sustainability

Article

Driving Manufacturing Companies toward Industry 5.0: A Strategic Framework for Process Technological Sustainability Assessment (P-TSA)

Marco Vacchi [1,2], Cristina Siligardi [1] and Davide Settembre-Blundo [2,3,*]

[1] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, 41125 Modena, Italy; marco.vacchi@gresmalt.it (M.V.); cristina.siligardi@unimore.it (C.S.)
[2] Gresmalt Group, Via Regina Pacis 136, 41049 Sassuolo, Italy
[3] Department of Business Administration, Rey-Juan-Carlos University, 28032 Madrid, Spain
* Correspondence: davide.settembre@gresmalt.it

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.

Keywords: technological sustainability; innovation; manufacturing; competitiveness; Industry 5.0; processes; sustainability assessment; ceramic industry

Citation: 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

Academic Editor: Giada La Scalia

Received: 26 December 2023
Revised: 10 January 2024
Accepted: 10 January 2024
Published: 12 January 2024

1. 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 paper 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 paper 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.

1.1. 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 [1]. Technological innovation plays a crucial role in improving the efficiency, productivity, competitiveness [2], and resilience [3] 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 [4].

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 [5,6] 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 [7]. 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 [8]. 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 [9]. 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 [10]. The document argues that Industry 4.0 primarily focuses on technology and growth, neglecting the environmental, social, and sustainable development dimensions [11]. 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 [12].

Industry 4.0 utilized technological innovation to promote digital transformation. Industry 5.0, on the other hand, aims to create more sustainable industrial ecosystems [13] 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 [14]. 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 [15]. Today, however, technological innovation and sustainability are closely interconnected and must be addressed together [16]. This is why we talk about sustainable innovation, and the new paradigm of Industry 5.0 is an example of this [17]. 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 [18]. 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 [19].

Sustainability can generally be seen as the ability of a complex organization to perpetuate itself [20] by integrating the economic, social, and environmental dimensions [21]. 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 [22]. 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 [23]. 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 [24]. However, there is still a lack of clear definitions and limited recognition of the concept of technological sustainability in the scientific literature [25]. A holistic view is needed to consider technology as an integral part of sustainability, along with the environment, economy, and society.

Vacchi et al. [25] 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 [26]. This framework utilizes methods such as life cycle assessment (LCA) [27], social life cycle assessment (S-LCA) [28], and life cycle costing (LCC) [29]. These methods follow the standardized steps defined by ISO 14040 [30] and can be integrated with each other in a holistic approach called life cycle sustainability assessment (LCSA) [31].

1.2. 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 [25]. It should be noted that in the limited number of studies available, researchers primarily use the term "technological sustainability" to discuss sustainable technologies [32], the sustainability of technological processes [33], technological competitiveness [34], or the influence of technology on other dimensions of sustainability [35]. 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. [25] in a manufacturing context, adopting the process perspective.

2. Methodology

In this paper, the methodology called process technological sustainability assessment (P-TSA) [25] is used, which follows the same steps as life cycle assessment (LCA) analysis in accordance with ISO 14040 [36]. These steps include goal and scope definition, life cycle inventory analysis, and life cycle impact assessment and interpretation [37]. 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 [38], 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 [39]. Due to the large production volumes, this industry is characterized by a high resource intensity, evidenced by the specific consumption of production factors [40]. 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 [41]. 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 [42], real-time assessment of organizational environmental impact [43], organizational social impact [44], and the life cycle cost of the product [45].

The company under study specializes in the production of porcelain tiles [46] 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 [47]. 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.

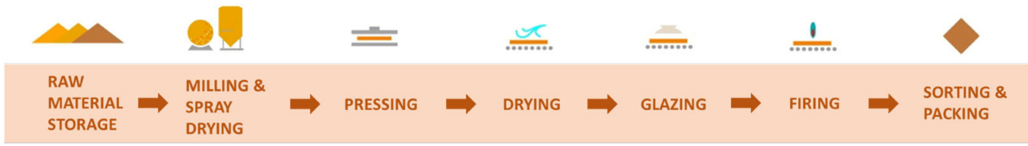

Figure 1. Flow chart of the ceramic tile manufacturing process, elaborated upon from [43].

The authors considered it 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.

3. 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 [30]. 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.

3.1. Definition of the Goal and Scope of the P-TSA

This cradle-to-gate (CTG) analysis [48] 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 gate). The data used in the analysis were exclusively the primary data and covered 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 modeling 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 [49].

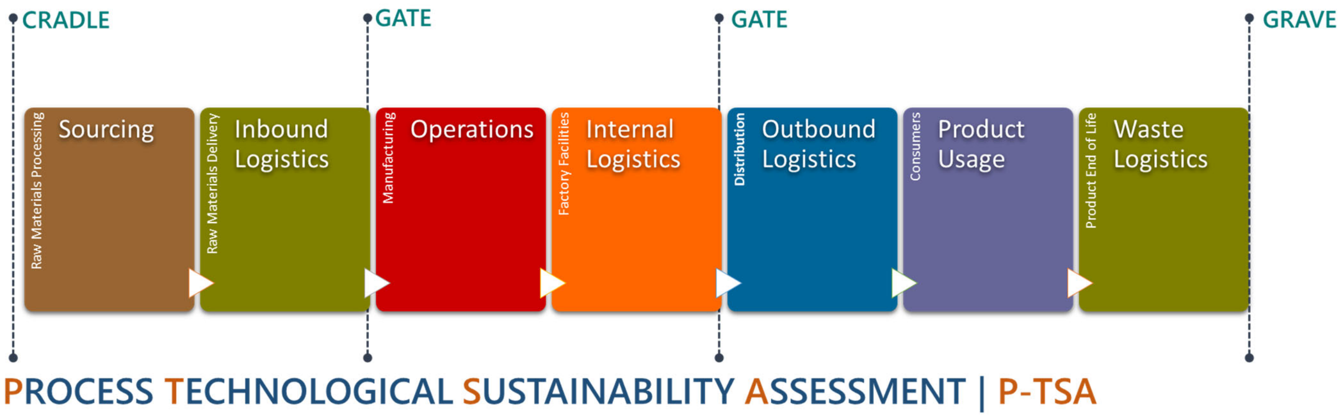

Figure 2. Life cycle approach to assessing process technological sustainability (P-TSA), adapted from the model by Vacchi et al. [25].

3.2. 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 the primary data collected in real time from the production lines, leveraging the IoT technologies of the Industry 4.0 paradigm. The collected 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 [43]. All categories and items of the primary data collected are presented in Table 1.

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 products (ceramic tiles), quantities produced, and sales volumes.

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	%

Table 1. *Cont.*

Inventory Category	Inventory Item	Measure Unit
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

3.3. Technological Impact Assessment

Based on the inventory data collected, the impact assessment calculated the technological impact of the ceramic tile production process. After defining the technological inventory, following the model proposed by Vacchi et al. [25], the Process Technological Sustainability Index (P-TSI) was calculated. For each impact category of input/output availability (IOA), operational performance (OP), and technical quality (TQ), technological metrics were used to create indicators.

According to Vacchi et al. [25], for the 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 such that each activity $a \in A$, and let "i_a" represent the input associated with each activity "a", where $\forall\, a \in A\ \exists\, i_a$. The stock coverage rate (SCR) for each input "i_a" was defined as follows:

$$SCR_{i_a}^{t} = \frac{AS_{i_a}^{t}}{AC_{i_a}^{t}} \tag{1}$$

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

$$PI_{a}^{t} = \frac{ROU_{a}^{t}}{RIN_{a}^{t}} \tag{2}$$

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 the 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:

$$OCR_{o_a}^{t} = \frac{QP_{o_a}^{t}}{AT_{o_a}^{t}} \tag{3}$$

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 subindexes for the impact categories along with their corresponding indicators.

Table 2. Subindexes and indicators of P-TSI.

Index	Subindexes	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 [50], the indicators were aggregated into the corresponding subindexes (input/output availability index (IOAI), operational performance index (OPI) and technical quality index (TQI)) with the arithmetic mean. This standardization process involves converting the original values into a format that reflects how many standard deviations a given value deviates from the mean [51]. This method was chosen for its ability to ensure a balanced contribution of each indicator to the aggregated indices [50]. 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 subindexes (*IOAI*, *OPI*, and *TQI*).

Given the set of subindexes $H = \{h_j\}$ $(j = 1, \ldots, J)$, we assigned to each subindex "h_j" a weight "$w_j \geq 0$" such that $\sum_{j=1}^{J} w_j = 1$. The composite index was formalized as follows:

$$PTSI^t = \sum_{j=1}^{J} w_j h_j^t \tag{4}$$

$$PTSI^t = \left[w_{IOA}\ IOAI^t\right] + \left[w_{OP}\ OPI^t\right] + \left[w_{TQ}\ TQI^t\right] \tag{5}$$

Vacchi et al. [25] 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. Subindex weights for scenarios 1, 2 (assumptions of supply stability), 3 (assumptions of supply instability), and 4 (focus on operational performance).

Subindexes	Subindex Weights Scenario 1	Subindex Weights Scenario 2	Subindex Weights Scenario 3	Subindex 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.

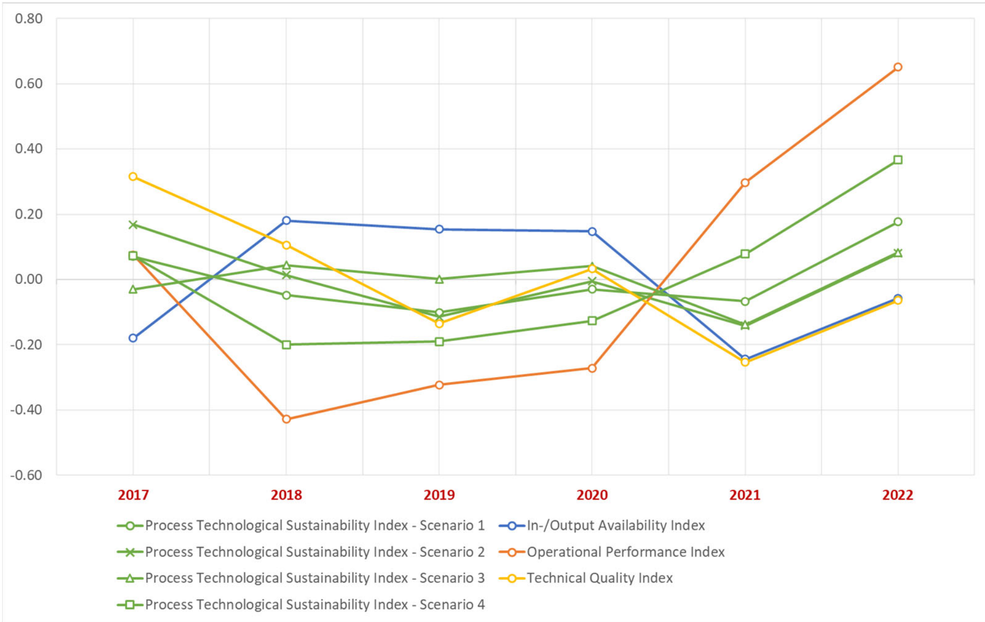

Figure 3. Annual IOAI, OPI, TQI, and P-TSI of scenarios 1, 2, 3, and 4.

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.

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.

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-2017	0.65	−0.64	0.36	0.12	0.22	0.33	−0.18
Feb-2017	−0.09	0.52	0.23	0.22	0.23	0.10	0.34
Mar-2017	−0.49	0.57	0.13	0.07	0.09	−0.15	0.27
Apr-2017	−0.03	0.31	0.28	0.19	0.23	0.10	0.24
May-2017	−0.48	0.03	0.20	−0.08	0.03	−0.24	−0.03
Jun-2017	−0.66	0.09	0.05	−0.17	−0.08	−0.37	−0.07
Jul-2017	−0.65	−0.04	0.39	−0.10	0.10	−0.32	−0.07
Aug-2017	0.30	−0.34	0.71	0.22	0.42	0.25	0.00
Sep-2017	−0.62	0.00	0.18	−0.15	−0.02	−0.33	−0.09
Oct-2017	−0.47	0.28	0.41	0.08	0.21	−0.14	0.16
Nov-2017	−0.44	0.20	0.21	−0.01	0.08	−0.18	0.07
Dec-2017	0.80	−0.09	0.62	0.44	0.51	0.59	0.23

Table 5. *Cont.*

Month-Year	IOAI	OPI	TQI	P-TSI Scenario 1	P-TSI Scenario 2	P-TSI Scenario 3	P-TSI Scenario 4
Jan-2018	0.02	−0.30	0.79	0.17	0.42	0.11	−0.02
Feb-2018	−0.25	0.08	0.68	0.17	0.37	0.00	0.13
Mar-2018	−0.33	0.08	0.13	−0.04	0.03	−0.16	0.01
Apr-2018	−0.38	0.22	0.09	−0.02	0.02	−0.17	0.07
May-2018	−0.28	0.02	0.07	−0.06	−0.01	−0.15	−0.03
Jun-2018	−0.51	0.18	0.36	0.01	0.15	−0.20	0.08
Jul-2018	−0.45	0.44	0.13	0.04	0.08	−0.16	0.20
Aug-2018	3.56	−5.31	0.77	−0.33	0.11	1.23	−2.32
Sep-2018	−0.31	−0.37	−0.27	−0.32	−0.30	−0.31	−0.34
Oct-2018	−0.32	0.05	−0.43	−0.23	−0.31	−0.27	−0.12
Nov-2018	−0.36	−0.05	−0.53	−0.31	−0.40	−0.33	−0.21
Dec-2018	1.80	−0.20	−0.56	0.35	−0.02	0.93	0.13
Jan-2019	1.20	−1.39	0.36	0.05	0.18	0.51	−0.52
Feb-2019	−0.30	−0.27	0.23	−0.11	0.03	−0.19	−0.18
Mar-2019	−0.54	−0.26	0.34	−0.15	0.04	−0.31	−0.20
Apr-2019	−0.27	−0.14	0.06	−0.11	−0.04	−0.18	−0.12
May-2019	−0.25	0.01	−0.27	−0.17	−0.21	−0.20	−0.10
Jun-2019	−0.44	−0.01	−0.19	−0.21	−0.20	−0.31	−0.13
Jul-2019	−0.40	0.23	−0.72	−0.29	−0.46	−0.34	−0.08
Aug-2019	2.80	−1.70	−0.63	0.16	−0.16	1.22	−0.58
Sep-2019	−0.43	−0.18	−0.71	−0.44	−0.55	−0.43	−0.33
Oct-2019	−0.47	−0.06	−0.47	−0.33	−0.39	−0.39	−0.22
Nov-2019	−0.26	−0.05	0.15	−0.06	0.03	−0.14	−0.05
Dec-2019	1.22	−0.06	0.21	0.46	0.36	0.76	0.25
Jan-2020	0.27	−0.62	0.25	−0.03	0.08	0.09	−0.27
Feb-2020	−0.37	0.20	0.44	0.09	0.23	−0.09	0.14
Mar-2020	0.66	−0.22	0.24	0.23	0.23	0.40	0.05
Apr-2020	2.49	−2.68	−0.71	−0.30	−0.46	0.81	−1.25
May-2020	0.06	−0.10	0.30	0.08	0.17	0.07	0.01
Jun-2020	−0.54	0.09	0.02	−0.15	−0.08	−0.31	−0.05
Jul-2020	−0.53	0.02	0.05	−0.15	−0.07	−0.30	−0.08
Aug-2020	0.83	−0.50	−0.01	0.11	0.06	0.40	−0.14
Sep-2020	−0.54	0.25	−0.14	−0.14	−0.14	−0.30	0.02
Oct-2020	−0.50	0.17	0.08	−0.08	−0.02	−0.25	0.02
Nov-2020	−0.25	0.01	0.20	−0.02	0.07	−0.11	−0.01
Dec-2020	0.20	0.12	−0.32	0.00	−0.13	0.08	0.05
Jan-2021	0.34	−0.70	−0.02	−0.13	−0.09	0.06	−0.36
Feb-2021	−0.38	0.23	−0.11	−0.08	−0.09	−0.20	0.04
Mar-2021	−0.66	0.42	0.04	−0.07	−0.03	−0.30	0.13
Apr-2021	−0.43	0.35	0.16	0.03	0.08	−0.16	0.15
May-2021	−0.60	0.36	−0.17	−0.14	−0.15	−0.32	0.06
Jun-2021	−0.59	0.30	−0.22	−0.17	−0.19	−0.34	0.02
Jul-2021	−0.53	0.42	−0.65	−0.25	−0.41	−0.37	0.02
Aug-2021	0.59	−0.05	−0.28	0.09	−0.06	0.29	0.03
Sep-2021	−0.57	0.52	−0.45	−0.17	−0.28	−0.33	0.11
Oct-2021	−0.34	0.45	−0.50	−0.13	−0.28	−0.21	0.10
Nov-2021	−0.28	0.49	−0.53	−0.11	−0.28	−0.18	0.13
Dec-2021	0.52	0.77	−0.32	0.33	0.07	0.41	0.50

Table 5. *Cont.*

Month-Year	IOAI	OPI	TQI	P-TSI Scenario 1	P-TSI Scenario 2	P-TSI Scenario 3	P-TSI Scenario 4
Jan-2022	0.42	−0.32	0.22	0.11	0.15	0.23	−0.06
Feb-2022	−0.18	0.75	0.07	0.21	0.15	0.06	0.43
Mar-2022	−0.64	0.70	−0.04	0.01	−0.01	−0.25	0.28
Apr-2022	−0.38	0.72	0.18	0.17	0.18	−0.05	0.39
May-2022	−0.37	0.79	0.01	0.15	0.09	−0.06	0.40
Jun-2022	−0.50	0.67	−0.18	0.00	−0.07	−0.20	0.27
Jul-2022	−0.22	0.43	−0.34	−0.05	−0.17	−0.12	0.15
Aug-2022	1.10	0.59	−0.56	0.38	0.00	0.67	0.46
Sep-2022	−0.34	0.79	−0.32	0.04	−0.10	−0.11	0.34
Oct-2022	−0.29	0.83	−0.13	0.14	0.03	−0.03	0.41
Nov-2022	−0.03	0.94	0.07	0.33	0.22	0.18	0.57
Dec-2022	0.73	0.92	0.26	0.64	0.48	0.68	0.75

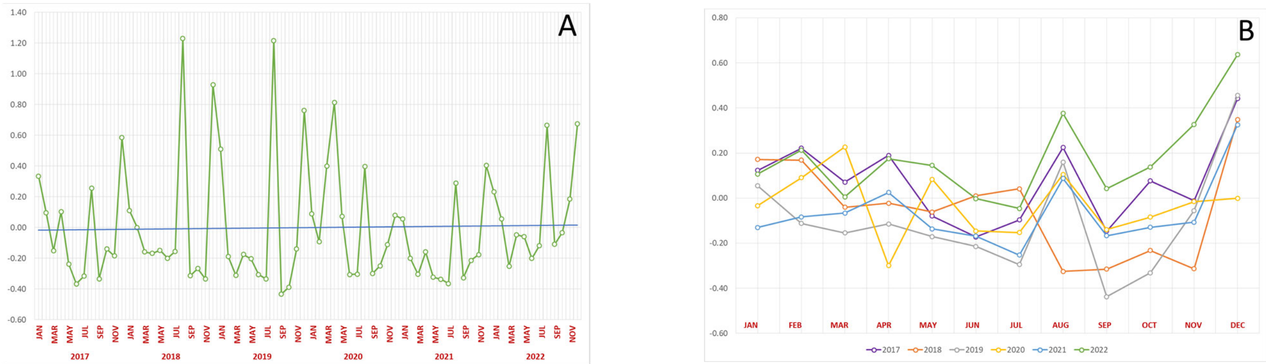

Figure 4. Process Technological Sustainability Index of scenario 1: (**A**) time series and (**B**) comparison between years.

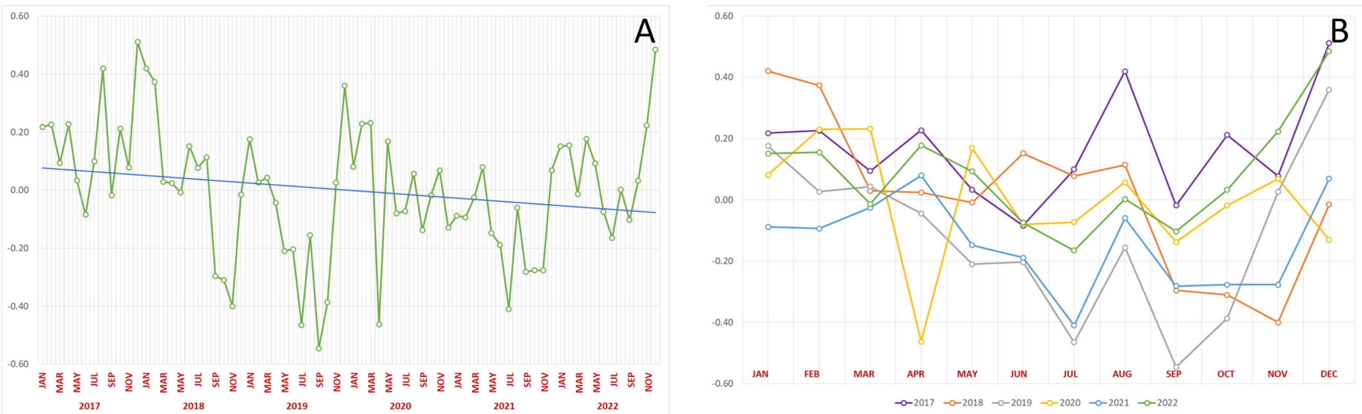

Figure 5. Process Technological Sustainability Index of scenario 2: (**A**) time series and (**B**) comparison between years.

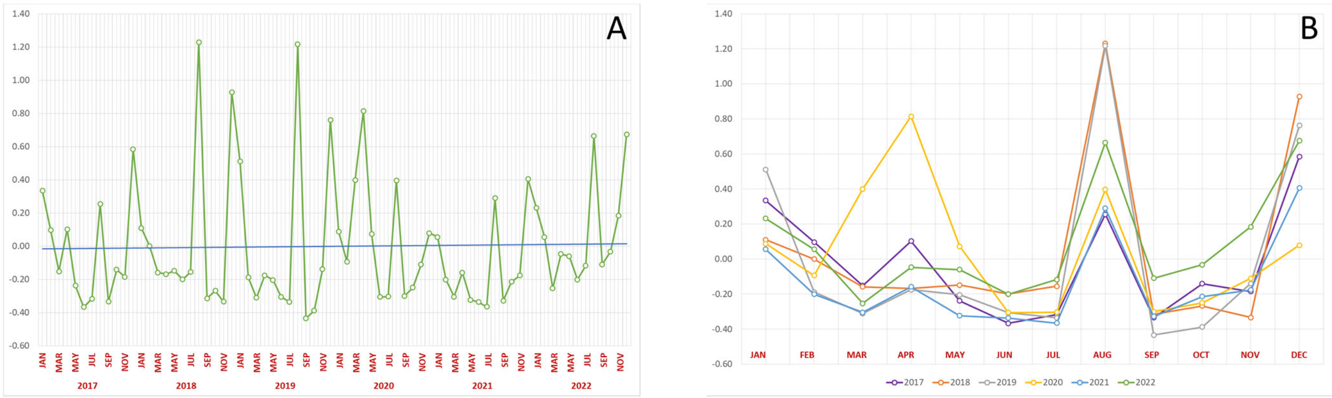

Figure 6. Process Technological Sustainability Index of scenario 3: (**A**) time series and (**B**) comparison between years.

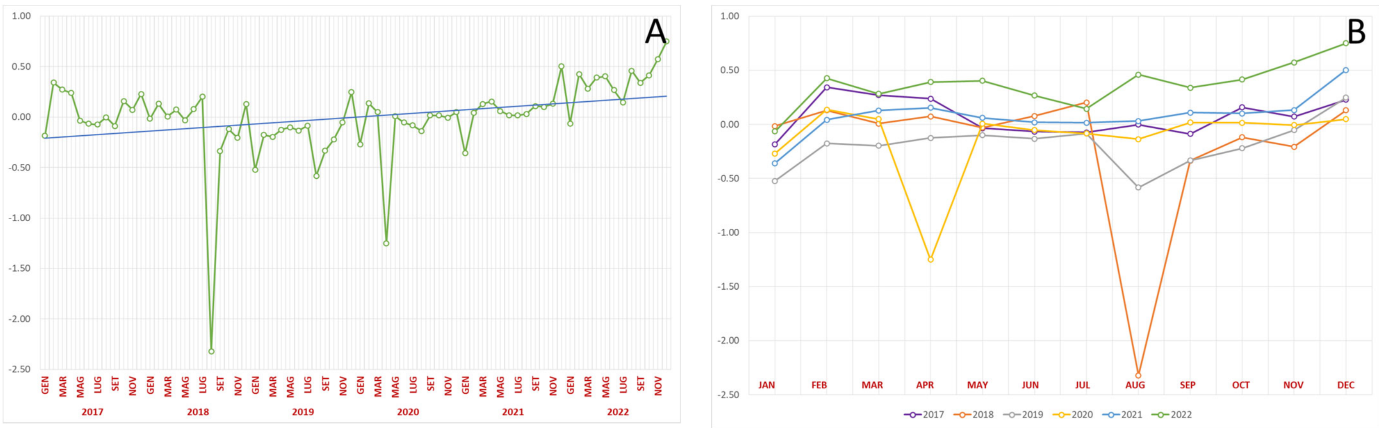

Figure 7. Process Technological Sustainability Index of scenario 4: (**A**) time series and (**B**) comparison between years.

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.

3.4. 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.

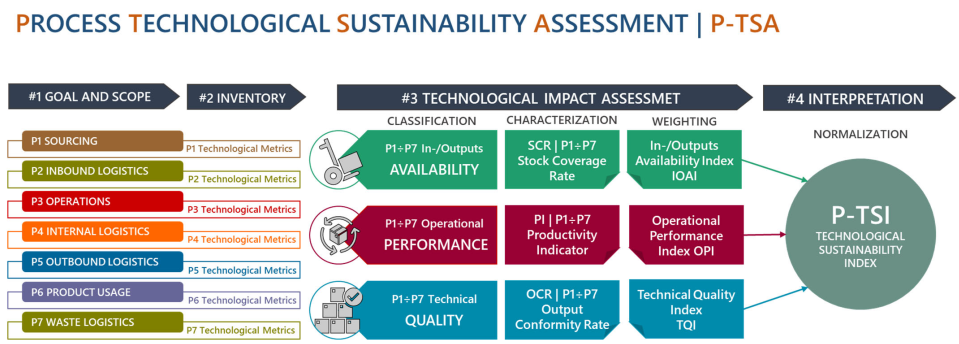

Figure 8. Holistic interpretive frameworks for the four phases of process technological sustainability assessment (P-TSA), adapted from the model by Vacchi et al. [25].

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.

3.4.1. 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 showed 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 the following:

I. Production Interruptions: Production interruptions for maintenance and the pandemic were found to have a significant impact on the P-TSI. During these periods, the IOAI component of the index became 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 resulted in higher environmental impacts due to the storage and handling of materials.

II. Technological Changes: The company's technological changes, such as digitalization of the glazing and decoration phases of the tiles, were found to have a negative impact on the P-TSI, particularly 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.

III. Sourcing: The weighting of the IOAI was found to have a significant impact on the P-TSI. When the IOAI 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.

IV. Production Volumes: The production volume was found to have a positive impact on the P-TSI. 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 can be 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.

3.4.2. 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.

The authors conducted a sensitivity analysis based on different scenarios of natural raw material supplies following the eco-design approach used in a previous study [42]. 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. [42].

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 [52]) of C1–C6 ceramic bodies [42].

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) [53]	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) [54]	≤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) [55]	≥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
Input/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 remain unchanged, while the TQI deteriorated 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) was 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 for different sourcing scenarios.

Indexes	C2/C1 (%)	C3/C1 (%)	C4/C1 (%)	C5/C1 (%)	C6/C1 (%)
Input/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.

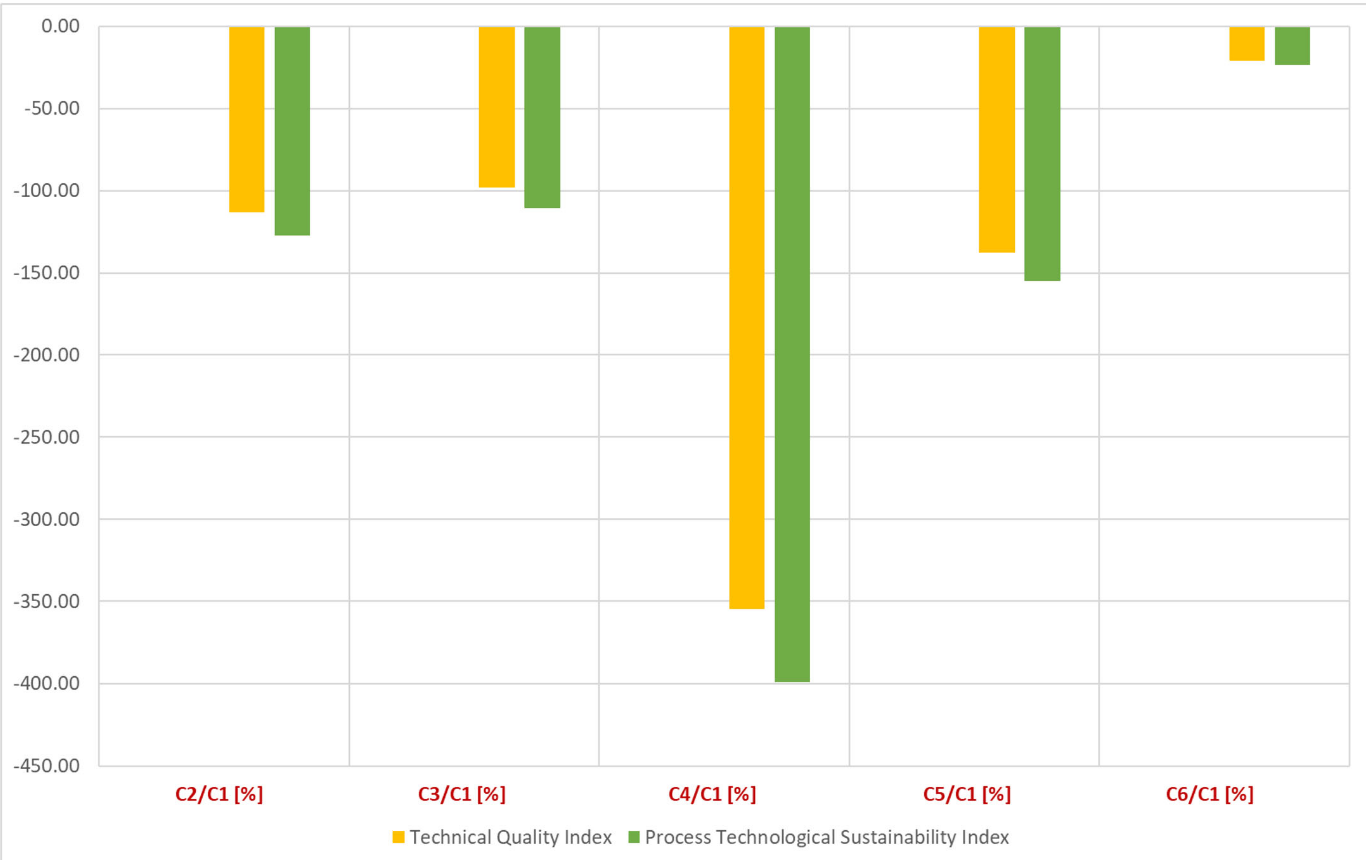

Figure 9. Sensitivity analysis performed for different sourcing scenarios.

3.5. 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 toward the sustainability goals outlined in the Industry 5.0 paradigm [56]. 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-driven 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 the following:

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, which are 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 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 exploratory 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.

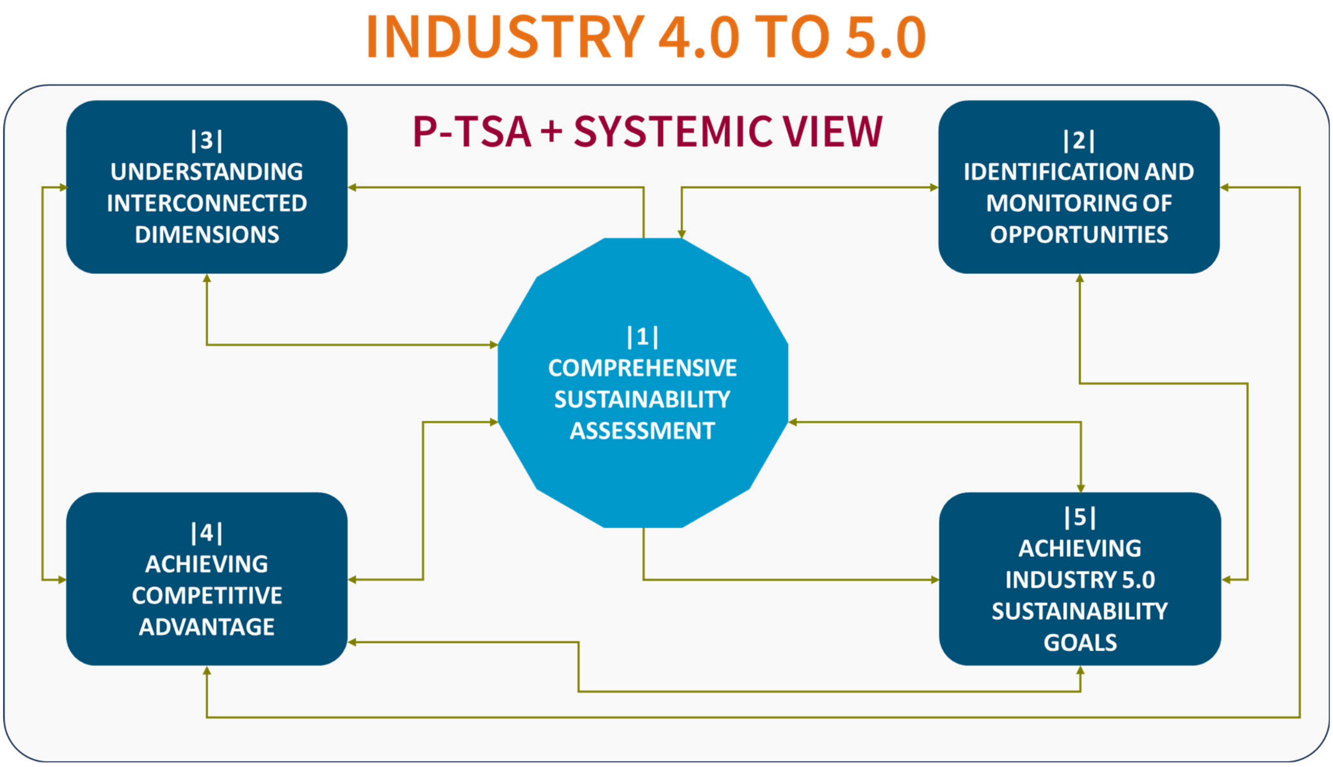

Figure 10. Industry 4.0 to Industry 5.0, using the P-TSA framework as a strategic enabler.

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. Conclusions and Outlook

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 [57]. 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.

4.1. Implications for 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 [25] and enabling the achievement of sustainable development goals [58]. In addition, the empirical analysis emphasizes the value of process technological sustainability as an integrated investigative framework for assessing whether a production system can maintain its balanced operational performance 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 technological 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 paradigm to the Industry 5.0 paradigm. Indeed, the ability of a manufacturing company to keep its operational performance balanced is strongly correlated with its environmental and socioeconomic performance, and technological sustainability can prove to be an integrating environment of the three classical pillars of sustainability. Consequently, the results obtained in this paper answer the second research question (RQ2).

4.2. Implications for Practitioners

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

a. Process technological sustainability assessment introduces into the manufacturing organization an analysis model that is easy to implement but effective for 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.
b. 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.
c. The P-TSA model has been proven to be an effective tool to support decision makers in both the industrial operations and business and corporate areas.

4.3. 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:

a. 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. [25] in their seminal study on technological sustainability.
b. 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.
c. 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.
d. 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.

e. 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.
f. 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.

Author Contributions: Conceptualization, M.V. and D.S.-B.; investigation, M.V.; methodology, M.V.; validation, C.S.; supervision, C.S.; data curation, D.S.-B.; resources, C.S.; writing—original draft preparation, D.S.-B.; writing—review and editing, M.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-funded by the Italian Ministry of Enterprises and Made in Italy under the measure "Development Contracts" (DM 05/12/2018), grant number F/160016/01-05/X41 (REDiRECT—REDuce REuse Ceramic Tiles).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors Marco Vacchi and Davide Settembre-Blundo were employed by the Gresmalt Group. The other author declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

References

1. Donbesuur, F.; Ampong, G.O.A.; Owusu-Yirenkyi, D.; Chu, I. Technological Innovation, Organizational Innovation and International Performance of SMEs: The Moderating Role of Domestic Institutional Environment. *Technol. Forecast. Soc. Change* **2020**, *161*, 120252. [CrossRef]
2. Liu, J.; Xie, J. Environmental Regulation, Technological Innovation, and Export Competitiveness: An Empirical Study Based on China's Manufacturing Industry. *Int. J. Environ. Res. Public. Health* **2020**, *17*, 1427. [CrossRef]
3. De Marchi, M.; Friedrich, F.; Riedl, M.; Zadek, H.; Rauch, E. Development of a Resilience Assessment Model for Manufacturing Enterprises. *Sustainability* **2023**, *15*, 16947. [CrossRef]
4. Cannavacciuolo, L.; Ferraro, G.; Ponsiglione, C.; Primario, S.; Quinto, I. Technological Innovation-Enabling Industry 4.0 Paradigm: A Systematic Literature Review. *Technovation* **2023**, *124*, 102733. [CrossRef]
5. Michael Rada INDUSTRY 5.0—Definition. Available online: https://www.linkedin.com/pulse/industrial-upcycling-definition-michael-rada/ (accessed on 9 October 2023).
6. Michael Rada INDUSTRY 5.0—from Virtual to Physical. Available online: https://www.linkedin.com/pulse/industry-50-from-virtual-physical-michael-rada/ (accessed on 9 October 2023).
7. Rojas, C.N.; Adolfo, G.; Peñafiel, A.; Fernando, D.; Buitrago, L.; Andrés, C.; Romero, T.; Matos, P.V.; Christopoulos, T.P.; Co, G.A.A.P. Society 5.0: A Japanese Concept for a Superintelligent Society. *Sustainability* **2021**, *13*, 6567. [CrossRef]
8. Esben, H. Østergaard WELCOME TO INDUSTRY 5.0—The "Human Touch" Revolution Is Now under Way. Available online: https://info.universal-robots.com/hubfs/Enablers/White%20papers/Welcome%20to%20Industry%205.0_Esben%20%C3%98stergaard.pdf?submissionGuid=00c4d11f-80f2-4683-a12a-e821221793e3 (accessed on 9 October 2023).
9. Coelho, P.; Bessa, C.; Landeck, J.; Silva, C. Industry 5.0: The Arising of a Concept. *Procedia Comput. Sci.* **2023**, *217*, 1137–1144. [CrossRef]
10. Directorate-General for Research and Innovation (European Commission). *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; European Comission: Brussels, Belgium, 2021. [CrossRef]
11. Zhou, K.; Liu, T.; Zhou, L. Industry 4.0: Towards Future Industrial Opportunities and Challenges. In Proceedings of the 2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), Zhangjiajie, China, 15–17 August 2015; pp. 2147–2152. [CrossRef]
12. Alves, J.; Lima, T.M.; Gaspar, P.D. Is Industry 5.0 a Human-Centred Approach? A Systematic Review. *Processes* **2023**, *11*, 193. [CrossRef]
13. Raja Santhi, A.; Muthuswamy, P. Industry 5.0 or Industry 4.0S? Introduction to Industry 4.0 and a Peek into the Prospective Industry 5.0 Technologies. *Int. J. Interact. Des. Manuf. (IJIDeM)* **2023**, *17*, 947–979. [CrossRef]

14. Karia, N. Antecedents and Consequences of Environmental Capability towards Sustainability and Competitiveness. *Sustainability* **2022**, *14*, 12146. [CrossRef]
15. Heikkurinen, P.; Ruuska, T. Technology and Sustainability: An Introduction. In *Sustainability beyond Technology: Philosophy, Critique, and Implications for Human Organization*; Oxford University Press: Oxford, UK, 2021; pp. 1–26. [CrossRef]
16. Wang, K.H.; Umar, M.; Akram, R.; Caglar, E. Is Technological Innovation Making World "Greener"? An Evidence from Changing Growth Story of China. *Technol. Forecast. Soc. Change* **2021**, *165*, 120516. [CrossRef]
17. Ghobakhloo, M.; Iranmanesh, M.; Morales, M.E.; Nilashi, M.; Amran, A. Actions and Approaches for Enabling Industry 5.0-Driven Sustainable Industrial Transformation: A Strategy Roadmap. *Corp. Soc. Responsib. Environ. Manag.* **2023**, *30*, 1473–1494. [CrossRef]
18. Li, S.; Kallas, Z. Meta-Analysis of Consumers' Willingness to Pay for Sustainable Food Products. *Appetite* **2021**, *163*, 105239. [CrossRef] [PubMed]
19. Amendolagine, V.; Lema, R.; Rabellotti, R. Green Foreign Direct Investments and the Deepening of Capabilities for Sustainable Innovation in Multinationals: Insights from Renewable Energy. *J. Clean. Prod.* **2021**, *310*, 127381. [CrossRef]
20. Osorio, L.A.R.; Lobato, M.O.; Del Castillo, X.Á. Debates on Sustainable Development: Towards a Holistic View of Reality. *Environ. Dev. Sustain.* **2005**, *7*, 501–518. [CrossRef]
21. Rodríguez, R.; Svensson, G.; Wood, G. Determining Corporate Direction in Sustainable Development: A Multi-Dimensional Framework in B2B. *J. Bus. Ind. Mark.* **2021**, *36*, 1–17. [CrossRef]
22. Nieddu, M.; Bertani, F.; Ponta, L. The Sustainability Transition and the Digital Transformation: Two Challenges for Agent-Based Macroeconomic Models. *Rev. Evol. Political Econ.* **2021**, *3*, 193–226. [CrossRef]
23. Hughes, L.; Dwivedi, Y.K.; Rana, N.P.; Williams, M.D.; Raghavan, V. Perspectives on the Future of Manufacturing within the Industry 4.0 Era. *Prod. Plan. Control* **2022**, *33*, 138–158. [CrossRef]
24. Kozlova, E.P.; Kuznetsov, V.P.; Garina, E.P.; Romanovskaya, E.V.; Andryashina, N.S. Methodological Bases of the Assessment of Sustainable Development of Industrial Enterprises (Technological Approach). *Lect. Notes Netw. Syst.* **2020**, *91*, 670–679. [CrossRef]
25. 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. [CrossRef]
26. Mazzi, A. Introduction. Life Cycle Thinking. In *Life Cycle Sustainability Assessment for Decision-Making: Methodologies and Case Studies*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 1–19. [CrossRef]
27. Bisinella, V.; Christensen, T.H.; Astrup, T.F. Future Scenarios and Life Cycle Assessment: Systematic Review and Recommendations. *Int. J. Life Cycle Assess.* **2021**, *26*, 2143–2170. [CrossRef]
28. Ramos Huarachi, D.A.; Piekarski, C.M.; Puglieri, F.N.; de Francisco, A.C. Past and Future of Social Life Cycle Assessment: Historical Evolution and Research Trends. *J. Clean. Prod.* **2020**, *264*, 121506. [CrossRef]
29. Rödger, J.M.; Kjær, L.L.; Pagoropoulos, A. Life Cycle Costing: An Introduction. In *Life Cycle Assessment: Theory and Practice*; Springer: Cham, Switzerland, 2017; pp. 373–399. [CrossRef]
30. *ISO 14040:2006b*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
31. Visentin, C.; Trentin, A.W. da Silva Trentin, A.W.; Braun, A.B.; Thomé, A. Life Cycle Sustainability Assessment: A Systematic Literature Review through the Application Perspective, Indicators, and Methodologies. *J. Clean. Prod.* **2020**, *270*, 122509. [CrossRef]
32. Jun, S. Bayesian Count Data Modeling for Finding Technological Sustainability. *Sustainability* **2018**, *10*, 3220. [CrossRef]
33. Dewulf, J.; Van Langenhove, H.; Mulder, J.; Van Den Berg, M.M.D.; Van Der Kooi, H.J.; De Swaan Arons, J. Illustrations towards Quantifying the Sustainability of Technology. *Green. Chem.* **2000**, *2*, 108–114. [CrossRef]
34. Kim, J.M.; Sun, B.; Jun, S. Sustainable Technology Analysis Using Data Envelopment Analysis and State Space Models. *Sustainability* **2019**, *11*, 3597. [CrossRef]
35. Silva, R.M.; Silva, A.R.C.; Lima, T.M.; Charrua-Santos, F.; Osório, G.J. Energy Sustainability Universal Index (ESUI): A Proposed Framework Applied to the Decision-Making Evaluation in Power System Generation. *J. Clean. Prod.* **2020**, *275*, 124167. [CrossRef]
36. Barragán-Ocaña, A.; Silva-Borjas, P.; Luna-López, K.A.; del Pilar Longar-Blanco, M. Technological Development and Mitigation of Environmental Impact through ISO 14000: A Review. *Int. J. Product. Qual. Manag.* **2022**, *36*, 27–45. [CrossRef]
37. Dong, S.; Li, C.; Xian, G. Environmental Impacts of Glass- and Carbon-Fiber-Reinforced Polymer Bar-Reinforced Seawater and Sea Sand Concrete Beams Used in Marine Environments: An LCA Case Study. *Polymers* **2021**, *13*, 154. [CrossRef]
38. Horrillo, A.; Gaspar, P.; Díaz-Caro, C.; Escribano, M. A Scenario-Based Analysis of the Effect of Carbon Pricing on Organic Livestock Farm Performance: A Case Study of Spanish Dehesas and Rangelands. *Sci. Total Environ.* **2021**, *751*, 141675. [CrossRef]
39. Confindustria Ceramica. *National Statistical Survey on Italian Ceramic Tile Industry*; EDICER: Sassuolo, Italy, 2022; Volume 43.
40. Ancona, M.A.; Branchini, L.; Ottaviano, S.; Bignozzi, M.C.; Ferrari, B.; Mazzanti, B.; Salvio, M.; Toro, C.; Martini, F.; Benedetti, M. Energy and Environmental Assessment of Cogeneration in Ceramic Tiles Industry. *Energies* **2022**, *16*, 182. [CrossRef]
41. Contini, G.; Peruzzini, M.; Bulgarelli, S.; Bosi, G. Developing Key Performance Indicators for Monitoring Sustainability in the Ceramic Industry: The Role of Digitalization and Industry 4.0 Technologies. *J. Clean. Prod.* **2023**, *414*, 137664. [CrossRef]
42. Vacchi, M.; Siligardi, C.; Iveth Cedillo-González, E.; Ferrari, A.M.; Settembre-Blundo, D.; Bressanelli, G.; Adrodegari, F.; Cristina, D.; Pigosso, A.; Prida, V. 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. [CrossRef]

43. Cucchi, M.; Volpi, L.; Ferrari, A.M.; García-Muiña, F.E.; Settembre-Blundo, D. Industry 4.0 Real-World Testing of Dynamic Organizational Life Cycle Assessment (O-LCA) of a Ceramic Tile Manufacturer. *Environ. Sci. Pollut. Res.* **2022**, *1*, 124546–124565. [CrossRef] [PubMed]
44. García-Muiña, F.; Medina-Salgado, M.S.; González-Sánchez, R.; Huertas-Valdivia, I.; Ferrari, A.M.; Settembre-Blundo, D. Industry 4.0-Based Dynamic Social Organizational Life Cycle Assessment to Target the Social Circular Economy in Manufacturing. *J. Clean. Prod.* **2021**, *327*, 129439. [CrossRef]
45. Hingst, L.; Dér, A.; Herrmann, C.; Nyhuis, P. Towards a Holistic Life Cycle Costing and Assessment of Factories: Qualitative Modeling of Interdependencies in Factory Systems. *Sustainability* **2023**, *15*, 4478. [CrossRef]
46. Amorós, J.L.; Blasco, E.; Moreno, A.; Feliu, C. Kinetics of the Transformations Occurring during the Firing Process of an Industrial Spray-Dried Porcelain Stoneware Body. *Ceram. Int.* **2022**, *48*, 17611–17620. [CrossRef]
47. Dondi, M.; García-Ten, J.; Rambaldi, E.; Zanelli, C.; Vicent-Cabedo, M. Resource Efficiency versus Market Trends in the Ceramic Tile Industry: Effect on the Supply Chain in Italy and Spain. *Resour. Conserv. Recycl.* **2021**, *168*, 105271. [CrossRef]
48. Kolahchian Tabrizi, M.; Bonalumi, D.; Lozza, G.G. Analyzing the Global Warming Potential of the Production and Utilization of Lithium-Ion Batteries with Nickel-Manganese-Cobalt Cathode Chemistries in European Gigafactories. *Energy* **2024**, *288*, 129622. [CrossRef]
49. Weidema, B.P.; Pizzol, M.; Schmidt, J.; Thoma, G. Attributional or Consequential Life Cycle Assessment: A Matter of Social Responsibility. *J. Clean. Prod.* **2018**, *174*, 305–314. [CrossRef]
50. Pollesch, N.L.; Dale, V.H. Normalization in Sustainability Assessment: Methods and Implications. *Ecol. Econ.* **2016**, *130*, 195–208. [CrossRef]
51. Mazziotta, M.; Pareto, A. Methods for Constructing Composite Indicators: One for All or All for One. *Ital. J. Econ. Demogr. Stat.* **2013**, *67*, 67–80.
52. *ISO 10545:1994-2023*; Test Standards for Ceramic Tiles. ISO: Geneva, Switzerland, 1994.
53. *ISO 10545-2:2018*; Ceramic Tiles Part 2: Determination of Dimensions and Surface Quality. ISO: Geneva, Switzerland, 2018.
54. *ISO 10545-3:2018*; Ceramic Tiles Part 3: Determination of water absorption, apparent porosity, apparent relative density and bulk density. ISO: Geneva, Switzerland, 2018.
55. *ISO 10545-4:2019*; Ceramic Tiles Part 4: Determination of modulus of rupture and breaking strength. ISO: Geneva, Switzerland, 2019.
56. Ben Youssef, A.; Mejri, I. Linking Digital Technologies to Sustainability through Industry 5.0: A Bibliometric Analysis. *Sustainability* **2023**, *15*, 7465. [CrossRef]
57. Biancardi, A.; Colasante, A.; D'Adamo, I.; Daraio, C.; Gastaldi, M.; Uricchio, A.F. Strategies for Developing Sustainable Communities in Higher Education Institutions. *Sci. Rep.* **2023**, *13*, 20596. [CrossRef] [PubMed]
58. Ali, S.M.; Appolloni, A.; Cavallaro, F.; D'Adamo, I.; Di Vaio, A.; Ferella, F.; Gastaldi, M.; Ikram, M.; Kumar, N.M.; Martin, M.A.; et al. Development Goals towards Sustainability. *Sustainability* **2023**, *15*, 9443. [CrossRef]