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Disruption in Resource-Intensive Supply Chains: Reshoring and Nearshoring as Strategies to Enable Them to Become More Resilient and Sustainable

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Abstract: Disruption in many supply chains has shown the vulnerability of global supply networks, especially resource-intensive ones, due to the simultaneous effects of pandemics and geopolitical crises. Reshoring and nearshoring strategies are the possible responses of manufacturing companies to disruptions in order to adapt to unforeseen events. The supply chain for the Italian ceramic sector, which is characterized by a high intensity of natural and energy resource consumption and a sourcing system with a high geopolitical risk, is examined in this study. The functional decomposition technique was used to analyze the supply chain; then, three scenarios were developed as potential remedies for the unexpected termination of Ukrainian plastic clay supply. The study also showed that complex issues require multifaceted analysis approaches, which is why a transdisciplinary approach was chosen. In addition, the analysis of the ceramic industry showed that nearshoring and reshoring strategies can reduce supply risk and have a positive impact on the environment. The study also showed how bringing extraction sources closer to factories significantly reduces CO_2 emissions to the atmosphere from transportation. The main contribution of this paper is the analysis of the complexity of supply chains in times of disruption, configuring reshoring and nearshoring options through transdisciplinarity.

Keywords: supply chain disruptions; manufacturing; reshoring; nearshoring; resilience; sustainability

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1. Introduction

The effects of the pandemic crisis and global geopolitical tensions [1] are causing supply chain disruption phenomena by pushing governments to adopt forms of protectionism that are slowing down international economic trade after decades of increasing integration [2]. Manufacturing enterprises must maximize the usage of production components and reconfigure supply chains using reshoring and nearshoring strategies in this environment of a global crisis and interruptions in the supply chains of natural and energy resources [3]. The system of value creation and capture has drastically changed, which necessitates a substantial effort by industries to reinvent processes, organizational models, products, and business models [4] in a sustainable perspective [5]. To respond to unforeseen market shocks, it is therefore vital to diversify supply sources and create new supply chains that are more resilient, agile, flexible [6,7], and green [8], as well as to reduce the carbon footprint of supply chains [9]. The use of proper design tools and a cross-disciplinary approach to innovation [10], i.e., not just the simple overlap of technical and managerial expertise but also their successful integration, can effectively help the management of this transition [11].

In the manufacturing industry, the industrial site refers to the location where a firm chooses to procure its raw materials (inputs), process them, and turn them into finished goods (outputs) for sale to consumers [12]. It follows that localization plays a crucial role in the process by which the company develops its strategic plans and decides on its competitive strategy [13]. Finding the ideal plant location necessitates considering the requirements of all company departments, not just the manufacturing ones, as it is closely tied to the sort of business the firm develops [14]. Manufacturing companies have a tendency to move their production from established to developing or emerging countries to cut costs or to take advantage of sales prospects presented by quickly increasing markets, especially since the late 20th century. Offshoring is a phenomenon that has been linked to globalization, economic integration, and the openness of countries to international trade [15]. In other words, manufacturing offshore is a technique used by businesses to adapt to changes in the competitive environment and gain new comparative advantages in order to become more competitive [16]. Offshoring can reduce production costs in the short run, but over the long run, it increases the risk of losing control of operations due to distance from the parent company, cultural and legal differences, language barriers that make communication more challenging, and even geopolitical situations that can occasionally impede performance [17].

The factors that first drove manufacturing companies to relocate, however, are no longer as strong. In fact, the disparity in labor costs between the West and emerging nations has narrowed over time, and these nations' labor and environmental protection laws have gotten increasingly similar to those of more industrialized nations [18]. Due to these factors, the practice of "reshoring", which involves reconsidering the site of an already offshored industry, has become increasingly popular [19,20]. In this operational model, manufacturing companies go back to domestic production in response to the need to re-industrialize developed economies in order to reduce risks and supply chain fragility [21,22]. However, it is not always viable to bring business back home. This occurs in certain industries because raw materials are required that are not available at home and in others because it would be too expensive to replicate manufacturing facilities. The migration of industrial operations to friendly, albeit far-off, countries that yet share the same value system and political alignment is known as friend-shoring in such circumstances [23]. Manufacturing businesses are less exposed to geopolitical risks as a result. If neither of these options works out, businesses might use nearshoring instead [24]. This form of offshoring entails a manufacturing company moving (or transferring from a distance) its operational procedures to nations near its corporate headquarters [25]. Additionally, starting in 2020, the COVID-19 outbreak and ensuing geopolitical unrest caused by local conflicts interrupted a number of supply lines, revealing their fragility and raising the possibility of a paradigm shift in globalization [26]. All of this has intensified the phenomenon of production being nearshored or reshored by many businesses in more developed nations [27].

The literature on reshoring and nearshoring strategies for manufacturing processes is extensive [28], but researchers have not yet thoroughly examined the same strategic alternatives for input sourcing practices [3] and green supplier selection [29]. One of the most important components of the manufacturing process in natural resource-intensive industries, such as the building, concrete, glass, ceramics, metals, etc., is the raw material supply network [30]. Over the past three decades, the process of globalization [31] and sustainability [32] has opened up new markets for natural raw materials, and outsourcing of sourcing has emerged as the greatest option for manufacturing companies to have resources in huge quantities and good quality at reasonable pricing [33]. However, the complexity of supply logistics became apparent during the pandemic and brought to light the need for manufacturing enterprises to outfit themselves with suitable systems for the best management of the resources deployed from a perspective of operational excellence [34] and circular economy [35]. As a result, managing value chains' growing complexity during disruptive periods necessitates the coexistence of a variety of engineering and socioeconomic expertise. However, a single interdisciplinary strategy that allows numerous disciplines to operate concurrently and only combines knowledge with an incremental logic without encouraging communication between other areas does not address the complexity issue [36].

The integrated approach that defines interdisciplinarity, which resides in the area between knowledge domains where disciplines might mix concepts, techniques, or instruments, could be the first step toward more effective problem solutions [37]. However, this information contamination only happens between fields that are similar culturally and have connections among themselves. The epistemological approach of transdisciplinarity, which seeks to create new knowledge by reaching beyond and fusing concepts and procedures of distinct disciplines, even if they are far apart, represents the true paradigm shift for complexity analysis [38]. According to Peruzzini and Stjepandi [39], this comprehensive and systemic viewpoint based on engineering and socio-economic expertise may be the most useful for understanding the complexity of supply chains and for coming up with solutions in reaction to rapid changes in the operational environment. Few examples of the use of transdisciplinarity in an operational setting as a perspective for resolving difficult issues in industry can be found in the literature [40]. Thus, it is clear from the literature that reshoring and nearshoring strategies relate primarily, if not exclusively, to the manufacturing phase. Meanwhile, the input supply stages are not considered despite their strategic relevance to both ensuring business continuity and defining their impact on the sustainability of the manufacturing supply chain and finished goods. Moreover, still the literature points out that production chains are characterized by systemic complexity, which is even more evident in the resource supply stages. Within this framework of complexity, mitigating the impacts of crises can also come through the digitization of the supply ecosystem. Having a digital system that connects all parts of the supply chain, and is supported by organizational transdisciplinarity, can enable one to see changes in demand with important anticipation. This makes organizations more flexible and agile in anticipating bottlenecks and adopting effective solutions such as implementing new business models [41,42]. To solve these critical issues, interdisciplinary approaches have not proven to be fully adequate because mere overlapping of expertise does not solve complexities.

Therefore, on the basis of the above theoretical grounds, the following knowledge gaps can be outlined:

- **GAP 1:** Reshoring and nearshoring strategies are widely described in the literature with respect to production processes [28] but not yet sufficiently for input sourcing processes [3].
- **GAP 2:** There is a lack of empirical examples in the literature of the application of the transdisciplinary approach to solving complexities in the production operations environment [40].

The present paper seeks to fill these gaps by considering the Italian ceramic industry that produces floor and wall tiles [43]. The choice of this manufacturing setting is due to the fact that it is a transformative industry that starts from natural raw materials to arrive at the finished product, thus characterized by a supply system with high geopolitical risk and high intensity of natural and energy resource use [44]. Unlike other sectors, such as the automotive industry, the ceramics industry presides over the entire supply chain and for this reason with a high degree of complexity that makes it particularly suitable for the purposes of this study.

The Italian ceramic industry (Table 1), generating a turnover of about EUR 6000 million in 2021 and directly employing more than 18,000 people, is the most significant cluster in the European ceramic supply chain along with the Spanish ceramic industry [45]. This industry is organized in a production district located mainly in the area of the city of Sassuolo in the Emilia-Romagna region of northern Italy.

Table 1. Relevant statistics for the ceramic sector in Italy during 2017–2021 [1].

	Tiles Production (Millions of m^2)	Turnover (EUR Million)	Exports (%)	No. of Employees
2021	435	6166	84	18,528
2020	344	5132	86	18,747
2019	401	5341	84	19,318
2018	416	5381	85	19,692
2017	395	5546	85	19,515

[1] Statistics for the years 2017–2021 as determined by Confindustria Ceramica, the business organization of the Italian ceramic industry.

Sector statistics show the strong export orientation of the Italian ceramic industry with 84% of turnover generated through foreign sales in 2021 but stable over the past five years. Regarding resource consumption, producing one square meter of ceramic tiles requires about 21 kg of natural raw materials, many of which are imported to Italy from other countries, including non-European countries. Therefore, since in 2021 the Italian ceramic industry produced 435 million square meters of tiles, the requirement for natural raw materials was [34]:

$$435 \text{ million m}^2 \times 21 \text{ kg/m}^2 = 9135 \text{ million tons}$$

The main sources of raw materials for the Italian ceramic industry are found in Turkey (sodium feldspar), Ukraine (ball clay), Germany (ball clay), and, to a lesser extent, Italy (potassium feldspar, kaolinitic volcanic clays, and sands) [46]. A recent study [47] stressed the complexity of this raw material supply chain and the high concentration of ball clay supplies from Ukraine and sodium feldspars from Turkey. Due to this reliance on just two primary raw material suppliers, the supply chain was disrupted as the conflict in Ukraine began in early 2021.

Based on these considerations, this study aims to answer this research question (RQ):

RQ. *Is transdisciplinarity an appropriate methodological approach for designing strategies to solve critical supply chain issues?*

The remainder of the paper is organized as follows. With attention to how the models of reshoring and nearshoring influence the strategies of manufacturing enterprises, Section 1 reviews pertinent research in the literature. The research setting and methodology used in the study are presented in Section 2. Section 3 outlines the results of the transdisciplinary analysis both from a strategic perspective with scenario analysis for sourcing options and from an environmental and technological perspective. Section 4 provides a discussion of the results and argues their theoretical and managerial implications. The last Section 5 draws conclusions and outlines the limitations of the research, as well as the next steps.

2. Methodological Design

Based on these presumptions, a preliminary feasibility analysis to determine the most resilient and sustainable sourcing tactics for the Italian ceramic sector is covered in this section. The methodological framework is transdisciplinary and integrates and combines several technical and management analytical techniques, including sectoral scenario analysis, strategic design of alternative scenarios, technological performance analysis, and environmental impact assessment. The research was conducted following the single in-depth case study approach considered appropriate for drawing inductive inferences aimed at gaining a better understanding of system complexity [48]. Finally, the logic of abductive inference already employed in previous managerial research [49,50] was followed to identify alternative procurement scenarios to the current one.

2.1. Manufacturing Process Overview

The flowchart in Figure 1 depicts the order of operations for the various production phases that make up the ceramic tile manufacturing process [51], also placing them within the product life cycle framework thus showing the boundaries of the system: cradle-to-gate [52]. A variety of ways, including ships, trains, and trucks, are used to carry raw materials from mines to manufacturers, depending on whether they are local or foreign (mostly from Tuscany, Sardinia, Piedmont, Calabria, and Emilia-Romagna) [46,53].

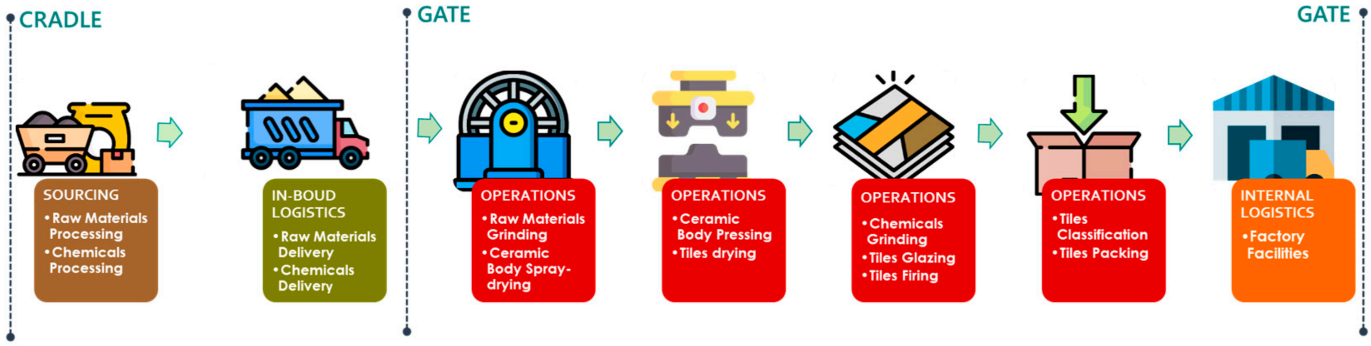

Figure 1. A flowchart illustrating the phases in the production of ceramic tile. Sources: adapted from Garcia-Muiña et al. [54]. (Icons source: https://www.flaticon.com/).

Raw materials are put into rotary mills for water milling after being stored in warehouses. The grinding bodies used are silica pebbles and/or sintered alumina spheres. At the conclusion of milling, a semi-finished product known as slurry is formed, consisting of a suspension of solids (66%) in water (33%) that is then dried in a vertical spray dryer to produce a granular powder with a residual humidity of around 6–7%. After being dried (to eliminate any remaining water), the ceramic products created from the spray-dried powders are digitally glazed and decorated. The glazed and decorated tiles are then moved onto roller kilns where they are fired in cycles lasting 30 to 50 min at a maximum temperature of 1200 to 1230 °C. The tiles can either be sent directly to the quality selection, packing, and palletizing department for the final product, which is then prepared to be sold to distributors or customers, or they can go through further finishing procedures (cutting and squaring).

2.2. Environmental Analysis Overview

In the present study, the environmental effects of different procurement scenarios were evaluated in the form of a cradle-to-gate assessment performed using the life cycle assessment (LCA) methodology and focusing the analysis on the global warming potential (GWP) [55]. LCA is a tool for investigating and evaluating the environmental impacts of a product or service at all stages of its life: extraction, production, distribution, use, and disposal. The international standards ISO 14040 (principles and framework for LCA) and ISO 14044 (requirements and guidelines for LCA) serve as reference documents for conducting an LCA [56]. The analysis, which highlights the GWP of ceramic production (i.e., the measure of how much energy the emissions of one ton of a gas will absorb over a given period of time, compared to the emissions of one ton of carbon dioxide) as a common indicator for comparing different supply scenarios, provides, through LCA, useful information on environmental impacts to support decision making [57].

2.3. Technological Analysis Overview

To test the technological feasibility of ceramic compositions corresponding to the different supply scenarios, prototype tiles were made in a laboratory environment following the procedure described by [46]. For this, raw material mixtures were ground in a laboratory mill, and the obtained slips were spray-dried to obtain powders pressed with a hydraulic pilot press at a pressure of 40 MPa. The 10 × 10 mm size tiles were then dried to remove residual moisture and fired in an industrial roller kiln at a maximum temperature of 1220 °C in a 40 min cycle. The following parameters [46] were determined as indicators of technological performance:

- Dimensional compliance, measured by comparing the actual length with the nominal length, measurements were taken with the CNE100 1000 mm fiftieth caliper, ±0.02 mm, following ISO 10545-2 [46].
- Water absorption compliance, measured under vacuum according to ISO 10545-3 [46], measurements were made with Bel Engineering M6202Di Model Precision balance, ±0.01 g.
- Flexural strength, according to ISO 10545-4 [46], measurements were performed with the Gabbrielli Technology Flexi 1000 LX-650, ±100 g.

With regard to the sectoral data used in this study, analyses conducted by the study center of the business association that groups Italian ceramic manufacturers were used. Materials for conducting the pilot tests were provided, along with technical data sheets, by the mining industries operating in Italy serving the ceramic industry.

3. Transdisciplinary Analysis's Findings

3.1. Assessment of Sectoral Scenarios

Porcelain tiles are the most popular type of tiles made in Italy. Their bodies are primarily made of three types of raw materials: (1) kaolinitic or illitic-kaolinitic clays (ball clays), which provide the plasticity required for tile forming; (2) sodic, potassium, or sodium-potassium feldspars, which melt during firing to form a glassy phase with an adequate viscosity for complete sintering of the product; and (3) quartz sand, with a framework function, contrasting deformations during drying and firing [58].

Clay supplies from the Donbas region were abruptly interrupted in the first half of 2022 owing to the interruption of the supply chain brought on by the conflict in Ukraine, which created significant issues for the ceramic industry. This incident demonstrated starkly how risk analysis and management still need to become ingrained in company culture in order to function as a vital component of the corporate sustainability assessment system. Ceramic producers would currently have strategic plans and alternate sourcing possibilities for Ukrainian clays if the geopolitical risk had been taken into account in 2014 with the Crimean conflict.

As with many complicated issues, functional decomposition—the process of breaking the difficult problem down into a number of simpler subproblems—can lead to the discovery of a potential solution [59]. Figure 2 illustrates the functional decomposition scheme of the primary complicated problem into subproblems and three potential solution assumptions in accordance with this approach.

In the case of the ceramic industry, the primary issue is the disruption of the supply chain of imported non-EU raw materials, which can be further broken down into three primary sub-issues: (1) Ukrainian clays are no longer available; (2) German clays are not as plastic as Ukrainian clays; and (3) Turkish feldspar is no longer available in the same quantities and with the same quality. Three additional issues are related to each of these: (1) it takes extremely plastic clays to manufacture huge ceramic slabs, (2) Italian clays are not as plastic as German clays, and (3) long-term regional geopolitical conflicts may make the Turkish feldspar supply system crucial.

The following three related explanatory hypotheses were established for each of the three subproblem categories, adhering to the logic of abductive inference. Accordingly: (1) alternative plastic clays to Ukrainian clays, given their limited quantity availability, could be used exclusively for the production of large slabs; (2) Italian and German clays, which have lower plasticity than Ukrainian clays and are more readily available; sodium, sodium-potassium, and potassium feldspars could be more widely used for at least partial replacement of Ukrainian clays; and (3) sodium, sodium-potassium, and potassium feldspar might be utilized more frequently to at least partially replace imported ones.

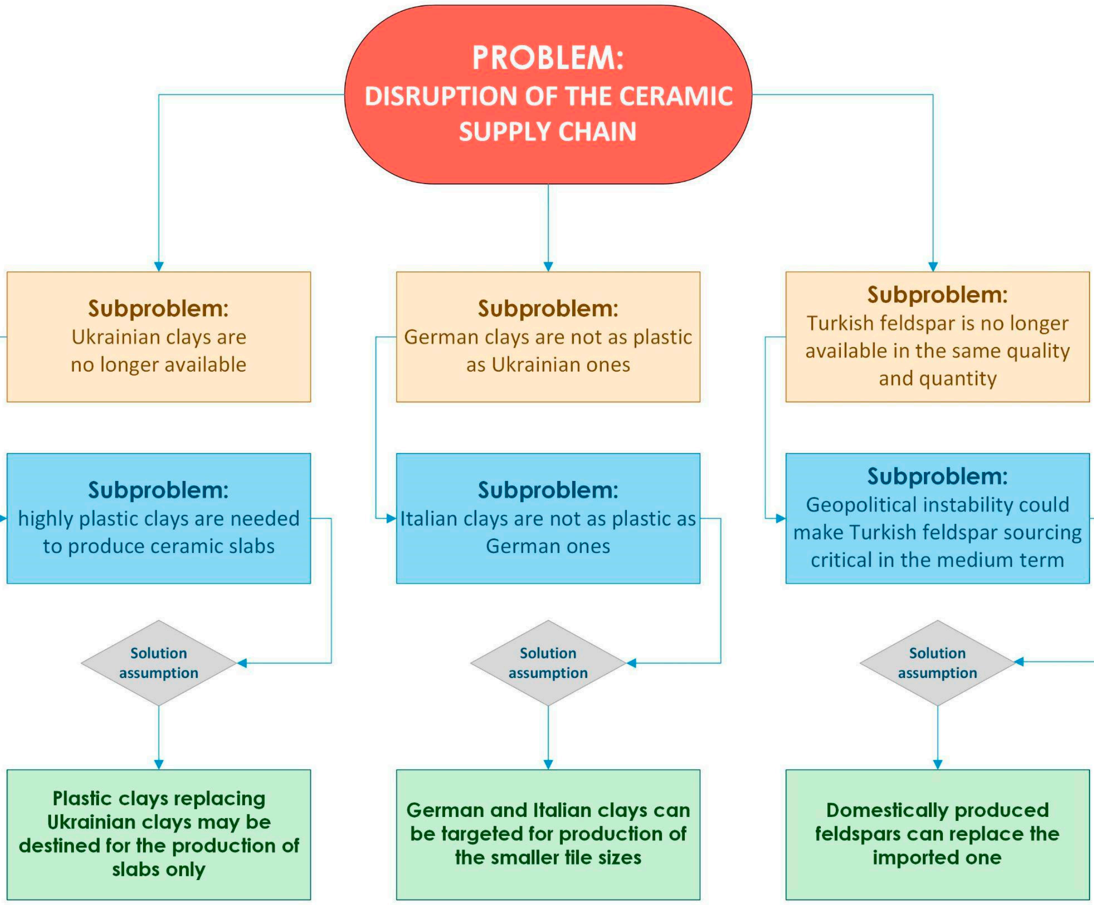

Figure 2. Framework for the functional decomposition of important concerns in the sourcing system for the Italian ceramic sector (sources: own elaboration).

3.2. Designing a Strategic Sourcing Option

Five potential ceramic body compositions (S1–S5) were hypothesized as alternatives to the sector average (S0) after the criticality functional decomposition technique (Figure 2) and abductive inference. These five compositions are depicted in Table 2.

Table 2. Summary of compositions of ceramic bodies related to different sourcing scenarios.

Raw Materials	Source	Sourcing Criticisms	S0	S1	S2	S3	S4	S5
High-plasticity ball clay	Ukraine	5	25%	10%				
Medium-plasticity ball clay	Germany	2	10%	25%	30%	30%	25%	20%
Low-plasticity kaolinitic clay	Italy	1	10%	10%	15%	30%	25%	30%
Medium-plasticity red-bed clays	Italy	3					10%	15%
Sodium feldspar	Turkey	4	35%	35%	35%	20%	20%	15%
Potassium feldspar	Italy	1	10%	10%	10%	15%	10%	10%
Quartz sand	Italy	1	10%	10%	10%			
Feldspathic sand	Italy	1				5%	10%	10%

The S0 composition, which was determined by cross-referencing data on raw material arrivals by ships at the port of Ravenna (Italy) and trains traveling straight to the Sassuolo ceramic area throughout 2019, reflects the industry's average.

Before the pandemic's spread and the war in Ukraine, this was a full and normal output year for the Italian ceramic sector. Composition S1 responds to the first premise, which is to allocate high-plasticity clays from Ukraine to the big ceramic slab manufacturing sector in order to reduce the usage of these materials. Because Composition S2 suggests a composition without high-supply-criticality clays and uses fewer plastic clays from Germany and Italy, it provides a solution to the second premise. Contrarily, Composition 3 tries to meet the third supposition, which is to replace imported feldspar with domestically produced versions. Compositions S4 and S5, however, go beyond the first three presumptions since they take into account red-bed clays, a form of raw material that is not currently taken into account in the manufacture of ceramic tiles [60,61].

The Sassuolo ceramic district in Italy and the Castellón ceramic sector in Spain historically mined enormous quantities of these clay minerals, which are particularly rich in iron oxide yet pliable and fairly melting. Up until the early 1990s in Italy and the early 2000s in Spain, they were both employed as the primary raw material for the creation of tiles, giving the ceramic body a distinctive red hue. Later, to satisfy the expanding market demand for tiles with a clear body rather than a red one, they were substituted with imported clay materials with a low iron concentration. Ancient resources are reclaimed for new use with the S4 and S5 compositions, including lowering the supply chain's criticality for the ceramic sector. These clays' illitic character lends them flexibility, but their high iron oxide concentration lends them fusibility. Therefore, by using them, the intention was to rebalance the ceramic body's clay component in favor of a local raw material (S4) and decrease the amount of imported feldspar because the iron served as a melting agent (S5).

On a scale of 1 to 5 ((1) extremely low, (2) low, (3) medium, (4) high, and (5) very high), Table 2 also offers an assessment of the amount of supply criticality for each raw material taken into consideration. For assigning the levels of supply criticality to the different scenarios, the methodological approach used by Settembre Blundo et al. [7] was followed. The procedure involves the creation of an expert panel consisting of twenty-one top positions identified on the boards of directors and among the top and middle management of a selected number of companies in the Italian ceramic industry.

Owing to supply interruption, Ukrainian clay is considered to be the most crucial, followed by Turkish sodium feldspar due to quality issues and local geopolitical unrest. Domestic raw resources and German clay have been given low or extremely low criticality ratings, respectively. The only exception is red-bed clays, which are given a medium criticality due to the fact that the mines from which these materials were extracted have been shut down, and resuming mining operations to meet potential demand may take a long time for the necessary permissions and may even be rejected by the regulatory authorities.

Table 3 displays the chemical analysis and degree of criticism for the substitute compositions (S1–S5) to the original composition prior to the supply issues (S0). While the introduction of red-bed clays produces a rise in iron oxide, the progressive replacement of Ukrainian clay with less pliable ones results in a steady decrease in the amount of aluminum oxide. The new compositions ought to be less plastic and burn with a deeper hue than the S0 body as a result. On the other hand, the weighted level gradually decreases from medium to low when it comes to soured critique. Then, actual data will be required to support these compositional assumptions' technical viability.

Table 3. Chemical composition and degree of criticism of ceramic body sourcing.

wt%	S0	S1	S2	S3	S4	S5
SiO_2	67.70	68.76	69.73	69.79	69.02	68.82
Al_2O_3	19.42	18.40	17.46	17.35	17.46	17.24
Fe_2O_3	0.85	0.89	0.91	1.09	1.67	2.03
TiO_2	0.64	0.64	0.59	0.56	0.57	0.54
MgO	0.44	0.42	0.40	0.38	0.57	0.65
CaO	0.87	0.86	0.86	0.61	0.56	0.53
Na_2O	3.99	3.94	3.97	2.60	2.72	2.34
K_2O	2.47	2.37	2.44	3.22	3.14	3.41
Loss On Ignition	3.70	3.75	3.65	4.36	4.25	4.34
Criticism level	3.15	2.70	2.35	1.90	2.05	1.95

3.3. Environmental Assessment of Sourcing Option

Following the midpoint analysis technique, the LCA methodology was utilized to identify the GWP as an effect category in order to confirm the potential environmental performance of various sourcing scenarios [62]. The LCA study was carried out in accordance with ISO 14040 and ISO 14044 standards, using a functional unit of 1 m^2 of porcelain tiles with a mass of 21 kg/m^2 (the typical value of the Italian ceramic industry). Instead, the steps of raw material extraction and transportation to the production units were the only ones included in the system boundaries that were established from the cradle to the factory gate [63].

Because it was assumed that these phases would remain constant by varying the raw material sourcing strategy, the entire product life cycle, i.e., including the manufacturing, use, and end-of-life phases (cradle to grave), was not taken into consideration for the purposes of this study. As a result (Figure 3), the composition of ceramic bodies changed. Additionally, it was chosen to exclusively consider the GWP as an effect category in this predictive environmental assessment since it is a significant signal directly connected to the use of fossil fuels in the logistics of moving raw materials from mines to manufacturers. In contrast to the present system, the novel techniques of nearshoring (Compositions S4 and S5) and reshoring (Compositions S1 through S3) for procuring raw materials result in a significant and progressive decrease in CO_2 emissions, as shown in Figure 3 (Composition S0).

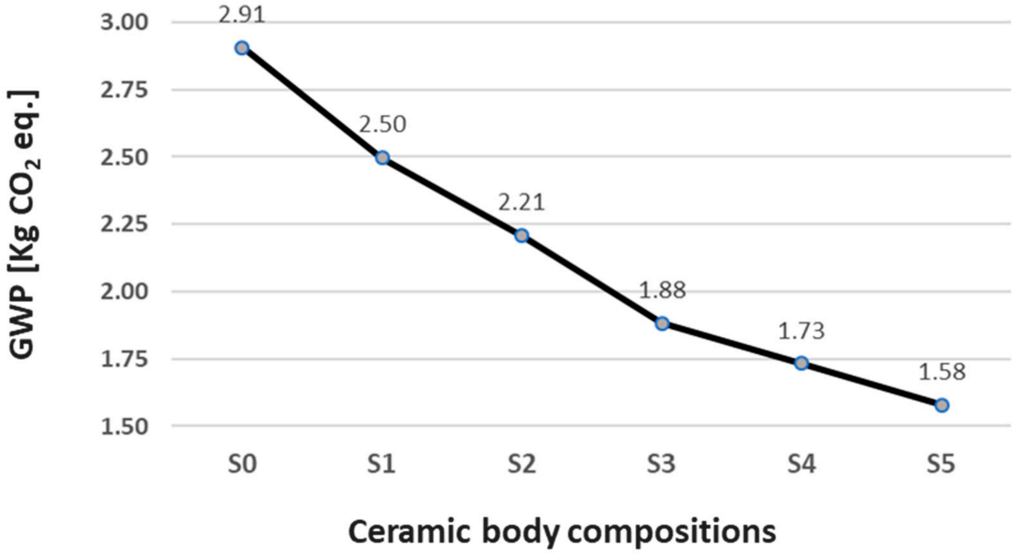

Figure 3. Global warming potential (GWP) of 1 m^2 of porcelain tiles, relating to the extraction and delivery of raw materials to factories for various ceramic body compositions.

3.4. Technological Assessment of Sourcing Option

To confirm their real industrial viability, the theories of several source scenarios were verified in a pilot laboratory setting.

The six body compositions were treated for this purpose using a lab procedure that could simulate operational settings in the workplace. The highest temperature for the 40 min cycle used to fire the 646 × 646 mm prototypes in an industrial roller kiln was 1220 °C. The outcomes of the testing are displayed in Table 4.

The following technological criteria were examined in line with current ISO requirements for ceramic tiles: bending strength, water absorption compliance, and dimensional compliance. Dimensional compliance was determined by comparing the actual length to the nominal one (ISO 10545-2), (ISO 10545-4). Only Composition S5, which is notably rich in red-bed clays, falls slightly short of permissible levels in terms of size. All compositions otherwise meet regulatory requirements. It would be sufficient to decrease the nominal length specified by each manufacturer to address the issue without changing how the body is created. For this study, an average duration that is indicative of the whole business was chosen. These studies enabled the technological viability [37] of nearshoring (Compositions S4 and S5) and alternative sourcing scenarios (Compositions S1–S3) without affecting the manufacturing process to be demonstrated using a laboratory technique.

Table 4. Technological properties of the ceramic bodies.

Technological Performance	**Composition of Ceramic Bodies**					
	S0	**S1**	**S2**	**S3**	**S4**	**S5**
Sourcing Strategy	**Starting Point**		**Reshoring**		**Nearshoring**	
Length (nominal L = 604 mm)	603.8	603.5	603.1	602.9	602.5	601.9
Dimensional conformity (ISO 10545-2)	L ± 2.0 mm	L ± 2.0 mm	L ± 2.0 mm	L ± 2.0 mm	L ± 2.0 mm	L ± 2.0 mm
Water absorption (%)	0.29	0.31	0.35	0.41	0.28	0.18
Water absorption conformity (ISO 10545-3)	≤0.5%	≤0.5%	≤0.5%	≤0.5%	≤0.5%	≤0.5%
Bending strength (N)	1780 ± 1	1759 ± 1	1734 ± 1	1691 ± 1	1682 ± 1	1715 ± 1
Bending strength conformity (ISO 10545-4)	≥1300 N	≥1300 N	≥1300 N	≥1300 N	≥1300 N	≥1300 N

4. Discussion

The functional decomposition technique was used in this study to analyze the complexity of the Italian ceramic tile manufacturing industry's material supply chain and to pinpoint some potential solutions for the pressing problems that the pandemic and geopolitical tensions have caused in this sector since the year 2020. The study also showed that complex issues require multifaceted approaches to analysis, which is why a transdisciplinary approach was chosen. This method is better than any other at capturing the interdependencies between the variables at play because it is supported by a variety of disciplines (both technical and managerial). Three scenarios were developed as potential remedies for the unexpected cessation of Ukrainian plastic clay supply thanks to the context analysis. In one instance, the use of the few extremely plastic clays that may yet arrive from Ukraine or other locations being investigated may be imagined for big ceramic slabs that constitute a niche (although an important one) in terms of the volume of total production. On the other hand, in the case of standard format ceramic tiles, where extremely flexible clays are not as crucial as for slabs, ceramic manufacturers may want to think about nearshoring and reshoring sourcing systems.

The technological viability of these scenario assumptions was subsequently demonstrated through empirical validation in a lab pre-pilot setting. Five porcelain ceramic bodies were developed and assessed in terms of their technical capabilities and potential effects on the environment. Compositions that were less problematic from the standpoint of the sourcing system than the typical industry composition in use prior to the pandemic and geopolitical crises were presented using European and local clays and feldspars. Laboratory studies have demonstrated that every solution complies with worldwide ISO requirements for ceramic tiles and has the ability to be industrialized. Finally, the environmental assessment demonstrated how moving mining sources closer to factories that manufacture goods significantly lowers CO_2 emissions to the atmosphere from transportation, with a focus on the GWP as an impact factor of LCA analysis.

By using a transdisciplinary approach, this study adds to our theoretical understanding of the consequences of pandemic and geopolitical tensions on production chains from the management analysis perspective. The analysis of the ceramics industry, which is a sector with a high reliance on raw materials, demonstrates further that the application of nearshoring and reshoring strategies not only reduces sourcing risk but also has a positive impact on the environment, both directly on the overall production process and indirectly on the final product. Because the empirical study of a significant European manufacturing sector shows that a comprehensive and synergistic approach between engineering and management skills is the most effective way to address the complexity of the business environment, these results also have significant operational implications for practitioners.

5. Conclusions

The results obtained provide a theoretical contribution to fill the gaps highlighted in the literature, namely: the configuration of reshoring and nearshoring scenarios for sourcing strategies and not only for the location of production units (GAP 1); and an empirical example of the application of the transdisciplinary approach (GAP 2). In addition, the results obtained positively answer the research question (RQ) asked in Section 2 by demonstrating through empirical validation that transdisciplinarity is a suitable methodological approach for solving critical supply chains in the manufacturing industry (GAP 2).

Finally, it is important to point out the research gaps that represent possible future lines of research. First, the analysis of the Italian ceramic industry should be replicated to the Spanish ceramic industry. In fact, jointly the two industries are the most important European ceramic production cluster. In addition, the strategic scenario analysis does not include the economic analysis that is essential for any business decision, and therefore this evaluation should be integrated into the research already carried out. Indeed, this study was conducted in a period when the prices of raw materials and other industrial inputs were very volatile and unclear, rendering any economic projection completely unrepresentative.

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