of this chapter is the subject of a scientific publication:

Vacchi, M.; Siligardi, C.; Settembre-Blundo, D. Driving Manufacturing Companies toward Industry 5.0: A Strategic Framework for Process Technological Sustainability Assessment (P-TSA). Sustainability 2024, 16, 695. https://doi.org/10.3390/su16020695

4.1 ABSTRACT

This study explores the complex nexus between technological innovation, Industry 4.0's transformative paradigm, and the emerging concept of Industry 5.0, highlighting the critical role of integrating sustainability into factories to enhance organizational competitiveness. In this context, confusion arises between the terms "sustainable technologies" and "technological sustainability" due to two factors: the misuse of the terms as synonyms and the misattribution of conceptual meaning to each term. To clarify this ambiguity, this study validates a conceptual framework for technological sustainability by examining the processes of a ceramic manufacturing company. This assessment highlights the potential of technological sustainability and its associated measurement model to facilitate the transition from Industry 4.0 to Industry 5.0. This research provides fundamental insights into technological sustainability and serves as a guide for future empirical efforts aimed at achieving a balanced and sustainable integration of technology into manufacturing practices.

4.2 INTRODUCTION

Technological innovation serves as a catalyst for advances in the efficiency, productivity, and overall competitiveness of the manufacturing sector. In the evolution to Industry 5.0, there is a significant shift toward human-centeredness, sustainability, and resilience. This new paradigm emphasizes the importance of not only technological advancement but also its alignment with ethical and environmental considerations. As a result, the integration of technology and sustainability is becoming critical for organizations aiming to maintain a competitive advantage in a rapidly changing landscape. Despite it being imperative to integrate technology and sustainability, the concept of technological sustainability often lacks precise definitions and widespread recognition. Therefore, it is critical to establish a comprehensive understanding of technological sustainability. This requires a holistic perspective to develop sustainable solutions that also effectively address the other dimensions of sustainability: economic, social, and environmental.

This chapter is structured as follows. The "Theoretical Background" section provides a brief theoretical overview of the relationships between technological innovation, Industry 4.0, Industry 5.0, and technological sustainability. The "Methodology" section explains the scope of the study and the adopted methodological framework. The section titled "Results and Discussion" presents the results of the technological assessment of the manufacturing company, following the four stages provided by the methodology. The study concludes with the

"Concluding Remarks" section, which highlights the theoretical and managerial implications of the study's results, addresses its limitations, and provides guidelines for future research.

4.2.1 Theoretical Background

Technological innovation refers to the introduction of new ideas, processes, or technologies that result in significant changes or improvements in various domains. This is achieved through the development of new products or solutions that use advanced technologies or innovatively exploit existing ones, providing benefits such as increased efficiency, improved performance, reduced costs, and new market opportunities [189]. Technological innovation plays a crucial role in improving the efficiency, productivity, competitiveness [190] and resilience [191] of operations in the manufacturing sector. Technological innovation enables the automation, optimization, and connection of production systems, promoting smarter and more interconnected manufacturing. This has been a key factor in the evolution toward Industry 4.0, or the digital transformation of industrial processes by fostering the development of customized solutions and energy efficiency and the creation of new business models [192].

Industry 4.0 marked a significant turning point in the digital transformation of industrial processes. However, the concept of Industry 5.0 is emerging as the next evolution in the industrial landscape. The term Industry 5.0 was coined by Michael Rada [193,194] in 2015, emphasizing the importance of considering people and the environment in the industrial context. In 2016, the Japan Business Federation introduced the concept of Society 5.0. This concept aims to use technology to contribute to human well-being and environmental protection. It was subsequently implemented in the industrial setting [195]. In 2018, Esben H. Østergaard, founder of Universal Robots, highlighted the importance of maintaining a focus on the human aspect even in highly digitized and technological manufacturing processes [196]. All these precedents have led to the development of the idea of Industry 5.0, which represents a new industrial revolution, the fifth in more than two centuries since the Industrial Revolution of the 18th century [197]. These previous revolutions involved the introduction of machines, the advent of electricity, automation and information technology, and the Industry 4.0 era, which began in 2013 and focused on digital transformation and manufacturing optimization.

Industry 5.0 unfolded just 10 years after the start of Industry 4.0. It is characterized by technology returning to being a tool in the service of humans and not vice versa. In a January 2021 document, the European Union defined the three fundamental pillars of Industry 5.0 as human-centeredness, sustainability, and resilience, which are also the goals of the Next Generation EU program [198]. The document argues that Industry 4.0 primarily focuses on technology and growth, neglecting the environmental, social, and sustainable development dimensions [199]. In the new vision of Industry 5.0, research and technological innovation are instead geared toward a transition to a sustainable, human-centered, and resilient European industry [200].

Industry 4.0 utilized technological innovation to promote digital transformation. Industry 5.0, on the other hand, aims to create more sustainable industrial ecosystems [201] by harnessing technological innovations and research. Thus, it becomes clear that the interconnection between technology and sustainability is crucial for corporate competitiveness, fostering profitable growth, market expansion, and improved profitability [202]. However, executives often overlook the synergistic relationships between technology and sustainability, thus missing opportunities to take full advantage of their mutually enabling potential. In the past, sustainability, particularly environmental sustainability, and technology were considered incompatible concepts, due to the negative impacts that many technological innovations had on the environment and society [203]. Today, however, technological innovation and sustainability are closely interconnected and must be addressed together [204]. This is why we talk about sustainable innovation, and the new paradigm of Industry 5.0 is an example this [205]. Companies are embracing sustainable innovation in response to the growing expectations of markets. Informed consumers are willing to pay more for sustainable products offered by trusted brands committed to the environment and society [206]. This trend is also driven by the global need to improve the world, which is influenced by the frequency of environmental phenomena and far-reaching social movements. Therefore, sustainable innovation becomes an additional motivation to invest in technologies that support sustainability [207].

Sustainability can generally be seen as the ability of a complex organization to perpetuate itself [208] by integrating the economic, social, and environmental dimensions [209]. In the specific context of modern manufacturing, this implies the adoption of digitization-based operational best practices to achieve an equilibrium where inputs are consumed as intensively as they can be regenerated [210]. Therefore, in order to achieve sustainable production, it is important to integrate product design with production planning to optimize resource use and to reduce environmental impact, energy consumption, emissions, and waste generation. The enabling technologies of Industry 4.0 can assist in achieving these goals [211]. In this effort, manufacturing companies face the challenge of balancing technological trade-offs, such as technical feasibility and quality, while also considering environmental, social, and economic trade-offs such as industrial costs [212]. However, there is still a lack of clear definitions and limited recognition of the concept of technological sustainability in the scientific literature [213]. A holistic view is needed to consider technology as an integral part of sustainability, along with the environment, economy, and society.

Vacchi et al. [213] proposed a conceptual model in a recent study that aimed to understand the technological dimension of sustainability and give technology the same weight as the other dimensions. In manufacturing, the degree of technological sustainability depends on optimizing the inputs to ensure the continuity of industrial operations. This approach is essential to address current challenges and develop sustainable solutions that consider all dimensions of sustainability. The technological sustainability model aligns with the life cycle thinking (LCT) framework [214]. This framework utilizes methods such as life cycle assessment (LCA) [215], social life cycle assessment (S-LCA) [216], and life cycle costing (LCC) [217]. These methods follow the standardized steps defined by ISO 14040 [218] and can be integrated with each other in a holistic approach called life cycle sustainability assessment (LCSA) [219].

4.2.2 Gap Identification and Research Aims

The current scientific literature shows that the term “technological sustainability” is often used indistinctly with the concept of “sustainability of technologies”. The latter primarily focuses on the environmental dimension and, to a lesser extent, the social and economic ones [213]. It should be noted that in the limited number of studies available, researchers primarily use the term “technological sustainability” to discuss sustainable technologies [220], the sustainability of technological processes [221], technological competitiveness [222], or the influence of technology on other dimensions of sustainability [223]. Considering these results, based on our current knowledge of the state of the art, it is evident that there is a gap in the scientific literature regarding the concept of technological sustainability, and more importantly, implementation examples are absent. Furthermore, there is a lack of a clear and consistent definition for this term, but more importantly, there is a failure to recognize technology as an integral component of sustainability alongside the environment, economy, and society. Based on the above observations, we aim to address the following research questions to fill this gap and further explore the concept of technological sustainability, including from a quantitative perspective:

RQ1: Is it possible to quantify the level of technological sustainability achieved by a manufacturing organization?

RQ2: How does technological sustainability fit into the transition from Industry 4.0 to Industry 5.0 in the manufacturing paradigm?

This empirical research aims to validate the conceptual model for technological sustainability assessment proposed by Vacchi et al. [213] in a manufacturing context, adopting the process perspective.

4.3 METHODOLOGY

In this study, the methodology called process technological sustainability assessment (P-TSA) [213] used, which follows the same steps as life cycle assessment (LCA) analysis in accordance with ISO 14040 [218]. These steps include goal and scope definition, life cycle inventory analysis, and life cycle impact assessment and interpretation [224]. Process technological sustainability assessment (P-TSA) is a framework that evaluates the sustainability of manufacturing processes by considering their impact on three dimensions: input/output availability (IOA), operational performance (OP), and technical quality (TQ). It uses a value chain perspective and a life cycle approach to identify and analyze relevant indicators for each dimension. Finally, it calculates a comprehensive Process Technology Sustainability Index (P-TSI) to quantify the overall sustainability of the process. P-TSA and LCA are both life cycle methodologies that consider the entire life cycle of a product or process. Both methods use a bottom-up approach, starting with the identification of environmental, economic, and social impacts at each stage of the life cycle and then aggregating them at the product or process level. Both methodologies consider the entire life cycle of the subject from production to disposal. Both methodologies analyze the impact (environmental or technological) of a product or process. Both methodologies aggregate the impacts at the product or process level to produce a single sustainability indicator. However, P-TSA and LCA also have some important differences. P-TSA uses three dimensions to assess technological sustainability (IOA, OP, and TQ), while LCA uses a wide range of indicators to assess environmental impacts. In addition, P-TSA uses a more detailed bottom-up approach than LCA, which often focuses only on the environmental impacts of a product or process.

The research was conducted by following a methodological approach based on a single case study [225], with the ceramic industry selected as the focus of analysis within the manufacturing sector. The ceramic sector is a significant element in the European economy, with Italy having 128 manufacturing companies that, in 2022, produced about 431 million square meters of tiles and employed 18,639 people [226]. Due to the large production volumes, this industry is characterized by a high resource intensity, evidenced by the specific consumption of production factors [227]. In addition, the Italian ceramic industry is a high-tech sector that, in recent years, has implemented Industry 4.0 methodologies and processes at all stages of production lines. Thanks to these developments, the ceramic industry has achieved a high level of competitiveness, gaining significant improvements in efficiency, costs, flexibility, and production quality while at the same time reducing energy consumption and minimizing environmental impacts [228]. The company under consideration is an Italian ceramic tile manufacturer that has already implemented digital technologies as part of Industry 4.0 for several purposes. These include the transition to a circular economy model [229], real-time assessment of organizational environmental impact [230], organizational social impact [231], and the life cycle cost of the product [232].

The company under study specializes in the production of porcelain tiles [233] of various sizes at its three plants. The production process begins with the procurement of raw materials, such as ball clays, feldspars, and sands. These materials come not only from Italy but also from non-EU territories (such as Ukraine and Turkey) and European countries (e.g., Germany) and are transported to ceramic tile manufacturers by land or sea [234]. Upon arrival, the materials are ground with water in large mills, resulting in a solid/liquid suspension called slurry. The slurry is then subjected to a stream of hot air that turns it into spray-dried powder composed of fine particles. The spray-dried powder is further processed in the pressing stage, where it is formed into the desired size. After pressing and drying, the tiles undergo glazing and decoration with digital printers. Once decorated, the tiles are fired at high temperatures (about 1220 °C). After firing, further processes such as cutting, rectifying, polishing, and lapping can be applied. Rectification ensures perfectly square tiles, while cutting allows smaller sizes to be created from larger ones. Polishing involves the controlled removal of the surface layer using abrasive discs, while lapping gives the tiles a smooth but not completely reflective surface. Finally, the tiles are sent to the sorting line, which includes size and flatness control units, before being packaged. A simplified representation of the tiles' manufacturing cycle is shown in Figure 1.

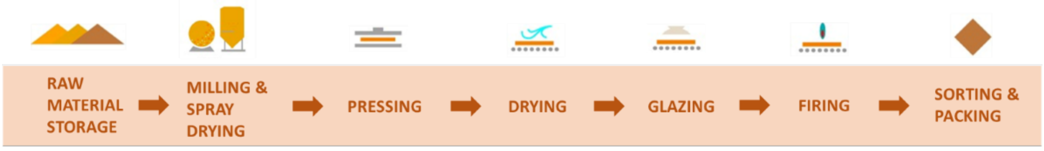


Figure 1 - Flow chart of the ceramic tile manufacturing process, elaborated upon from [230]

It is crucial to provide detailed information on the specific industry to which the company selected as a case study belongs. This information helps to better understand the operational context in which the research was conducted and provides a more solid foundation for the broader applicability of the proposed model for assessing technological sustainability.

The computational model underlying the P-TSA methodology was run using the Microsoft Power BI business intelligence tool. This tool was integrated with the company's enterprise resource planning (ERP) system, which continuously receives real-time process data from the factories through a manufacturing execution system (MES). The MES is connected to numerous sensors at every stage of the production process. The use of this sophisticated system enabled a dynamic assessment of the level of technological sustainability throughout the production process.

4.4 RESULTS AND DISCUSSION

The presentation of the data collection and processing, as well as the discussion of the P-TSA results, follows the same logic as the four phases of ISO 14040 for LCA. This choice is justified for several reasons. First, the four phases of ISO 14040 are a well-established and internationally recognized framework for sustainability assessment. Using it to present the data collection and discuss the results of the P-TSA helps to ensure that the methodology is clear and understandable to the reader. Second, the logical and sequential structure of the four phases of ISO 14040 makes the presentation of the P-TSA results more fluid and easier to follow. Finally, the four phases of ISO 14040 provide a solid foundation for discussing the P-TSA results, identifying the strengths and weaknesses of the process under review, and formulating recommendations for improvement.

4.4.1 Definition of the Goal and Scope of the P-TSA

This Cradle-to-Gate (CTG) analysis [235] uses the Process Technological Sustainability Assessment (P-TSA) framework to quantify the technological impact of porcelain tile production across three manufacturing plants identified as a case study. These plants share identical production technologies and produce the same product type. By isolating the technological impact of the production process itself, the CTG analysis provides a comprehensive assessment of the manufacturing phase, excluding the technological impact of support activities such as sales, marketing, design, research and development. The system boundaries were set at the factory gates because primary data from the distribution, use, and end-of-life phases of the ceramic product are not currently available.

Figure 2 illustrates the system boundaries and presents a schematic breakdown into modules that make up the entire ceramic tile production process, from the beginning to the end of the life cycle (cradle-to-grave). The data used in the analysis are exclusively primary and cover the different stages of the process, from the procurement of inputs to the exit of products through the gates of the three factories (CTG). These data are time series for the years between 2017 and 2022. Similar to Life Cycle Assessment (LCA) studies, the modelling used the attributional approach to assign the technological impact of the process without considering the impact of possible future changes in demand for the ceramic product [236].

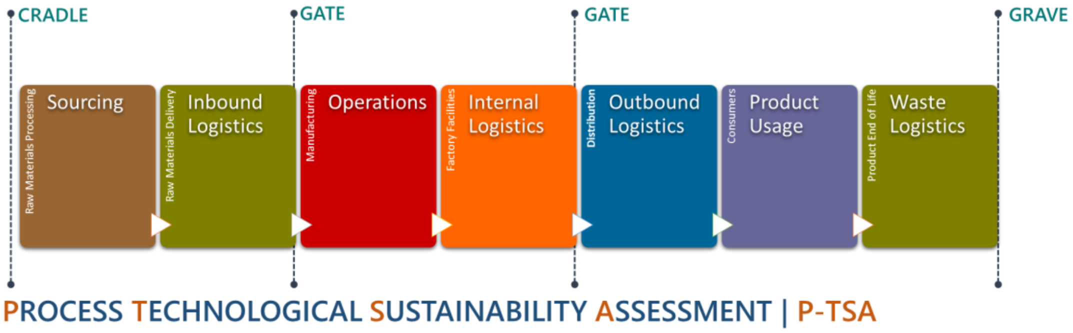


Figure 2 - Life cycle approach to assessing Process Technological Sustainability (P-TSA), adapted from the model of Vacchi et.al. [213].

4.4.2 Technological Inventory Analysis

To assess the technological impact of the company's production activities from cradle to gate, a comprehensive lifecycle inventory analysis was conducted across the three production plants between 2017 and 2022. This analysis used only primary data collected in real-time from the production lines, leveraging the IoT technologies of the Industry 4.0 paradigm. The collected data was seamlessly integrated with the company's ERP (Enterprise Resource Planning) system through a factory MES (Manufacturing Execution System), ensuring seamless data exchange and analysis [237]. All categories and items of primary data collected are presented in Table 1.

Table 1 - Data inventory for P-TSA.

Inventory category	Inventory item	Measure unit
Consumption	Raw materials	ton
	Spray-dried powder	ton
	Packaging components	pc
	Ceramic body stains	kg
	Glazes	kg
	Grits	kg
	Inks	kg
	Water	m^3
	Electricity	kWh
	Natural gas	Smc
Stock	Raw materials	ton
	Spray-dried powder	ton
	Packaging components	pc
	Ceramic body stains	kg
	Glazes	kg
	Grits	kg
	Inks	kg
	Tiles	m^2
Slurry analysis	Density	g/cm^3
	Viscosity	sec.
	Residue	%
Spray-dried powder analysis	Humidity	%
	Residue	%
	Loss On Ignition (L.O.I.)	%
	Water Absorption	%
	Shrinkage	%
Production	Tiles	ton
Tile analysis	Water Absorption	%
	Breaking strength	N
	Modulus of rupture	N/mm^2
	Dimensions	mm
Sales	Tiles	m^2

The inventory items were carefully curated to cover the critical phases of the manufacturing process: input consumption and storage, technological performance metrics of semi-finished products (slurry and spray-dried powder) and finished product (ceramic tiles), quantities produced, and sales volumes.

4.4.3 Technological Impact Assessment

Based on the inventory data collected, the impact assessment calculates the technological impact of the ceramic tile production process. After defining the technological inventory, following the model proposed by Vacchi et al. [213], the Process Technological Sustainability Index (P-TSI) was calculated. For each impact category Input/output availability (IOA), Operational performance (OP) and Technical quality (TQ), technological metrics were used to create indicators.

According to Vacchi et al. [213], for IOA, the average stock and average consumption were employed as the technological metrics for forming the Stock Coverage Rate (SCR) indicator.

Let 'A' be the set of organizational activities, so that each activity a ∈ A; and let 'i_a' represent the input associated with each activity 'a': ∀ a ∈ A ∃ i_a. The Stock Coverage Rate (SCR) for each input 'i_a' was defined as follows:

$$SCR_{i_a}^{t} = \frac{AS_{i_a}^{t}}{AC_{i_a}^{t}} \qquad (1)$$

where $SCR_{i_a}^{t}$ is the stock coverage rate of input i, in the activity a at time t, $AS_{i_a}^{t}$ is the average stock of input i in the activity a at time t, and $AC_{i_a}^{t}$ is the average consumption of input i in the activity a at time t.

Concerning OP, technological metrics such as inputs and outputs were employed to establish the Productivity Indicator. The Productivity Indicator (PI) was characterized as follows:

$$PI_{a}^{t} = \frac{ROU_{a}^{t}}{RIN_{a}^{t}} \qquad (2)$$

where PI_{a}^{t} is the productivity indicator of the activity a at time t, ROU_{a}^{t} is the real output in the activity a at time t, and RIN_{a}^{t} is the real input in the activity a at time t.

Lastly, for TQ, the chosen technological metrics encompassed the quality parameter under control and the acceptability threshold for this parameter.

Let 'o_a' be the output generated from each activity 'a', the OCR for each output 'o_a' was formalized as follows:

$$OCR_{o_a}^{t} = \frac{QP_{o_a}^{t}}{AT_{o_a}^{t}} \qquad (3)$$

where $OCR_{o_a}^{t}$ is the output conformity rate of output o in the activity a at time t, $QP_{o_a}^{t}$ is the quality parameter of output o in the activity a at time t, and $AT_{o_a}^{t}$ is the acceptability threshold of output o in the activity a at time t.

Table 2 illustrates the construction framework of the technological sustainability index, formed by aggregating the sub-indexes for the impact categories along with their corresponding indicators.

Table 2 - Sub-indexes and indicators of P-TSI.

Index	Sub-indexes	Indicators	AS / ROU / QP	AC / RIN / AT
TSI	IOAI	SCR (raw materials)	Stock - Raw materials	Consumption - Raw materials
		SCR (spray-dried powder)	Stock - Spray-dried powder	Consumption - Spray-dried powder
		SCR (packaging)	Stock - Packaging components	Consumption - Packaging components
		SCR (ceramic body dyes)	Stock - Ceramic body dyes	Consumption - Ceramic body dyes
		SCR (glazes)	Stock - Glazes	Consumption - Glazes
		SCR (grits)	Stock - Grits	Consumption - Grits
		SCR (inks)	Stock - Inks	Consumption - Inks
		SCR (tiles)	Stock - Tiles	Sales - Tiles
	OPI	PI (spray-dried powder)	Production - Tiles	Consumption - Spray-dried powder
		PI (water)	Production - Tiles	Consumption - Water
		PI (electricity)	Production - Tiles	Consumption - Electricity
		PI (natural gas)	Production - Tiles	Consumption - Natural gas
	TQI	OCR (slurry)	Slurry analysis - Slurry quality index	Acceptability Threshold for Slurry quality index
		ORC (spray-dried powder)	Spray-dried powder analysis - Spray-dried powder quality index	Acceptability Threshold for Spray-dried powder quality index
		OCR (Breaking strength)	Tile analysis - Breaking strength	Acceptability Threshold for Breaking strength
		OCR (Modulus of rupture)	Tile analysis - Modulus of rupture	Acceptability Threshold for Modulus of rupture
		OCR (Dimensions)	Tile analysis - Dimensions	Acceptability Threshold for Dimensions
		OCR (Water Absorption)	Tile analysis - Water Absorption	Acceptability Threshold for Water Absorption

After applying the z-score standardization [238] the indicators were aggregated into the corresponding sub-indexes (In-/Output Availability Index (IOAI), Operational Performance Index (OPI) and Technical Quality Index (TQI)) by arithmetic mean. This standardization process, which involves converting the original values into a format that reflects how many standard deviations a given value deviates from the mean [239], was chosen for its ability to ensure a balanced contribution of each indicator to the aggregated indices [238]. Unlike other normalization methods, such as min-max or logarithmic transformation, z-score standardization effectively neutralizes the impact of extreme variations in individual indicators, thus avoiding distortions in the overall results.

Finally, the comprehensive Process Technological Sustainability Index (P-TSI) was established by consolidating the scores derived from the sub-indexes (IOAI, OPI, and TQI).

In particular, given the set of sub-indexes H = {hj} (j = 1, …, J), we assign to each sub-index ‘h_j’ a weight ‘$w_j \geq 0$’, such that $\sum_{j=1}^{J} w_j = 1$. The composite index was formalized as follows:

$$TSI^t = \sum_{j=1}^{J} w_j \, h_j^t \quad (4)$$

$$TSI^t = [w_{IOA}\, IOAI^t] + [w_{OP}\, OPI^t] + [w_{TQ}\, TQI^t] \quad (5)$$

Vacchi et al. [213] proposed a model where equal weights are assigned to the indexes as a weighting criterion. However, they recommended adapting the criterion to the specific needs of the organizational unit under study. Following this recommendation, the present research explores a comparative analysis between the weighting scheme with equal weights and three other scenarios simulating different production conditions, with the aim of assessing its applicability to and effectiveness in the case study.

Table 3 shows the w_j weights used for the four different scenarios: (1) a scenario with equal weights; (2) a scenario in which stable supply and production conditions are assumed, while the relevance of the qualitative dimension of the outcome is emphasized; (3) a scenario in which criticality in the supply of inputs is expected, and for this reason, this dimension is stressed; and (4) a scenario in which the main emphasis is placed on the company’s operational performance, suggesting that the main objective is to maximize the efficiency and effectiveness of production operations or services. After normalization, the values assumed annually by the IOAI, OPI, and TQI indices are shown in the first three columns of Table 4. The last four columns of the table represent the annual values of the Process Technological Sustainability Index (P-TSI) for each scenario described in Table 3. Regarding the P-TSI, this index was calculated using a weighted average as defined in Equation (5).

Table 3 - Sub-index weights for scenarios 1, 2 (assumptions of supply stability), 3 (assumptions of supply instability) and 4 (focus on operational performance).

Sub indexes	Sub-index weights Scenario 1	Sub-index weights Scenario 2	Sub-index weights Scenario 3	Sub-index weights Scenario 4
IOAI	33.33%	20.00%	60.00%	20.00%
OPI	33.33%	20.00%	20.00%	60.00%
TQI	33.33%	60.00%	20.00%	20.00%

Table 4 - Annual IOAI, OPI, TQI, and P-TSI of scenarios 1, 2, 3 and 4.

Years	IOAI	OPI	TQI	P-TSI Scenario 1	P-TSI Scenario 2	P-TSI Scenario 3	P-TSI Scenario 4
2017	-0.18	0.08	0.31	0.07	0.17	-0.03	0.07
2018	0.18	-0.43	0.11	-0.05	0.01	0.04	-0.20
2019	0.15	-0.32	-0.14	-0.10	-0.11	0.00	-0.19
2020	0.15	-0.27	0.03	-0.03	-0.01	0.04	-0.13
2021	-0.24	0.30	-0.25	-0.07	-0.14	-0.14	0.08
2022	-0.06	0.65	-0.06	0.18	0.08	0.08	0.37

Furthermore, it is important to emphasize that an increase in the values of the IOAI, OPI, TQI, and P-TSI was interpreted as a positive signal, indicating an improvement in input availability, operational performance, quality, and technological sustainability, respectively. These increments reflect favorable progress in the corresponding metrics, suggesting that the policies or technological innovations implemented had a beneficial impact in the analyzed context.

Figure 3, on the other hand, pictures the trends on an annual basis of the indices for the four scenarios considered in this study as well. The analysis of the indices for the period between 2017 and 2022 demonstrates the model's ability to capture significant events affecting the manufacturing sector during this period. Specifically, the IOAI showed an improvement in 2018 compared with 2017 due to interventions that expanded storage facilities for raw materials, chemical compounds, and semi-finished goods. The index then remained stable from 2018 to 2020, with a sharp decline in 2021 due to the disruption of global supply chains caused by the pandemic. A slight recovery can be observed in 2022. The OPI is closely linked to production volumes as it is based on the consumption of key production factors (ceramic mix, water, electricity, and natural gas). This index showed a gradual increase from 2019, with particularly high values in 2021 and 2022 due to the robust economic recovery following the pandemic. Finally, the TQI highlighted a decline in product quality in 2021 due to the substitution of raw materials with lower-quality alternatives to address the supply chain disruption. In 2022, following the post-pandemic supply emergency, the index showed a recovery, approaching the average for the period.

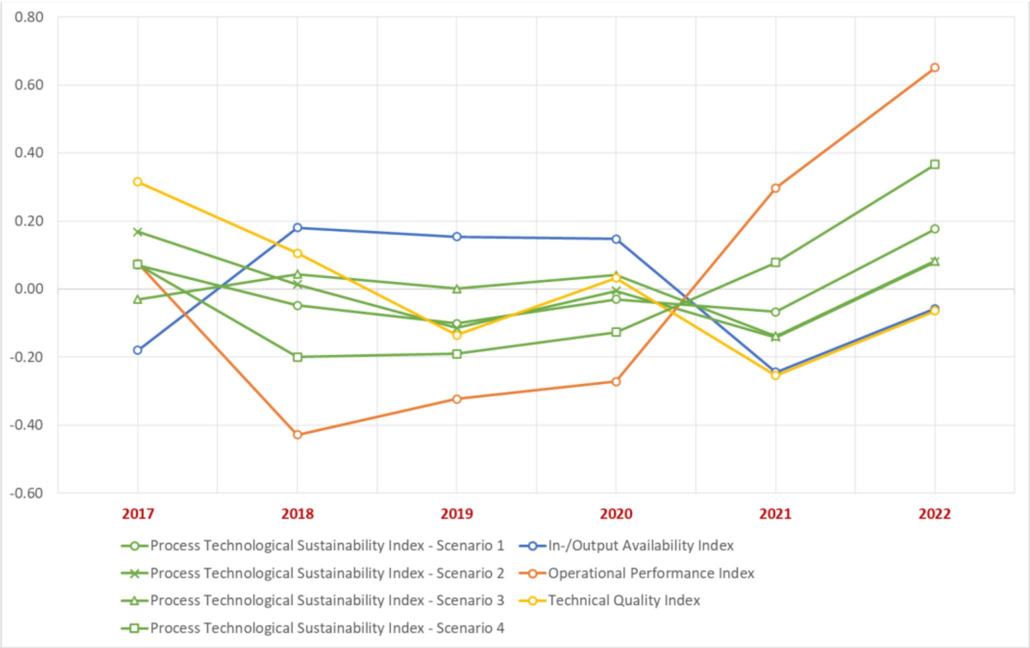


Figure 3 - Annual IOAI, OPI, TQI and P-TSI of scenarios 1, 2, 3, and 4.

In contrast, the annual integrated index showed similar values for the four scenarios over the study period of 2017–2022. Therefore, the absence of significant variations in the annual averages justified a higher level of granularity by considering the monthly values during the entire period from 2017 to 2022. Table 5 follows the same structure as Table 4 but presents data for each index and scenario for all months within the years considered.

Table 5 - Monthly IOAI, OPI, TQI and P-TSI of scenarios 1, 2, 3 and 4.

Month-year	IOAI	OPI	TQI	P-TSI Scenario 1	P-TSI Scenario 2	P-TSI Scenario 3	P-TSI Scenario 4
Jan-17	0.65	-0.64	0.36	0.12	0.22	0.33	-0.18
Feb-17	-0.09	0.52	0.23	0.22	0.23	0.10	0.34
Mar-17	-0.49	0.57	0.13	0.07	0.09	-0.15	0.27
Apr-17	-0.03	0.31	0.28	0.19	0.23	0.10	0.24
May-17	-0.48	0.03	0.20	-0.08	0.03	-0.24	-0.03
Jun-17	-0.66	0.09	0.05	-0.17	-0.08	-0.37	-0.07
Jul-17	-0.65	-0.04	0.39	-0.10	0.10	-0.32	-0.07
Aug-17	0.30	-0.34	0.71	0.22	0.42	0.25	0.00
Sep-17	-0.62	0.00	0.18	-0.15	-0.02	-0.33	-0.09
Oct-17	-0.47	0.28	0.41	0.08	0.21	-0.14	0.16
Nov-17	-0.44	0.20	0.21	-0.01	0.08	-0.18	0.07
Dec-17	0.80	-0.09	0.62	0.44	0.51	0.59	0.23
Jan-18	0.02	-0.30	0.79	0.17	0.42	0.11	-0.02
Feb-18	-0.25	0.08	0.68	0.17	0.37	0.00	0.13
Mar-18	-0.33	0.08	0.13	-0.04	0.03	-0.16	0.01
Apr-18	-0.38	0.22	0.09	-0.02	0.02	-0.17	0.07

May-18	-0.28	0.02	0.07	-0.06	-0.01	-0.15	-0.03
Jun-18	-0.51	0.18	0.36	0.01	0.15	-0.20	0.08
Jul-18	-0.45	0.44	0.13	0.04	0.08	-0.16	0.20
Aug-18	3.56	-5.31	0.77	-0.33	0.11	1.23	-2.32
Sep-18	-0.31	-0.37	-0.27	-0.32	-0.30	-0.31	-0.34
Oct-18	-0.32	0.05	-0.43	-0.23	-0.31	-0.27	-0.12
Nov-18	-0.36	-0.05	-0.53	-0.31	-0.40	-0.33	-0.21
Dec-18	1.80	-0.20	-0.56	0.35	-0.02	0.93	0.13
Jan-19	1.20	-1.39	0.36	0.05	0.18	0.51	-0.52
Feb-19	-0.30	-0.27	0.23	-0.11	0.03	-0.19	-0.18
Mar-19	-0.54	-0.26	0.34	-0.15	0.04	-0.31	-0.20
Apr-19	-0.27	-0.14	0.06	-0.11	-0.04	-0.18	-0.12
May-19	-0.25	0.01	-0.27	-0.17	-0.21	-0.20	-0.10
Jun-19	-0.44	-0.01	-0.19	-0.21	-0.20	-0.31	-0.13
Jul-19	-0.40	0.23	-0.72	-0.29	-0.46	-0.34	-0.08
Aug-19	2.80	-1.70	-0.63	0.16	-0.16	1.22	-0.58
Sep-19	-0.43	-0.18	-0.71	-0.44	-0.55	-0.43	-0.33
Oct-19	-0.47	-0.06	-0.47	-0.33	-0.39	-0.39	-0.22
Nov-19	-0.26	-0.05	0.15	-0.06	0.03	-0.14	-0.05
Dec-19	1.22	-0.06	0.21	0.46	0.36	0.76	0.25
Jan-20	0.27	-0.62	0.25	-0.03	0.08	0.09	-0.27
Feb-20	-0.37	0.20	0.44	0.09	0.23	-0.09	0.14
Mar-20	0.66	-0.22	0.24	0.23	0.23	0.40	0.05
Apr-20	2.49	-2.68	-0.71	-0.30	-0.46	0.81	-1.25
May-20	0.06	-0.10	0.30	0.08	0.17	0.07	0.01
Jun-20	-0.54	0.09	0.02	-0.15	-0.08	-0.31	-0.05
Jul-20	-0.53	0.02	0.05	-0.15	-0.07	-0.30	-0.08
Aug-20	0.83	-0.50	-0.01	0.11	0.06	0.40	-0.14
Sep-20	-0.54	0.25	-0.14	-0.14	-0.14	-0.30	0.02
Oct-20	-0.50	0.17	0.08	-0.08	-0.02	-0.25	0.02
Nov-20	-0.25	0.01	0.20	-0.02	0.07	-0.11	-0.01
Dec-20	0.20	0.12	-0.32	0.00	-0.13	0.08	0.05
Jan-21	0.34	-0.70	-0.02	-0.13	-0.09	0.06	-0.36
Feb-21	-0.38	0.23	-0.11	-0.08	-0.09	-0.20	0.04
Mar-21	-0.66	0.42	0.04	-0.07	-0.03	-0.30	0.13
Apr-21	-0.43	0.35	0.16	0.03	0.08	-0.16	0.15
May-21	-0.60	0.36	-0.17	-0.14	-0.15	-0.32	0.06
Jun-21	-0.59	0.30	-0.22	-0.17	-0.19	-0.34	0.02
Jul-21	-0.53	0.42	-0.65	-0.25	-0.41	-0.37	0.02
Aug-21	0.59	-0.05	-0.28	0.09	-0.06	0.29	0.03
Sep-21	-0.57	0.52	-0.45	-0.17	-0.28	-0.33	0.11
Oct-21	-0.34	0.45	-0.50	-0.13	-0.28	-0.21	0.10
Nov-21	-0.28	0.49	-0.53	-0.11	-0.28	-0.18	0.13
Dec-21	0.52	0.77	-0.32	0.33	0.07	0.41	0.50

Jan-22	0.42	-0.32	0.22	0.11	0.15	0.23	-0.06
Feb-22	-0.18	0.75	0.07	0.21	0.15	0.06	0.43
Mar-22	-0.64	0.70	-0.04	0.01	-0.01	-0.25	0.28
Apr-22	-0.38	0.72	0.18	0.17	0.18	-0.05	0.39
May-22	-0.37	0.79	0.01	0.15	0.09	-0.06	0.40
Jun-22	-0.50	0.67	-0.18	0.00	-0.07	-0.20	0.27
Jul-22	-0.22	0.43	-0.34	-0.05	-0.17	-0.12	0.15
Aug-22	1.10	0.59	-0.56	0.38	0.00	0.67	0.46
Sep-22	-0.34	0.79	-0.32	0.04	-0.10	-0.11	0.34
Oct-22	-0.29	0.83	-0.13	0.14	0.03	-0.03	0.41
Nov-22	-0.03	0.94	0.07	0.33	0.22	0.18	0.57
Dec-22	0.73	0.92	0.26	0.64	0.48	0.68	0.75

The values of the P-TSI indicator, expressed monthly and presented in Table 5, were then plotted for each scenario. On one hand, the time series for the period of 2017–2022 was plotted, and on the other hand, the monthly variation over the years was plotted. These plots are referred to as "A" and "B" in Figures 4–7. The light blue trend line in the graphs of type (A) is linear, and it was automatically calculated using MS 365 Excel.

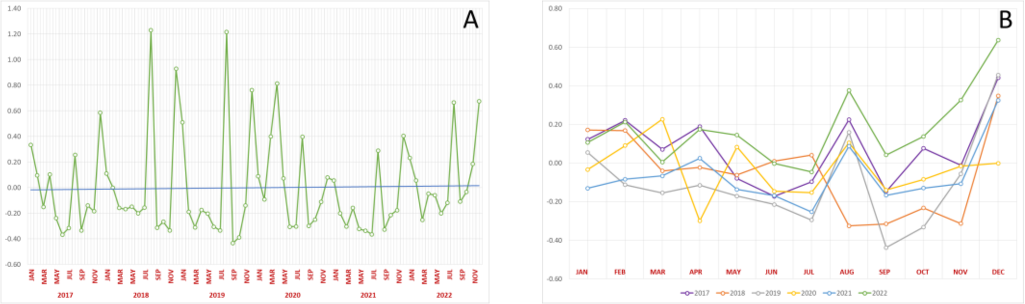


Figure 4 - Process Technological Sustainability Index of Scenario 1: (A) time series; (B) comparison between years.

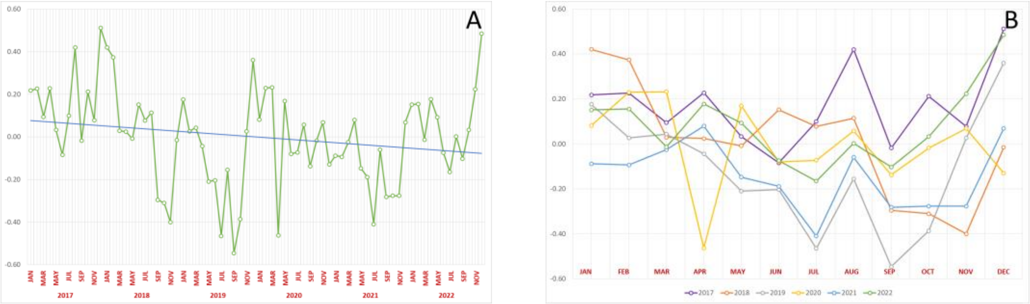


Figure 5 - Process Technological Sustainability Index of Scenario 2: (A) time series; (B) comparison between years.

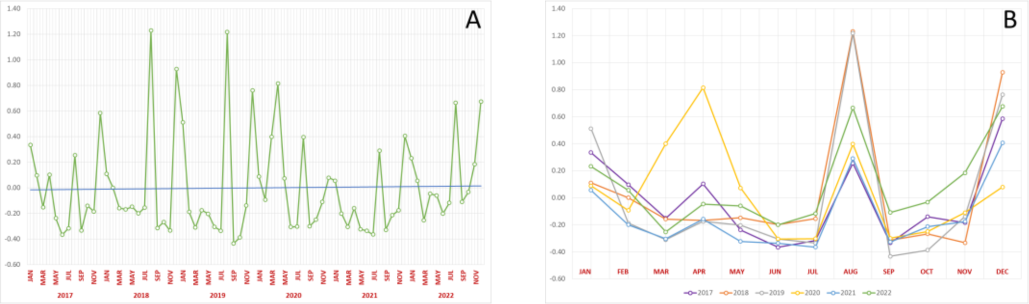


Figure 6 - Process Technological Sustainability Index of Scenario 3: (A) time series; (B) comparison between years.

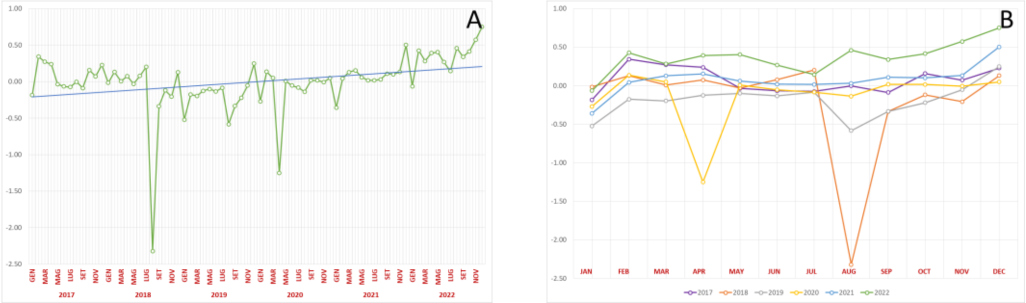


Figure 7 - Process Technological Sustainability Index of Scenario 4: (A) time series; (B) comparison between years.

Figure 4A shows the monthly time trend of the P-TSI, which was constructed by giving equal weight to the IOAI, OPI, and TQI subindices (Scenario 1). Positive peaks relative to the average occurred during production interruptions for maintenance (August and December) and due to the pandemic (March and April 2020). During these months, the IOAI component of the index became particularly relevant due to increased inventory levels. Conversely, negative peaks relative to the average correspond to the periods of production recovery in January–February and September–October, as well as the recovery in May–June 2020 following the production shutdown due to the pandemic. The trend line, shown in light blue on the graph, indicates a tendency toward stability. Figure 4B shows the annual comparison of the monthly trend of the P-TSI for scenario 1. While the graphs show a similar pattern, there was a dip in the index in April 2020 due to the pandemic-related production stoppage, followed by a moderate recovery. Overall, the year 2022 stands out as the most technologically sustainable, with index values consistently above average throughout the months. This trend is attributed to the significant production volumes aimed at meeting the demand for ceramic tiles after the pandemic, allowing for an even more efficient use of production factors and factory facilities.

Figure 5A illustrates the monthly temporal evolution of the P-TSI for scenario 2. In this scenario, the TQI subindex had a higher weight of 60%, while the IOAI and OPI maintained a constant weight of 20% each. The negative peaks relative to the average observed after the maintenance shutdowns in August 2018 and 2019 were due to the technological changes that the company underwent during these periods, characterized by the completion of digitalization of the glazing and decoration phases of the tiles. These process revamps required adjustments and modifications to the production cycles, which had a negative impact on the product quality. As a result, the trend line, shown in light blue on the graph, highlights a tendency for the P-TSI to decrease, although a significant recovery of the index can be observed in 2022, when it exceeded the average values. Figure 5B shows the annual comparison of the monthly trend of the P-TSI for scenario 2. Even in this configuration, the graphs show a similar pattern, but there is a clear trend toward improved technological sustainability performance in the second quarter of each year analyzed.

Figure 6A shows the monthly time evolution of the P-TSI for scenario 3, highlighting a significant weighting of the IOAI (60%), while the OPI and TQI both maintained a consistent weight of 20%. Overall, the graph, particularly the trend line (shown in light blue), highlights the consistency of the technological sustainability performance and the maintenance of the equilibrium of the production system over time. Figure 6B shows the annual comparison of the monthly trend of the P-TSI for scenario 3. In this scenario, where the importance of the sourcing dimension was emphasized, the monthly trend of the P-TSI showed similarity in all years, with positive peaks during production shutdowns for maintenance (August and December), resulting in an increase in the storage of production factors. However, a similar positive peak can be observed in April 2020, a period when there was a production stoppage due to the pandemic.

Figure 7A shows the monthly time evolution of the P-TSI for scenario 4, highlighting a significant weighting of the OPI (60%), while the IOAI and TQI both maintained a consistent weight of 20%. The troughs below the average correspond to plant shutdowns for maintenance in August and, to a lesser extent, in December, which represent periods of minimal productivity for the production system. However, starting in September 2018, the P-TSI experienced a significant increase, as shown by the trend line in blue in the figure. Figure 7B shows an annual comparison of the monthly trend of the P-TSI for scenario 2. Also in this configuration, the graphs show a similar pattern. However, a negative peak in technological sustainability can be observed in April 2020, which was attributed to the plant shutdown during the pandemic, and another more significant negative peak in August 2018, which was attributed to a longer production shutdown for maintenance compared with August in other years.

Scenario 4 emerged as the most technologically sustainable of the scenarios analyzed, with consistently high P-TSI scores. This can be attributed to its emphasis on operational performance, which is critical to the overall efficiency and sustainability of the production system. An increased focus on OPI promotes process optimization, reduced downtime, and improved resource utilization, resulting in a more sustainable and productive operation. While other scenarios showed positive trends, scenario 4 consistently outperformed them, establishing itself as the optimal choice for achieving long-term technological sustainability.

4.4.4 Technological Interpretation

As proposed in the conceptual model that this study aims to validate (Figure 8), Technological Interpretation represents the final phase of the P-TSA process implemented here.

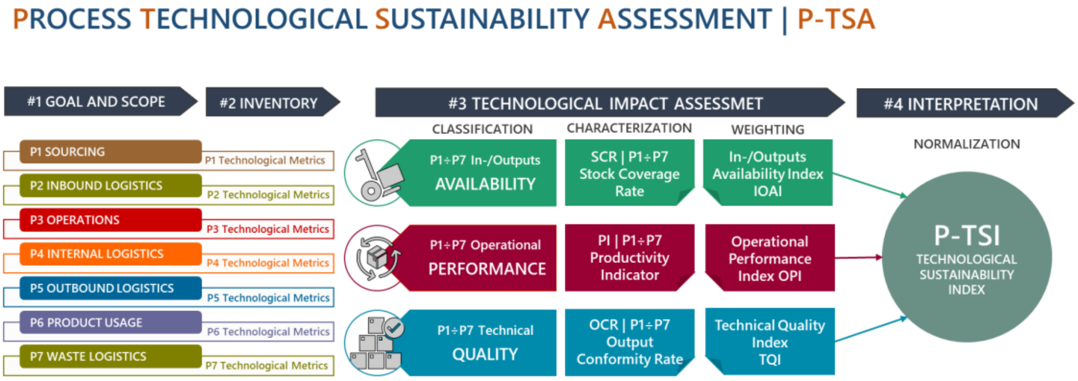


Figure 8 - Holistic interpretive frameworks for the four phases of Process Technological Sustainability Assessment (P-TSA), adapted from the model of Vacchi et.al. [24].

In this phase, the results of the previous inventory analysis and impact assessment procedures are summarized and discussed in order to draw conclusions and make recommendations regarding the initiatives to be undertaken. This process is tailored to the specific objectives and scope of the study.

4.4.4.1 Key Factors in Technological Assessment

The empirical validation of the Process Technological Sustainability Assessment (P-TSA) framework using real-time data collected from three ceramic tile manufacturing plants has shown promising results in quantifying the technological impact of the production process. The analysis confirms the effectiveness of the P-TSA in identifying key factors that influence technological sustainability, such as input/output availability (IOA), operational performance (OP), and technical quality (TQ). The analysis revealed that the technological impact of the ceramic tile production process is influenced by several factors, including:

1 Production Interruptions: Production interruptions for maintenance and the pandemic were found to have a significant impact on the P-TSI index. During these periods, the IOAI component of the index becomes particularly relevant due to increased inventory levels. This is because the company must rely on inventories of raw materials, components, and semi-finished products to maintain production when the production line is shut down. The increased inventory levels result in higher environmental impacts due to the storage and handling of materials.

2 Technological changes: The company's technological changes, such as the digitalization of the glazing and decoration phases of the tiles, were found to have a negative impact on the P-TSI index, particularly on the TQI component. These process changes required adjustments and modifications to the production cycles, which had a negative impact on product quality. This resulted in an increase in the number of defective tiles that had to be scrapped or reworked.

3 Sourcing: The weighting of the IOAI index was found to have a significant impact on the P-TSI index. When the IOAI index was weighted more heavily, the index values were more stable over time, indicating that the company was better at managing its inventory levels. This was because the company relied more on secure and reliable sources of supply for its raw materials, components, and semi-finished products.

4 Production Volumes: Production volume was found to have a positive impact on the P-TSI index. This is because when production volumes are high, the company is able to achieve

economies of scale, which can lead to lower environmental impacts per unit of product. This was particularly evident in 2022, when the index scores were consistently above average across the months. This trend is attributed to the significant production volumes to meet the post-pandemic demand for ceramic tiles.

Altogether, the analysis of the P-TSI suggests that the company can improve its technological sustainability performance by reducing production interruptions, implementing technological changes more carefully, diversifying its sourcing base, and increasing production volumes. The completeness of the inventory and impact assessment was supported using primary data collected in real time from production lines, leveraging IoT technologies of the Industry 5.0 paradigm. The data were seamlessly integrated with the company's enterprise resource planning (ERP) system through a factory manufacturing execution system (MES), ensuring seamless data exchange and analysis. The analysis was also consistent with the goal and scope of the P-TSA, which is to quantify the technological impact of porcelain tile production. The analysis considered the entire production process, from the procurement of inputs to the exit of products through the gates of the three factories. The impact analysis of the key factors of technological impact was carried out by varying the weights of the IOAI, OPI and TQI. The results of this analysis suggest that the IOAI is the most sensitive factor, followed by the OPI and the TQI. Based on the interpretation of the technological results, valuable insights can be gained regarding the factors that can influence the technological impact of the porcelain tile manufacturing process. By identifying these factors, the company can take proactive measures to improve its technological sustainability performance.

4.4.4.2 Sensitivity Analysis in P-TSA

Sensitivity analysis is a key component of the P-TSA framework, providing insights into the potential variability of technological sustainability outcomes under varying conditions. By systematically examining how the P-TSI responds to changes in key parameters and assumptions, organizations can gain a deeper understanding of the factors that drive their technological sustainability performance and identify areas for improvement. Among the various approaches to sensitivity analysis, scenario analysis is a valuable tool for evaluating the impact of different sourcing strategies on the P-TSI. This approach involves defining alternative scenarios that reflect different sourcing locations, suppliers, or materials, allowing for a comprehensive assessment of the company's technological sustainability performance across a range of possibilities. The decision to employ scenario analysis is driven by several compelling reasons.

Firstly, it aligns with the holistic nature of the P-TSA framework, which encompasses the entire production process from sourcing to final product delivery. Scenario analysis enables the evaluation of technological sustainability across the entire value chain, considering the interconnectedness of different production stages and their collective impact on the environment. Secondly, scenario analysis facilitates a more nuanced understanding of the factors that influence technological sustainability. By exploring multiple scenarios, organizations can isolate the impact of specific parameters such as the availability of sustainable materials, the cost of sourcing, or the environmental impact of transportation on the overall P-TSI. This granular analysis allows for targeted decision making aimed at optimizing technological sustainability performance. Moreover, scenario analysis contributes to a more robust and reliable assessment of technological sustainability. By evaluating the index across a range of conditions, organizations can gain a better understanding of the variability in their technological sustainability performance and the uncertainty associated with their P-TSA results. This enhanced understanding can support informed decision making and support the development of more effective sustainability strategies.

It is conducted a sensitivity analysis based on different scenarios of natural raw material supplies following the eco-design approach used in a previous study [41]. With the aim of minimizing environmental impact, the eco-design approach of the previous study focused on analyzing the composition of the porcelain stoneware body produced by the company. This composition consisted mainly of ball clays, sodium, and potassium feldspars and sands.

Table 6 illustrates the eco-design strategy adopted. Starting from the initial formulation of the body (C1), a gradual reduction was planned until the Ukrainian ball clay was eliminated, as well as a reduction in Turkish sodium feldspar. At the same time, the quantities of German ball clay and domestic raw materials (kaolinitic clays, sodium and potassium feldspars, and feldspathic and quartz sands) were increased (compositions C2, C3, C4, C5, and C6). This change in sourcing had an impact on the incoming logistics, as the transportation system of raw materials varies according to their origin. Ukrainian ball clay is transported by train, ship, and truck; Turkish feldspar is transported by truck, ship, and truck; German clay is transported by truck and train; and domestic raw materials are transported exclusively by truck. From an environmental perspective, German ball clay has the advantage of being transported primarily by rail, which has a lower environmental impact than trucking and a shorter distance than Ukrainian ball clay. Domestic raw materials benefit from a shorter distance between the mine and factory, contributing to an overall reduction in the environmental impact of transportation.

Table 6 - Sourcing scenarios proposed by Vacchi et.al. [229].

Raw Materials (wt.%)	C1	C2	C3	C4	C5	C6
Ukraine Ball Clay	30	25	20	15	10	/
German Ball Clay	15	20	20	25	25	30
Turkish Na-Feldspar	37	35	30	25	20	20
Italian Kaolinitic Clay	/	/	10	15	20	30
Italian K-Feldspar	10	10	10	10	15	15
Italian Feldspar Sand	/	/	10	10	10	5
Italian Quartz Sand	8	10	/	/	/	/

Ukrainian ball clays exhibit superior qualitative performance compared with German ball clays and Italian kaolinitic clays, particularly in their plasticity. This property imparts mechanical strength to the ceramic body both before and after firing, as well as the ability to control linear shrinkage during firing, thereby influencing the final dimensions of the tiles, particularly their length. Similarly, Turkish sodium feldspars have significantly higher fusibility than Italian feldspars. These differences lead to variations, including potentially harmful ones, in the quality of the final product compared with the limits set by international standards. Consequently, the significant environmental improvement achieved through eco-design is not necessarily compatible with maintaining the current level of production quality. In this study, a technological design approach (techno-design) was used to assess whether the sensitivity of the

P-TSA tool could verify the technological feasibility of the C2–C6 compositions compared with the C1 reference production standard. To achieve this, considering the technological feasibility performance of the year of 2017 (optimal during the analysis period in terms of the P-TSI), all parameters were kept constant, except for those related to the technological quality performance, which were replaced by the values shown in Table 7.

Table 7 - Technological performance (ISO 10545) of C1÷C6 ceramic bodies [38].

Technological properties	C1	C2	C3	C4	C5	C6
Length (nominal N = 604 mm)	603.7 ± 0.1	601.3 ± 0.1	604.6 ± 0.1	608.1 ± 0.1	605.1 ± 0.1	603.2 ± 0.1
Linear shrinkage (%)	6.55 ± 0.02	6.92 ± 0.02	6.41 ± 0.02	5.87 ± 0.02	6.33 ± 0.02	6.63 ± 0.02
Dimensional conformity (ISO 10545-2)	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm	N ± 2.0 mm
Water absorption (%)	0.39 ± 0.01	0.18 ± 0.01	0.49 ± 0.01	0.61 ± 0.01	0.52 ± 0.01	0.27 ± 0.01
Water absorption conformity (ISO 10545-3)	≤0.5%	≤0.5%	≤0.5%	≤0.5%	≤0.5%	≤0.5%
Bending strength (N)	1749 ± 1	1592 ± 1	1482 ± 1	1420 ± 1	1510 ± 1	1767 ± 1
Bending strength conformity (ISO 10545-4)	≥1300 N	≥1300 N	≥1300 N	≥1300 N	≥1300 N	≥1300 N

The technological characteristics related to quality, as shown in Table 7, were included in the calculation system, keeping the other metrics constant for the 2017 production year. To perform the sensitivity analysis, Scenario 2 (Table 3) was adopted, emphasizing the weight of the quality dimension in the P-TSA assessment. The results are presented in Table 8.

Table 8 - IOAI, OPI, TQI and P-TSI of C1÷C6 formulations.

Indexes	C1	C2	C3	C4	C5	C6
In-/Output Availability Index	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
Operational Performance Index	0.08	0.08	0.08	0.08	0.08	0.08
Technical Quality Index	0.31	-0.04	0.01	-0.80	-0.12	0.25
Process Technological Sustainability Index	0.17	-0.05	-0.02	-0.50	-0.09	0.13

The IOAI and OPI subindices remain unchanged, while the TQI index deteriorates significantly. This decrease is reflected in the final Technological Sustainability Index (P-TSI). The results show that the composition closest to the technological sustainability performance of the reference production (C1) is C6, which also showed the best environmental performance in the eco-design study.

To assess the response of the technological sustainability assessment model to variations in qualitative performance, a sensitivity analysis was performed by measuring the deviation of each formulation (C2÷C6) from the production standard (C1). The results of this analysis are shown in Table 9.

Table 9 - Sensitivity analysis performed on different sourcing scenarios.

Indexes	C2/C1 [%]	C3/C1 [%]	C4/C1 [%]	C5/C1 [%]	C6/C1 [%]
In-/Output Availability Index	0.00	0.00	0.00	0.00	0.00
Operational Performance Index	0.00	0.00	0.00	0.00	0.00
Technical Quality Index	-113.34	-98.29	-354.74	-137.60	-20.88
Process Technological Sustainability Index	-127.45	-110.53	-398.91	-154.73	-23.48

The figures show a significant percentage of deviation for the TQI, ranging from −20.88% (C6) to −354.74% (C4). These results were also reflected in the overall technological sustainability index, which varied between −23.48 for the C6 composition and −398.91 for the C4 composition.

To ensure clarity, the data from Table 9 have been visualized in the histograms of Figure 9, which shows the behavior of the TQI and P-TSI. It is important to note that changes in the raw materials had a significant impact on the performance of the final product. The sensitivity analysis indicates that a techno-design approach can be pursued in parallel with eco-design with careful weighting of the indices and while also considering different weights for the two approaches.

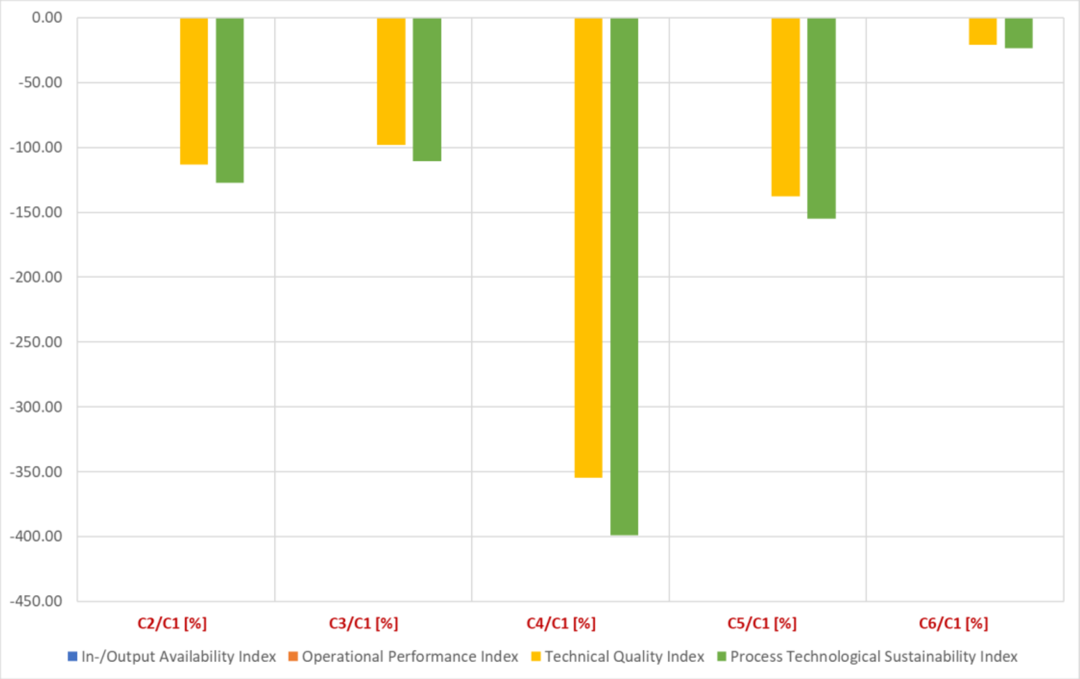


Figure 9 - Sensitivity analysis performed on different sourcing scenarios.

4.4.5 P-TSA as a strategic enabler toward Industry 5.0

The Process Technological Sustainability Assessment (P-TSA) framework has the potential to become a powerful tool to support manufacturing companies on their ambitious journey towards the sustainability goals outlined in the Industry 5.0 paradigm[240]. It enables companies to proactively identify and monitor opportunities for improvement, understand their interrelationships with the various dimensions of sustainability, and thereby gain a competitive advantage. This framework is of critical strategic importance in the context of the transition to Industry 5.0, serving as a bridge between Industry 4.0 and the vision of advanced manufacturing. The integration of technological sustainability into the production process is a distinctive aspect of the P-TSA. In addition, the model, complemented by the inclusion of environmental, social, and economic metrics, can provide a systemic view to assess the sustainability of production processes. This approach responds to the needs of Industry 5.0, which requires a deep integration between technologies aimed at minimizing environmental and social impacts. In this systemic perspective, P-TSA emerges as a catalyst for an in-depth understanding of the relationships between technological sustainability and the other dimensions of sustainability. This awareness emerges as an essential pillar in the context of Industry 5.0, where an integrated approach to sustainability is key to driving the use of technologies to reduce environmental and social impacts. Bridging the gap between Industry 4.0 and Industry 5.0 and the role played by P-TSA in this transition is highlighted in Table 10 below.

Table 10 - P-TSA Framework for the transition from Industry 4.0 to Industry 5.0.

INDUSTRY 4.0			INDUSTRY 5.0		
FOCUS	TOOLS	EFFECTS	FOCUS	TOOLS	EFFECTS
Efficiency and optimization	IoT, automation, data analytics	Reduced costs, improved productivity	Sustainable manufacturing	P-TSA framework, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA)	Reduced environmental impact, improved resource efficiency
Data-drive decision-making	Predictive maintenance, supply chain management	Increased agility and responsiveness	Human-centered automation	Augmented reality, wearables	Enhanced human-machine interaction, improved worker safety and well-being
Collaboration and connectivity	Cloud computing, collaborative robots	Enhanced communication and knowledge sharing	Intelligent production systems	Machine learning, artificial intelligence	Predictive maintenance, personalized product

The transition from Industry 4.0 to Industry 5.0 involves a paradigm shift from automation and data collection to intelligent manufacturing and human-centered automation. Therefore, summarizing the concepts previously outlined, the P-TSA framework aligns with this shift by enabling manufacturers to achieve:

1 Comprehensive Sustainability Assessment: P-TSA can integrate environmental, economic, and social metrics, providing a systemic view of corporate sustainability throughout the process or product life cycle.
2 Identification and Monitoring of Opportunities: P-TSA enables manufacturing companies to identify and monitor improvement opportunities across all stages of the production process, aligning with the integrated approach demanded by Industry 5.0.

3 Understanding Interconnected Dimensions: The framework assists companies in understanding the intricate relationships between technological sustainability and other sustainability dimensions, such as economic and social aspects, essential for Industry 5.0's systemic sustainability approach.
4 Achieving Competitive Advantage: Companies investing in technological sustainability gain a competitive advantage by improving efficiency, reducing costs, and enhancing attractiveness to consumers and investors.
5 Achieving Industry 5.0 Sustainability Goals: By leveraging the P-TSA, manufacturing companies can strategically achieve the sustainability goals of Industry 5.0. The framework serves as a critical foundation, allowing them to identify improvement opportunities, understand sustainability relationships, and gain a competitive edge in the evolving industrial landscape.

The above points can be viewed as constructs of an explanatory conceptual model that illustrates how technological sustainability in general, and the P-TSA framework in particular, can effectively support the transition from Industry 4.0 to Industry 5.0. A schematic representation of this model is shown in Figure 10.

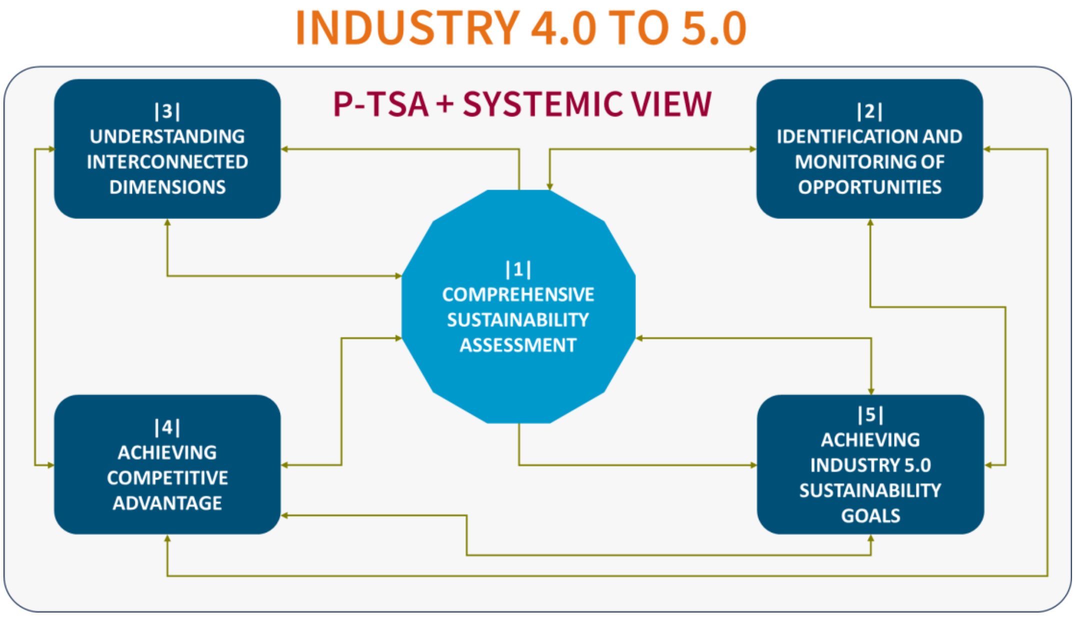


Figure 10 - Industry 4.0 to 5.0 using the P-TSA framework as a strategic enabler.

The following is an analysis of the interdependencies among the five constructs of the model in Figure 10. A comprehensive sustainability assessment (1) serves as the cornerstone and (2) provides a solid foundation for identifying improvement opportunities. This thorough assessment not only identifies areas for improvement, but also deepens the understanding of the interconnected dimensions (3) within the manufacturing processes, promoting a synergistic and integrated approach to sustainability. Achieving a competitive advantage (4) is closely linked to this comprehensive sustainability assessment (1). By identifying opportunities for improvement (2) and understanding the interconnected dimensions (3), companies can strategically position themselves to gain a competitive advantage. This strategic alignment with sustainability principles not only increases efficiency but also aligns with the core tenets of

Industry 5.0. In addition, leveraging the holistic capabilities of the P-TSA framework (1–4) is imperative in the pursuit of Industry 5.0's goals (5). The framework, with its comprehensive sustainability assessment, identification of improvement opportunities, understanding of interrelated dimensions, and strategic alignment, becomes the linchpin for creating a unified and effective sustainability strategy. In essence, successful implementation of the Industry 5.0 paradigm may also depend on leveraging the capabilities of the P-TSA framework to drive manufacturing processes toward a sustainable and technologically advanced future.

4.5 CONCLUDING REMARKS

The research presented in this study shows the empirical validation of the process technological sustainability assessment (P-TSA) methodological framework, based on the life cycle approach and in line with ISO 14040, by implementing it in a ceramic tile manufacturing company. The method, from a value chain perspective, identifies seven main activities for technological sustainability analysis through three technological impact categories (IOA, OP, and TQ). By combining technological metrics, three general indicators were defined for each impact category: the stock coverage rate (SCR) indicator, productivity indicator (PI), and output compliance rate (OCR). The indicators were then weighted to be aggregated into general technological impact subindices (IOAI, OPI, and TQI). Finally, the integration of the three subindices was used to create the process technological sustainability index (P-TSI), which quantified the change in technological sustainability over the period from 2017 to 2022.

The results show that the empirical validation of the process technological sustainability assessment (P-TSA) framework using real-time data from three ceramic tile manufacturing plants provided significant insights. P-TSA effectively identified key factors influencing technological sustainability, including input/output availability (IOA), operational performance (OP), and technical quality (TQ). Notable findings highlighted the impact of production interruptions on the P-TSI, with the IOAI component being critical during maintenance and pandemic-related shutdowns. Technological changes, such as digitalization, had a negative impact on the index, especially the technical quality. The weighting of the IOAI played a key role, stabilizing scores through effective inventory management. Higher production volumes had a positive impact on the P-TSI, demonstrating economies of scale in 2022. Overall, the analysis suggests opportunities for improvement, highlighting the need to minimize disruptions, carefully implement technological changes, diversify sourcing, and increase production volumes. The rigor of the study, using real-time IoT data, aligns with the goals of P-TSA. Sensitivity analysis highlighted the primary impact of the IOAI.

The empirical validation of the model also suggests that implementing a robust framework for technological sustainability requires consideration of the entire product life cycle, from design and production to end-of-life disposal. This approach requires not only environmentally efficient manufacturing processes but also responsible sourcing of materials, ethical labor practices, and a commitment to minimizing manufacturing impacts throughout the supply chain. In addition, it is essential to foster collaboration among technological developers, industry, academia, policy makers, and environmental experts [53]. These collaborative efforts can help establish industry standards, guidelines, and certifications that ensure the integration of sustainable practices into technological advances. Recognizing the interconnectedness of technological progress and its impact on society and the environment is critical to promoting a balanced and sustainable path for manufacturing innovation.

The findings of this research have important implications for both theory and practice.

4.5.1 Implications to Academia

From a theoretical perspective, by validating the conceptual model of technological sustainability in an operational context, this research contributes to filling the gap in the literature on the role of technology in maintaining the three pillars of sustainability [213] and enabling the achievement of sustainable development goals [241]. In addition, the empirical analysis emphasizes the value of process technology sustainability as an integrated investigative framework for assessing whether a production system can maintain its operational performance in balance over time. Consequently, this study provides an affirmative answer to the first research question (RQ1) arising from the literature review: it is indeed possible to quantify the degree of process technology sustainability achieved by a manufacturing organization.

Nevertheless, as a theoretical contribution, this study shows that technological sustainability can represent a knowledge and methodological framework for the transition from the Industry 4.0 to the Industry 5.0 paradigm. Indeed, the ability of a manufacturing company to keep its operational performance in balance is strongly correlated with its environmental and socio-economic performance, and technological sustainability can prove to be an integrating environment of the three classical pillars of sustainability. Consequently, the results obtained in this study answer the second research question (RQ2).

4.5.2 Implications to Practitioners

From a practitioner's perspective, the empirical validation of the P-TSA has three important implications:

1 Process Technological Sustainability Assessment introduces into the manufacturing organization an analysis model that is easy to implement but effective in growing a culture of sustainability within the organization. This could be the first step that lays the foundation for the subsequent implementation of more methodologically complex environmental (LCA), social (S-LCA) and economic (LCC) impact assessment tools, mainly due to the difficulty of data collection.
2 The P-TSA model provides a better understanding of the performance of production lines as a whole, rather than as stand-alone pieces of equipment, allowing for an integrated view of the factory.
3 The P-TSA model is proving to be an effective tool to support decision makers in both the industrial operations and business and corporate areas.

4.5.3 Limitations and Future Research Directions

Although the introduction of the P-TSA concept is innovative in the field of sustainability assessment, the model has some limitations that could be the basis for future lines of research:

1 The P-TSA framework follows the process-then-factory approach, which has been functional in its empirical validation due to the relative ease of conducting inventory analysis. However, it would also be appropriate to implement and validate organizational and product approaches, such as those theorized by Vacchi et al.[24]. in their seminal study on technological sustainability.

2 Unlike the other impact assessment tools in the life cycle thinking family (LCA, S-LCA, and LCC), the P-TSA framework validated in this study does not include a reference to a specific functional unit. To have a holistic view of the life cycle tools, and to be able to compare the impact results, it would be appropriate to modify the model to include the functional unit in the calculation system.

3 Direct links to environmental and socioeconomic impacts were not quantitatively explored in this study. Mechanisms of systemic integration among the four pillars of sustainability (environment, economy, society, and technology) in their organizational, process, and product dimensions should be further explored.

4 In the current P-TSA framework, the weights assigned to the indicators used to calculate the subindices (IOAI, OPI, and TQI) and the process technological sustainability index (P-TSI) are subjective. This means that the P-TSI values can vary depending on the individual preferences of the person performing the calculation. This subjectivity can be addressed by using machine learning (ML) or artificial intelligence (AI) techniques to automatically determine the weights of the indicators.

5 The sensitivity analysis carried out in this study highlighted the importance of technology-oriented design or, more precisely, sustainability at the technological level. This concept, which we could call “techno-design”, could complement the eco-design approach within a systemic perspective encompassing all dimensions of sustainability. The relationship between these two design approaches needs to be further explored.

6 Finally, to make technological sustainability results more accessible to stakeholders, it would be interesting to extend the footprint family framework with a new technological footprint based on the technological sustainability model.

5 CONCLUSIONS

The research presented in this thesis has explored the intersection of technological innovation, sustainability, and the transition to Industry 5.0 in the manufacturing sector. The findings offer a comprehensive understanding of technological sustainability and its potential to drive sustainable practices in manufacturing.

The first chapter demonstrated the feasibility of using Industry 4.0 technologies, smart data, and Life Cycle Assessment methodology to develop a circular eco-design model for ceramic tile manufacturing. The model was successfully applied to optimize raw material transport systems, significantly improving the environmental performance of the ceramic product. This study highlights the potential of digital transformation to promote circular economy principles in manufacturing.

The second chapter established technological sustainability as a distinct concept, complementing environmental economic, and social dimensions of sustainability. It argued that technological sustainability goes beyond the sustainability of technological solutions to encompass the integration of technological advancements into sustainable production processes. The chapter provided a theoretical foundation for technological sustainability and its role in driving sustainable development.

The third chapter validated a conceptual framework for technological sustainability and applied it to assess the processes of a ceramic manufacturing company. The results demonstrated the potential of technological sustainability to guide the transition from Industry 4.0 to Industry 5.0.

The research presented in this thesis has made significant contributions to the understanding of technological sustainability and its role in sustainable manufacturing. It has developed a theoretical framework for technological sustainability, validated a measurement model, and applied the concepts to the ceramic manufacturing industry. The findings provide valuable insights for manufacturing companies seeking to integrate technological innovation into sustainable practices and pave the way for a more sustainable and responsible manufacturing future.

5.1 RESEARCH IMPLICATIONS

The study has significant implications for both academia and practitioners.

For Academia, the study validates a conceptual model of technological sustainability, helping to bridge the gap in the literature regarding the role of technology in maintaining the three pillars of sustainability and achieving the sustainable development goals.

The study also demonstrates the potential of technological sustainability to guide the transition from Industry 4.0 to Industry 5.0. By emphasizing the importance of sustainability across all aspects of manufacturing, it provides a framework for developing more holistic and responsible manufacturing systems.

For Practitioners, the study introduces the TSA (Technological Sustainability Assessment) model as a practical tool for assessing technological sustainability in manufacturing processes. This model is easy to implement and provides a holistic view of production line performance, allowing practitioners to identify areas for improvement and make informed decisions about technological investments.

The validation of the TSA model has three key implications for practitioners:

1 Introduction of an analysis model for Technological Sustainability: the TSA model provides a standardized framework for assessing technological sustainability, allowing companies to benchmark their performance against industry standards and identify opportunities for improvement.
2 Better understanding of production line performance: the TSA model provides a detailed analysis of technological impacts of production lines, enabling practitioners to make informed decisions about resource allocation, process optimization, and technological upgrades.
3 Effectiveness of the TSA model as a decision-support tool: the TSA model has been successfully applied to a real-world case study, demonstrating its effectiveness in supporting decision-making in both industrial operations and corporate and business areas.

Overall, the study provides a valuable contribution to both academia and practice, advancing our understanding of technological sustainability and offering practical tools for its implementation in manufacturing.

5.2 LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

The research has a number of limitations that could be addressed in future research.

1 Sectoral applicability: the research has focused primarily on the ceramic manufacturing sector. Future research could explore the applicability of the conceptual framework and measurement model to other manufacturing sectors, such as automotive, electronics, and textile.
2 Theoretical expansion: the study validated the P-TSA model for assessing technology sustainability, but it only examined the process-factory approach. Future research could expand the framework to encompass organizational and product approaches, providing a more comprehensive assessment of technological sustainability across the entire manufacturing value chain.
3 Functional unit for comparison: the TSA framework lacks a specific reference to a functional unit, which makes it difficult to compare impact results with other life cycle assessment (LCA) tools. Future research could develop a standardized functional unit for technological sustainability assessments, allowing for benchmarking and comparison across different studies and industries.
4 Quantitative linkage to impacts: while the study acknowledges the linkages between technological impacts and environmental and socio-economic impacts, it does not provide a quantitative analysis of this relationship. Future research could develop a quantitative model to quantify the impact of technological choices on these three dimensions of sustainability.
5 Integration with Eco-Design: the research emphasizes the importance of orienting design towards technological sustainability, suggesting that this approach could be integrated with eco-design principles. Future research could explore how the concept of technological

sustainability can be aligned with existing eco-design methodologies to create a more holistic approach to sustainable product development.

6 Accessibility and Visibility: the TSA model, while valuable, is not well-known or widely adopted by manufacturing companies. To increase stakeholder accessibility to technology sustainability results, it is suggested that the footprint system be expanded to include a new footprint based on the technology sustainability model. This would make it easier for companies to communicate and track their progress towards technological sustainability goals.

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