Global Journal of Flexible Systems Management
https://doi.org/10.1007/s40171-024-00404-0

ORIGINAL RESEARCH

Exploring Systemic Sustainability in Manufacturing: Geoanthropology's Strategic Lens Shaping Industry 6.0

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Received: 23 February 2024 / Accepted: 22 May 2024
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Abstract *This seminal study explores systemic sustainability within the Industry 5.0 paradigm, using the strategic lens of geoanthropology to shape the emerging concept of Industry 6.0. A transdisciplinary approach is adopted, integrating geoanthropological insights into the analysis of the Italian ceramic district. Seven key factors are considered: resource consumption, production dynamics, innovation, environmental impact, social impact, market dynamics, and economic impact. Historical events such as changes in Italian industrial policy, market slowdowns, and the COVID-19 pandemic are identified as significant for the sector. A contingent analysis tailored to the unique characteristics of the ceramic district provides an in-depth understanding of its challenges and opportunities. The incorporation of geoanthropology provides a transdisciplinary perspective that allows for an in-depth examination of the complex interactions between people and their environment in an industrial setting. The study highlights the central role of innovation, digitalization, and government policies in driving positive changes in production efficiency, market dynamics, and economic impact. Nevertheless, challenges remain, including the delicate balance between environmental sustainability and resource consumption, as well as the effective management of the social impacts of digitization. To address these challenges, a systemic sustainability index derived from geoanthropological insights is proposed as a pragmatic tool to measure and guide the development of sustainability initiatives in the ceramic district. The results of this study not only pave the way for new horizons in sustainability assessment but also provide valuable insights for industrial district managers to formulate strategies that foster organizational flexibility and resilience.*

Keywords Geoanthropology · Industrial district · Industry 5.0 · Industry 6.0 · Manufacturing · Organizational flexibility · Systemic sustainability · Transdisciplinary analysis

JEL Classification O13 · O33 · L61 · J11 · Q56 · Q57

Introduction

Industrial districts (IDs) offer a valuable lens for investigating how firms generate and share sustainable value within a region-specific area (Sassanelli & Terzi, 2022). IDs are clusters of small- and medium-sized enterprises (SMEs) that specialize in producing business-related goods (Celetti et al., 2023). These SMEs employ a skilled

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Published online: 20 June 2024

workforce with deep product knowledge, which fosters innovation through learning by doing (Hervas-Oliver et al., 2023a, 2023b). Interdependence between firms in IDs goes beyond business and manufacturing to include a cultural dimension. This cultural dimension contributes to the creation of long-term collaborative relationships based on trust and knowledge sharing (Görmar & Harfst, 2019). One of the strengths of IDs is their ability to balance specialization and flexibility without central coordination. Firms adapt to market demands and promote their competitiveness through local synergies (Hervas-Oliver et al., 2023a, 2023b). Therefore, IDs are not simply agglomerations of firms producing similar goods, but dynamic networks of interactions, knowledge sharing, and mutual support that drive territorial competitiveness and economic growth (Alberti et al., 2021). These unique characteristics of IDs have led scholars to consider the meso-economic level as a distinct set of analytical units between the micro-level of individual firms and the macro-level of the national economy (Sforzi & Boix, 2019). Industrial districts (IDs) are meso-economic spaces where manufacturing activities thrive, facilitating interactions between economic actors (firms and public institutions) and improving the competitiveness of the area (Claver-Cortés et al., 2019). In a supply chain not organized into an ID, individual companies may undertake environmental or social initiatives, but their impact may be limited or undermined by the uncooperative and/or unsustainable behavior of other supply chain actors (Fiorini et al., 2023). Conversely, the collaborative efforts of companies within IDs can create the conditions necessary to promote sustainability in economic, social, and environmental terms (Grodach et al., 2023). Environmentally, IDs adopt green sourcing and production solutions that contribute to the environmental sustainability of the community (Ceglia et al., 2023a). Socially, IDs strengthen social ties and create an integrated and cohesive community (Rocha et al., 2020). Economically, IDs create jobs, strengthen local supply chains, and stimulate regional economic growth (Farinha et al., 2020). Finally, IDs align with the principles of the circular economy, which emphasizes resource efficiency, waste reduction, and product lifetime (Hervas-Oliver & Boix, 2022).

The potential of IDs to promote sustainability in manufacturing and serve as models for sustainable communities (Biancardi et al., 2023) depends on their ability to foster economic growth, social cohesion, environmental stewardship, and resilience within their localities (Ceglia et al., 2023b). Realizing this potential requires an integrated methodological approach that recognizes the inherent diversity among stakeholders and the influential role of contextual factors on sustainability outcomes (Canello & Vidoli, 2022). As the study of manufacturing sustainability expands beyond the traditional boundaries of IDs, a broader understanding of sustainable practices is emerging. While IDs have historically advanced sustainability through collaborative networks and localized synergies, the emergence of systemic sustainability (Pascarella & Bednar, 2022) represents a paradigmatic shift that delves deeper into the intricate interplay of socio-economic and environmental factors within manufacturing environments. Amidst this transformative landscape, concepts such as organizational flexibility (Joseph Jerome et al., 2023) and Industry 5.0 (Barata & Kayser, 2023; Coelho et al., 2023) are gaining prominence, advocating human-centered approaches that integrate cutting-edge technologies such as artificial intelligence, the Internet of Things (IoT), and robotics with human expertise. This integration not only increases production efficiency but also fosters adaptive and agile production processes, thereby enhancing organizational flexibility to meet dynamic market demands (Turner et al., 2023). The convergence of systemic sustainability, organizational flexibility, and Industry 5.0 underscores the need for a comprehensive sustainability framework in manufacturing. By harmonizing these concepts, manufacturing ecosystems can skillfully navigate market volatility while addressing environmental imperatives and fostering social cohesion. This integrated approach recognizes the inherent dynamism of manufacturing systems and underscores the critical role of flexibility and adaptability in addressing evolving challenges (Singh et al., 2021; Srivastava & Bag, 2023; Le & Mohiuddin, 2024). Moreover, flexibility enables companies to adapt quickly and cost-effectively to changes in their environment, technology, organization, and strategy, thereby improving efficiency and organizational performance (D'Adamo et al., 2023). This adaptability promotes stakeholder engagement and facilitates the formation of ecosystems that integrate sustainability and digitalization, in line with the principles of Industry 5.0 (Shukla & Singh, 2023). In Industry 5.0, flexibility allows companies to seamlessly adapt to evolving technological landscapes and organizational structures, fostering innovation, and increasing productivity (Hu et al., 2022; Malaviya & Wadhwa, 2005). This synergy underscores the importance of adaptive and agile approaches to meet dynamic market demands, while advancing sustainability goals (Jiménez-Partearroyo et al., 2023). It also helps in mitigating risks related to economic dimensions and cost control, including regulatory systems and market distortions, such as the alignment of climate policy flexibility mechanisms and the implementation of measures such as the carbon border adjustment mechanism (Barraza de la Paz et al., 2023).

Nevertheless, during this transformative landscape and the emergence of new paradigms, it is critical to acknowledge the significant gaps in our understanding that require attention. First, there is a lack of standardized approaches and tools to measure and evaluate the effectiveness of sustainable practices within the evolving framework of systemic sustainability and the Industry 5.0 paradigm (Vacchi et al., 2024). This deficiency poses challenges for academics and practitioners alike in assessing the impact of initiatives and determining optimal strategies. Second, there is a gap in understanding the practical challenges associated with implementing sustainable practices and integrating concepts such as organizational agility and Industry 5.0 into manufacturing operations. Issues such as organizational change management, employee training, and seamless integration of advanced technologies persist and require innovative solutions (Smuts & Van der Merwe, 2022). Furthermore, a deeper transdisciplinary understanding of the intersection between sustainability, organizational agility, and Industry 5.0 is imperative (Carayannis & Morawska-Jancelewicz, 2022). The integration of knowledge from diverse fields such as engineering, economics, environmental sciences, and social sciences is essential to address the multifaceted challenges in manufacturing (Leng et al., 2022). In addition, the lack of best practices and case studies demonstrating the successful adoption of emerging concepts such as systemic sustainability and organizational agility limits our ability to draw practical lessons from past experiences (Gigauri & Janjua, 2023). There is also an urgent need for a deeper understanding of the long-term impact of sustainable practices and emerging concepts in manufacturing (D'Adamo & Rosa, 2016). This involves assessing the economic, social, and environmental impacts over time, considering changes in the competitive and technological landscape. Finally, recent research has shed light on a significant gap in assessing sustainability performance, particularly within IDs, highlighting the need for a contingent approach to provide scholars and practitioners with actionable insights for crafting effective sustainability strategies and operations (Bressanelli et al., 2022).

The gaps identified in understanding the implementation of sustainable practices within Industry 5.0 call for urgent attention and innovative solutions (Wang et al., 2023). As the industrial landscape shifts toward Industry 6.0, characterized by a broader vision and technological advancements, bridging these knowledge gaps becomes even more imperative to ensure a seamless transition and maximize the benefits of sustainable practices (Bhatti et al., 2021). This emerging paradigm is characterized by a broader and more inclusive vision than previous industrial revolutions, focusing on the use of technology to ensure principles such as the centrality of the consumer and social, environmental, and economic sustainability (Duggal et al., 2022). Industry 6.0, characterized by virtualized production, customer-centric ethics, and a dynamic supply chain, aims to balance human needs with technological challenges. Building on this concept, future scenarios envision emerging technologies revolutionizing production (Damaševičius & Misra (1 C.E.), 2024). Industry 6.0 emphasizes renewable energy, machine independence, interplanetary resource utilization, airborne platforms, anatomical enhancements, and quantum control, presenting significant evolution and new opportunities (Das & Pan, 2022). In this context, the transdisciplinary approach to systemic sustainability in industrial clusters, integrating the principles of Industry 5.0, provides a solid foundation for addressing the challenges and seizing the opportunities of Industry 6.0.

This study seeks to address the gap by adopting a contingency approach to sustainability assessment, originating from the idea of flexible organization in organizational research (Gromoff et al., 2012). This approach aims to provide insights into how contextual factors interact with sustainability outcomes in industrial districts. This innovative perspective can serve as a valuable tool in facilitating the development and implementation of adaptive and context-specific sustainability initiatives, ultimately enhancing the prospects of industrial districts gaining recognition as sustainable communities. To address the gap, this study will focus on four primary research questions:

- *RQ1* In which specific field of knowledge can the contingency approach for the analysis of the sustainability performance of IDs be embedded?
- *RQ2* How does the contingency approach to sustainability enable the design of context-adaptive initiatives in IDSs?
- *RQ3* In the context of Industry 5.0, how can a transdisciplinary approach improve knowledge of the systemic sustainability performance of IDs?
- *RQ4* How does the emerging paradigm of Industry 6.0 intersect with the principles of a transdisciplinary approach and systemic sustainability?

The remainder of the article is organized as follows: "Methodological background" section describes the study context and data source and processing, "Results and discussion" section reports the main results, and "Conclusions" section provides concluding remarks and implications.

Methodological Background

Study Context and Case Focus

To address the knowledge gaps and answer the research questions, a quantitative research approach using an in-depth single-case study design over a while was adopted

(Barbieri et al., 2022). The ceramic tile manufacturing district in Sassuolo, Italy, was selected as the case study for this research (Mattioli, 2019). Located in the province of Modena and the Emilia Romagna region in the north of the country, this district is considered a "hard-to-abate" (HTA) industry due to its high energy and raw material consumption (Rattle et al., 2023). This makes it particularly challenging to achieve significant decarbonization beyond current technology levels. The European Union's ambitious decarbonization targets, which aim to reduce CO_2 emissions by 55% by 2030 (compared to 1990 levels) and achieve carbon neutrality by 2050, further exacerbate this challenge (Bigerna & Polinori, 2022). Despite these obstacles, the ceramics district has gained international recognition for its strict environmental regulations to protect the environment and workers, as well as for its efforts to reduce emissions, recycle industrial water, minimize hazardous substances, and recycle processing waste (Boschi et al., 2023). In this respect, the ceramic district can serve as a model for sustainable industrial communities committed to ecological transition.

Assessing the sustainability performance of industrial districts requires a comprehensive methodology that accounts for the contextual complexities inherent in such assessments. These complexities arise from district-specific variables, including geographic location, production inputs, industrial assets, available technologies, and prevailing public policies, all of which can evolve (Bellandi et al., 2021). A contingency approach (Chavez et al., 2022) can be used to analyze this complex interplay and to understand the role of these factors in improving the efficiency of the industrial system. To illustrate the practical application of this framework, the ceramic district serves as a pertinent example of a "hard-to-abate" industry. This case study allows an examination of the operational achievements and environmental initiatives that underpin the sustainability of the industry.

Data Source

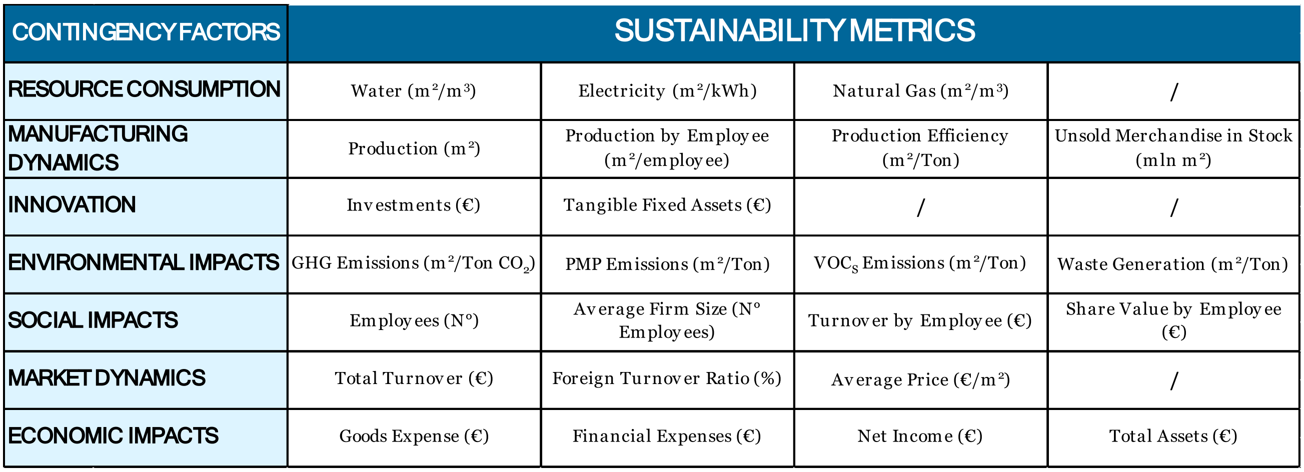
This study aims to address the methodological challenge of collecting data to assess the sustainability performance of the ceramic industry in Italy. To overcome the heterogeneity of the data, a customized dataset was constructed using a variety of sources (Van Den Blink & Steyn, 2018). Production and sales data were collected by consulting the annual reports published by the Italian Association of Ceramic Manufacturers (Confindustria Ceramica, 2023). Annual sectoral financial reports published in aggregate form were used to collect economic and financial data (Bignozzi et al., 2022). By cross-referencing the available data, 24 metrics were identified that are useful for assessing the sustainability performance of the industrial district. The metrics were then grouped into seven main contingency factors that describe the distinctly multidimensional nature of sustainability for this industry. The dataset covers 12 years, from 2010 to 2021, which includes three discontinuity factors: the financial crisis in 2010–2012, the digitization of processes introduced by district companies in 2015–2018, and the impact of the pandemic period in 2020–21. However, the years 2022 and 2023 could not be included due to the different timing of data publication. The units of measurement for the indicators have been adjusted to ensure that they can be interpreted positively by all. In other words, a higher value for each indicator indicates a positive impact. This is evident in the environmental indicators, where the measure is production per unit of emissions, or in the resource consumption indicators, where the measure is production per unit of resources consumed.

This adjustment is necessary for aggregating the indicators into contingency factors and facilitates. Figure 1 shows the framework for analyzing the sustainability performance of an industrial district using different sustainability metrics. The table is divided into two columns: the first column identifies the Contingency Factors, and the second column lists the corresponding Sustainability Metrics. There are seven rows in the table, each representing a different Contingency Factor. These Contingency Factors include Resource Consumption, Production Dynamics, Innovation, Environmental Impacts, Social Impacts, Market Dynamics, and Economic Impacts. Each Contingency Factor is characterized by specific metrics. By providing a comprehensive and multidimensional approach to interpreting an industrial district's sustainability performance, these factors can help identify areas where the industrial district can improve.

The dataset quantifying the performance metrics for each contingency factor over the period 2010–2021 is shown in Fig. 2.

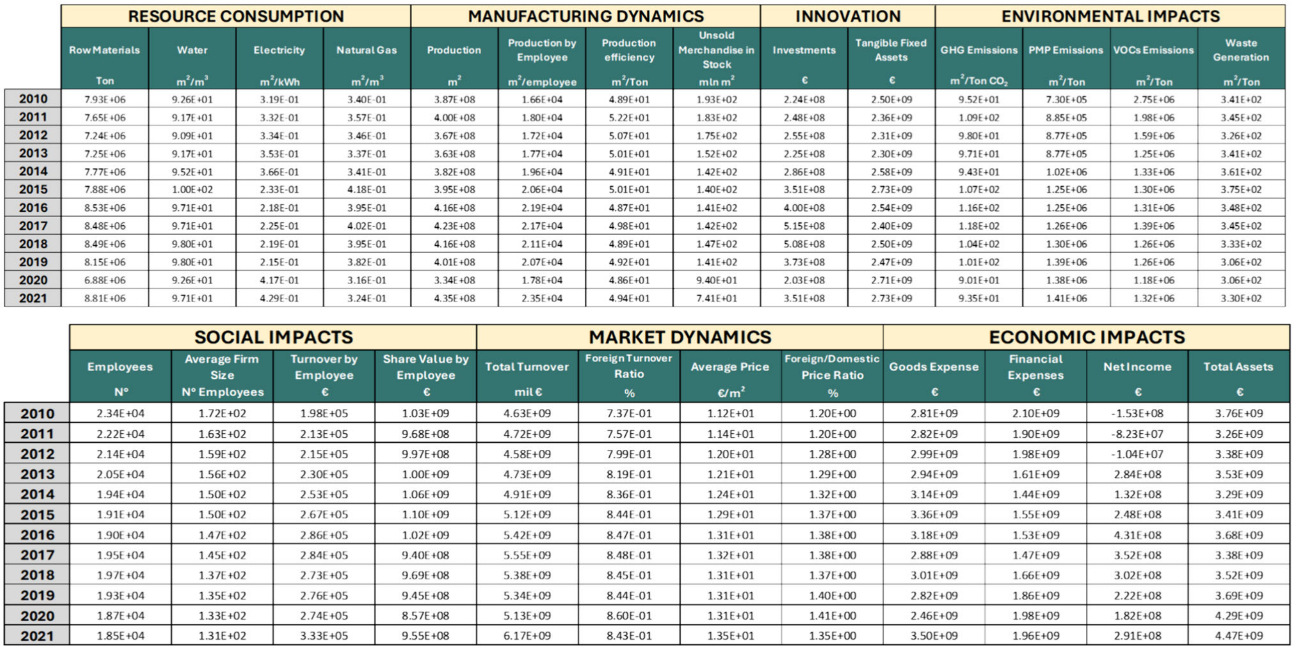
Here's a breakdown of the data set:

1. *Resource consumption* this factor measures how efficiently the district uses resources such as water, energy, and raw materials. Metrics include production per unit of water consumption, production per unit of energy consumption, and production per unit of raw materials consumed.
2. *Manufacturing dynamics* this factor assesses the efficiency and productivity of the manufacturing processes. Metrics include production per employee, production efficiency, and unsold merchandise in stock.
3. *Innovation* this factor measures the district's capacity for innovation and development of new technologies and processes. Metrics include investments in research



CONTINGENCY FACTORS	SUSTAINABILITY METRICS			
RESOURCE CONSUMPTION	Water (m²/m³)	Electricity (m²/kWh)	Natural Gas (m²/m³)	/
MANUFACTURING DYNAMICS	Production (m²)	Production by Employee (m²/employee)	Production Efficiency (m²/Ton)	Unsold Merchandise in Stock (mln m²)
INNOVATION	Investments (€)	Tangible Fixed Assets (€)	/	/
ENVIRONMENTAL IMPACTS	GHG Emissions (m²/Ton CO_2)	PMP Emissions (m²/Ton)	VOC_S Emissions (m²/Ton)	Waste Generation (m²/Ton)
SOCIAL IMPACTS	Employees (N°)	Average Firm Size (N° Employees)	Turnover by Employee (€)	Share Value by Employee (€)
MARKET DYNAMICS	Total Turnover (€)	Foreign Turnover Ratio (%)	Average Price (€/m²)	/
ECONOMIC IMPACTS	Goods Expense (€)	Financial Expenses (€)	Net Income (€)	Total Assets (€)

Fig. 1 Analytical framework for assessing the sustainability performance of an industrial district



	RESOURCE CONSUMPTION				MANUFACTURING DYNAMICS				INNOVATION		ENVIRONMENTAL IMPACTS			
	Row Materials Ton	Water m²/m³	Electricity m²/kWh	Natural Gas m²/m³	Production m²	Production by Employee m²/employee	Production efficiency m²/Ton	Unsold Merchandise in Stock mln m²	Investments €	Tangible Fixed Assets €	GHG Emissions m²/Ton CO_2	PMP Emissions m²/Ton	VOCs Emissions m²/Ton	Waste Generation m²/Ton
2010	7.93E+06	9.26E+01	3.19E-01	3.40E-01	3.87E+08	1.66E+04	4.89E+01	1.93E+02	2.24E+08	2.50E+09	9.52E+01	7.30E+05	2.75E+06	3.41E+02
2011	7.65E+06	9.17E+01	3.32E-01	3.57E-01	4.00E+08	1.80E+04	5.22E+01	1.83E+02	2.48E+08	2.36E+09	1.09E+02	8.85E+05	1.98E+06	3.45E+02
2012	7.24E+06	9.09E+01	3.34E-01	3.46E-01	3.67E+08	1.72E+04	5.07E+01	1.75E+02	2.55E+08	2.31E+09	9.80E+01	8.77E+05	1.59E+06	3.26E+02
2013	7.25E+06	9.17E+01	3.53E-01	3.37E-01	3.63E+08	1.77E+04	5.01E+01	1.52E+02	2.25E+08	2.30E+09	9.71E+01	8.77E+05	1.25E+06	3.41E+02
2014	7.77E+06	9.52E+01	3.66E-01	3.41E-01	3.82E+08	1.96E+04	4.91E+01	1.42E+02	2.86E+08	2.58E+09	9.43E+01	1.02E+06	1.33E+06	3.61E+02
2015	7.88E+06	1.00E+02	2.33E-01	4.18E-01	3.95E+08	2.06E+04	5.01E+01	1.40E+02	3.51E+08	2.73E+09	1.07E+02	1.25E+06	1.30E+06	3.75E+02
2016	8.53E+06	9.71E+01	2.18E-01	3.95E-01	4.16E+08	2.19E+04	4.87E+01	1.41E+02	4.00E+08	2.54E+09	1.16E+02	1.25E+06	1.31E+06	3.48E+02
2017	8.48E+06	9.71E+01	2.25E-01	4.02E-01	4.23E+08	2.17E+04	4.98E+01	1.42E+02	5.15E+08	2.40E+09	1.18E+02	1.26E+06	1.39E+06	3.45E+02
2018	8.49E+06	9.80E+01	2.19E-01	3.95E-01	4.16E+08	2.11E+04	4.89E+01	1.47E+02	5.08E+08	2.50E+09	1.04E+02	1.30E+06	1.26E+06	3.33E+02
2019	8.15E+06	9.80E+01	2.15E-01	3.82E-01	4.01E+08	2.07E+04	4.92E+01	1.41E+02	3.73E+08	2.47E+09	1.01E+02	1.39E+06	1.26E+06	3.06E+02
2020	6.88E+06	9.26E+01	4.17E-01	3.16E-01	3.34E+08	1.78E+04	4.86E+01	9.40E+01	2.03E+08	2.71E+09	9.01E+01	1.38E+06	1.18E+06	3.06E+02
2021	8.81E+06	9.71E+01	4.29E-01	3.24E-01	4.35E+08	2.35E+04	4.94E+01	7.41E+01	3.51E+08	2.73E+09	9.35E+01	1.41E+06	1.32E+06	3.30E+02

	SOCIAL IMPACTS				MARKET DYNAMICS				ECONOMIC IMPACTS			
	Employees N°	Average Firm Size N° Employees	Turnover by Employee €	Share Value by Employee €	Total Turnover mil €	Foreign Turnover Ratio %	Average Price €/m²	Foreign/Domestic Price Ratio %	Goods Expense €	Financial Expenses €	Net Income €	Total Assets €
2010	2.34E+04	1.72E+02	1.98E+05	1.03E+09	4.63E+09	7.37E-01	1.12E+01	1.20E+00	2.81E+09	2.10E+09	-1.53E+08	3.76E+09
2011	2.22E+04	1.63E+02	2.13E+05	9.68E+08	4.72E+09	7.57E-01	1.14E+01	1.20E+00	2.82E+09	1.90E+09	-8.23E+07	3.26E+09
2012	2.14E+04	1.59E+02	2.15E+05	9.97E+08	4.58E+09	7.99E-01	1.20E+01	1.28E+00	2.99E+09	1.98E+09	-1.04E+07	3.38E+09
2013	2.05E+04	1.56E+02	2.30E+05	1.00E+09	4.73E+09	8.19E-01	1.21E+01	1.29E+00	2.94E+09	1.61E+09	2.84E+08	3.53E+09
2014	1.94E+04	1.50E+02	2.53E+05	1.06E+09	4.91E+09	8.36E-01	1.24E+01	1.32E+00	3.14E+09	1.44E+09	1.32E+08	3.29E+09
2015	1.91E+04	1.50E+02	2.67E+05	1.10E+09	5.12E+09	8.44E-01	1.29E+01	1.37E+00	3.36E+09	1.55E+09	2.48E+08	3.41E+09
2016	1.90E+04	1.47E+02	2.86E+05	1.02E+09	5.42E+09	8.47E-01	1.31E+01	1.38E+00	3.18E+09	1.53E+09	4.31E+08	3.68E+09
2017	1.95E+04	1.45E+02	2.84E+05	9.40E+08	5.55E+09	8.48E-01	1.32E+01	1.38E+00	2.88E+09	1.47E+09	3.52E+08	3.38E+09
2018	1.97E+04	1.37E+02	2.73E+05	9.69E+08	5.38E+09	8.45E-01	1.31E+01	1.37E+00	3.01E+09	1.66E+09	3.02E+08	3.52E+09
2019	1.93E+04	1.35E+02	2.76E+05	9.45E+08	5.34E+09	8.44E-01	1.31E+01	1.40E+00	2.82E+09	1.86E+09	2.22E+08	3.69E+09
2020	1.87E+04	1.33E+02	2.74E+05	8.57E+08	5.13E+09	8.60E-01	1.31E+01	1.41E+00	2.46E+09	1.98E+09	1.82E+08	4.29E+09
2021	1.85E+04	1.31E+02	3.33E+05	9.55E+08	6.17E+09	8.43E-01	1.35E+01	1.35E+00	3.50E+09	1.96E+09	2.91E+08	4.47E+09

Fig. 2 Data set and overview of the key metrics used to assess the sustainability performance of the Italian ceramic tile district

and development, number of patents filed, and new product introductions.

4. *Environmental impacts* this factor assesses the district's impact on the environment, such as air and water pollution and greenhouse gas emissions. Metrics include greenhouse gas emissions per unit of production, particulate matter emissions per unit of production, and VOC emissions per unit of production.
5. *Social impacts* this factor assesses the district's impact on the local community, such as employment, wages, and working conditions. Metrics include number of employees, employee turnover rate, and average wage.
6. *Market dynamics* this factor assesses the district's competitiveness and position in the market. Metrics include foreign turnover ratio, average price, and export/domestic sales ratio.
7. *Economic impacts* this factor assesses the district's financial performance and contribution to the local economy. Metrics include financial expenses, net income, and total assets.

This data set is the basis for the statistical analysis that follows.

Data Processing

To comprehensively assess the evolution of sustainability in the industrial district, we employ a data-driven methodology that is particularly relevant in the systemic context of Industry 5.0. This approach integrates advanced technologies and data analytics to improve decision-making processes by facilitating the analysis and visualization of complex data sets. Our method begins by identifying and analyzing seven contingency factors that influence the sustainability of industrial districts, observing their evolution and interrelationships over time.

The methodology consists of two main phases: quantification and data scaling. In the quantification phase, weights are assigned to each indicator according to its importance within its contingency factor, to aggregate these weighted indicators into an overall sustainability index. Since the importance of each factor (criteria) significantly impacts the final decision, researchers have created various methods to assign weights to these factors (Mishra et al., 2023). This is followed by the scaling phase, where data corresponding to each factor are normalized to maintain its relevance and allow its aggregation from the weights calculated above. The result is an index that serves as an overall Key Performance Indicator (KPI), providing a systemic view of the industrial district's sustainability performance and supporting strategic decisions.

Starting the data processing, the first step is the weighting of the indicators to aggregate them into their corresponding contingency factor. This task is performed through dimensionality reduction techniques, combining the original indicators into indexes that represent their behavior comprehensively. To follow a purely data-driven method of weighting and aggregating indicators, Principal Component Analysis (PCA) will be employed as an effective statistical technique for simplifying databases while keeping the overall nature of the original data (Ayadi et al., 2024). The PCA method aggregates the original variables by creating orthogonal vectors or Principal Components, assigning coefficients to each indicator according to its variability relative to the rest. Based on the PCA method, we create an indicator aggregation model considering these considerations:

- We consider variability as the relative information contributed by each variable, and therefore, each principal component (PC) represents the aggregation of indicators according to the information contributed by each one in that component (Mohsine et al., 2023).
- By calculating the first principal component (PC1) on the indicators of each contingency factor, the indicators aggregation formula is obtained according to the information provided relative to the vector representing the contingency factor.
- The indicators are selected based on their direct impact on their contingency factor. The remaining principal components of the PCA are orthogonal to PC1, representing the information of the indicators that do not directly impact their contingency factor.

Based on these considerations, the R code of the model is created to obtain the aggregation values of the indicators or weights, using the "prcomp" command as the key package to operate the PCA. First, we divide the database into different contingency factors, to be able to apply a PCA for each of them. Then, the PCA-based indicator aggregation process is performed, which consists of three steps as shown in Table 1. First, PC1 is calculated on the indicators of a contingency factor. The second stage consists of getting the polynomial representation of PC1, with the coefficients corresponding to each indicator. When adding values, the weights must be positive and add up to unity, so the third step consists of dividing the absolute value of each coefficient by the sum of the absolute values of all the coefficients.

Then we move on to the normalization of the indicators, following a data-driven model that is robust and integrable in the information system of an industrial district. In this case, we employ sigmoid normalization to scale and compare indicator values due to their characteristics that fit perfectly with our case study. Sigmoid standardization combines two important data preprocessing techniques: normalization (also known as *z*-score normalization) and sigmoid transformation. Normalization and sigmoid transformation together form a powerful preprocessing method for data analysis and machine learning, where standardization rescales data to have a mean of 0 and a standard deviation of 1, improving comparability across features. The subsequent sigmoid transformation maps these standardized values to a bounded (0, 1) range, improving the interpretability of the data in each interval. The formula for this combined approach is:

$$x_s = \frac{1}{1 + e^{\left(\frac{x-\mu}{\sigma}\right)}}$$

where x is the input value to be standardized and transformed. μ is the mean of the dataset, which helps center the data around 0. σ is the standard deviation of the dataset, which scales the data so that it has unit variance. x_s represents the sigmoid function applied to the standardized value of x.

This methodological approach remains relatively unexplored in data analysis, as reflected by the lack of studies in the literature (Liang & Ren, 2022; Wang et al., 2018). In our study, sigmoid standardization is preferred over max–

Table 1 Principal component analysis process applied to sustainable index definition

Step 1: Calculating the first principal component (PC1)

Given a set of social indicators $X = [x_1, x_2, \ldots, x_n]$ where each x_i represents an indicator and n is the total number of indicators, PCA transforms this set into principal components

The first principal component (PC1) is calculated by finding the vector of coefficients $a = [a_1, a_2, \ldots, a_n]$ that maximizes the variance of X projected onto a subject to $\|a\| = 1$. This can be formulated as the optimization problem:

$\max\limits_{a} Var(Xa)$ subject to $\|a\|^2 = 1$

Step 2: Representation of PC1

PC1 is represented as the weighted sum of the original indicators by their coefficients:

$PC1 = a_1x_1 + a_2x_2 + \ldots + a_nx_n$

This can be expressed in matrix form as $PC1 = Xa$.

Step 3: Weighting the coefficients

To ensure the coefficients are positive and sum to one, we perform a normalization:

$a_i' = \frac{|a_i|}{\sum_1^n |a_k|}$

This transforms each a_i coefficient into a weight a_i' for the corresponding indicator, ensuring all weights are positive and their sum equals 1

min standardization because it handles outliers more efficiently by compressing all values into an interval (0, 1) by taking the extreme data as a reference without distorting the distribution.

Finally, the value of the contingency factor is obtained by the polynomic formula shown below, adding the product of each scaled indicator by its weight.

$$C.\text{Factor}_j = \sum_{i=1}^{n} a_i' x_{si}$$

where x_{si} corresponds to the i indicator value standardized. a_i' corresponds to the weight for the corresponding indicator i. $C.\text{Factor}_j$ corresponds to the index value for each contingency factor.

This methodology maximizes the retention of critical information by systematically integrating diverse indicators into a contingency factor. This objective and methodical approach ensures the generation of meaningful results that are crucial for assessing the sustainability of industrial districts. Notably, this method offers substantial improvements over more subjective approaches, providing enhanced objectivity, robustness, flexibility, and adaptability across various contexts. These attributes, documented extensively in the literature (Abdella et al., 2020; Beiragh et al., 2020; Reisi et al., 2014), establish our methodology as a superior tool for facilitating precise and strategic decision-making in the evolving landscape of Industry 5.0.

Results and Discussion

Knowledge Framework

The multidimensional contingency factor approach to assessing the sustainability of industrial districts requires an innovative analytical framework to provide a transformative interpretation of sustainability. Such a framework must be based on solid theoretical foundations, represented in this study by systemic sustainability and geoanthropology. Systemic sustainability, as an innovative paradigm, requires an analytical approach that goes beyond simple post-reporting to provide a transformative measurement that considers the interconnections and interdependencies among the elements of the system (Mouthaan et al., 2023). Similarly, geoanthropology constitutes a transdisciplinary conceptual basis for analyzing sustainability in industrial settings, providing an integrated perspective for understanding the complex interactions between humans and their natural and social environments (Bätzing, 2023).

Before laying the foundation for the multidimensional analytical framework, however, it is essential to provide a clear definition of the concepts of "*systemic sustainability*" and "*geoanthropology*," starting with the etymological meaning of the words themselves. Sustainability comes from the Latin word "*sustentare*," meaning "to support" or "to maintain," indicating the ability to maintain a state or equilibrium over time (Vargas-Hernández et al., 2021). Systemic comes from "*system*," which in turn comes from the Greek "*systēma*" (σϐστημα), meaning "set of interconnected parts (Löbler, 2016). Thus, systemic sustainability refers to the ability to maintain the equilibrium and harmonious functioning of a complex system over the long term, considering the interconnectedness and interdependence of its components. Regarding geoanthropology, "geo" is derived from the Greek "*ge*" meaning "Earth," and "anthropology" is derived from "*anthropos*" (man) and "*logos*" (study), indicating the interdisciplinary study of the interactions between humans and their natural environment, with a focus on geographic, ecological, cultural, and social aspects (Rispoli, 2022).

The concept of systemic sustainability is based on the idea that any complex system, such as a business or an ecosystem, is made up of multiple interrelated and interacting elements. These systems include not only environmental and economic aspects but also social and cultural dimensions (Sztangret, 2020). Geoanthropology provides a theoretical and methodological framework for understanding these complex interactions by examining how humans relate to their natural and social environments (Renn, 2021). Based on deductive inferences from existing literature, it can be concluded that geoanthropology plays a central role in systemic sustainability by elucidating the linkages between human activities and their lasting environmental and social impacts. This comprehensive approach facilitates the formulation of sustainability strategies that consider the intricate interplay between environmental, social, and economic factors within a system, thereby promoting a sustainable and harmonious equilibrium. The theoretical and methodological foundations of systemic sustainability, which emphasize the interconnectedness of complex systems across environmental, economic, social, and cultural domains, are firmly grounded in geoanthropology. As an emerging scientific field, geoanthropology offers a holistic perspective on human–environment interactions, incorporating geophysical, ecological, anthropological, and socio-economic dimensions within a transdisciplinary and systems framework.

Geoanthropology can be considered a field of knowledge because it takes into a holistic view the interactions between the geophysical and environmental dimensions and the anthropological and socio-economic dimensions of a complex system (Barker & Barker, 1988). Geoanthropology is an emerging scientific discipline dedicated to the study of the complex relationships between humans and their environment, encompassing the interactions between natural and socio-economic capital (Renn, 2022). The discipline draws on a wide range of analytical methodologies from the natural, social, and engineering sciences, all integrated within the overarching framework of geoscience and anthropology. Two fundamental characteristics are central to defining the discipline: first, a transdisciplinary approach that generates a comprehensive perspective on human–environment interactions, and second, a systemic perspective that recognizes these interactions as integral components of a complex and interrelated system (Bätzing, 2023).

The systemic view of geoanthropology is equally applicable to the study of manufacturing organizations, providing a comprehensive framework for assessing the interactions between individuals, the geographic context, and production processes. Within this framework, geoanthropology can examine the interrelationships between natural resources, the actors involved in production processes, and other complex systems. Emphasis is placed on the role of natural resources in shaping production dynamics, the social and economic interactions associated with production, and the complex interactions between production processes and various other factors, including geopolitics, regulatory frameworks, and industrial policies. If we think of geoanthropology as a new discipline that studies human interaction with the planet, its object of study is the technosphere (Renn, 2022). The technosphere, a defining concept in geoanthropology, encompasses the complex network of human-made technologies and infrastructures that form an interdependent system interacting with Earth's spheres, including the lithosphere, atmosphere, hydrosphere, and biosphere. The technosphere exerts profound environmental and socio-economic impacts while serving as an enabler of human capabilities, fostering growth and prosperity. However, it is critical to recognize that the technosphere also imposes constraints, as exemplified by climate change (Picot & Guillaume, 2023).

Figure 3 presents the transdisciplinary approach of this study, based on the geoanthropological framework proposed by the Max Planck Institute for the History of Science. Four interpretive perspectives, focusing on Time, Life, Society, and Earth, explore the transformative dynamics of the diachronic and synchronic relationship between humanity and the planet in the Anthropocene (Barker & Barker, 1988). These perspectives are intertwined in a transitional space between the "hard sciences" and the "soft sciences": the technosphere (Pipere & Lorenzi, 2021). Within the four interpretive domains are identified the seven contingency factors already described in Figs. 1 and 2, while at the center of the diagram is the technosphere as the space where systemic cross-interaction occurs between human activity and the planet in the past, present, and future. The sustainability assessment model adopted in this study is based precisely on quantifying the systemic interactions of the contingency factors.

Furthermore, geoanthropology's systems perspective extends to production organizations, providing a framework for assessing the interactions between individuals, the environment, and production processes. Within this framework, geoanthropology explores the interrelationships between natural resources, production processes, and

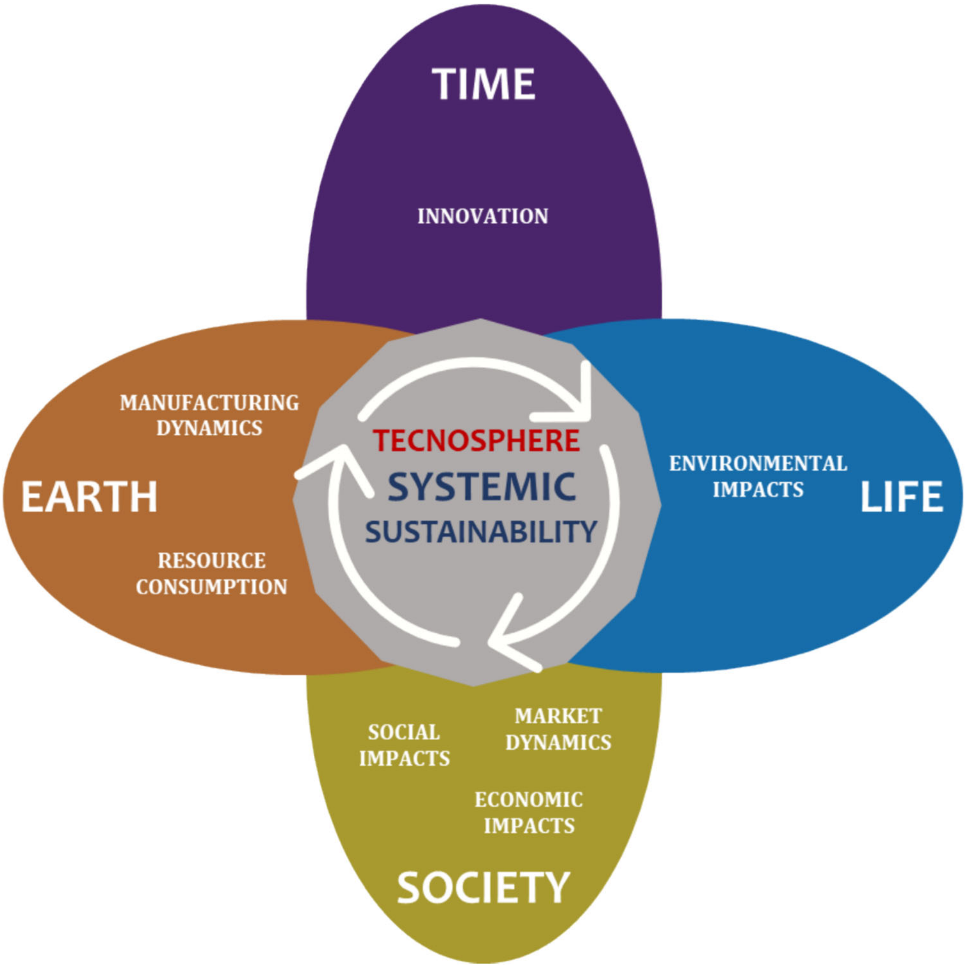


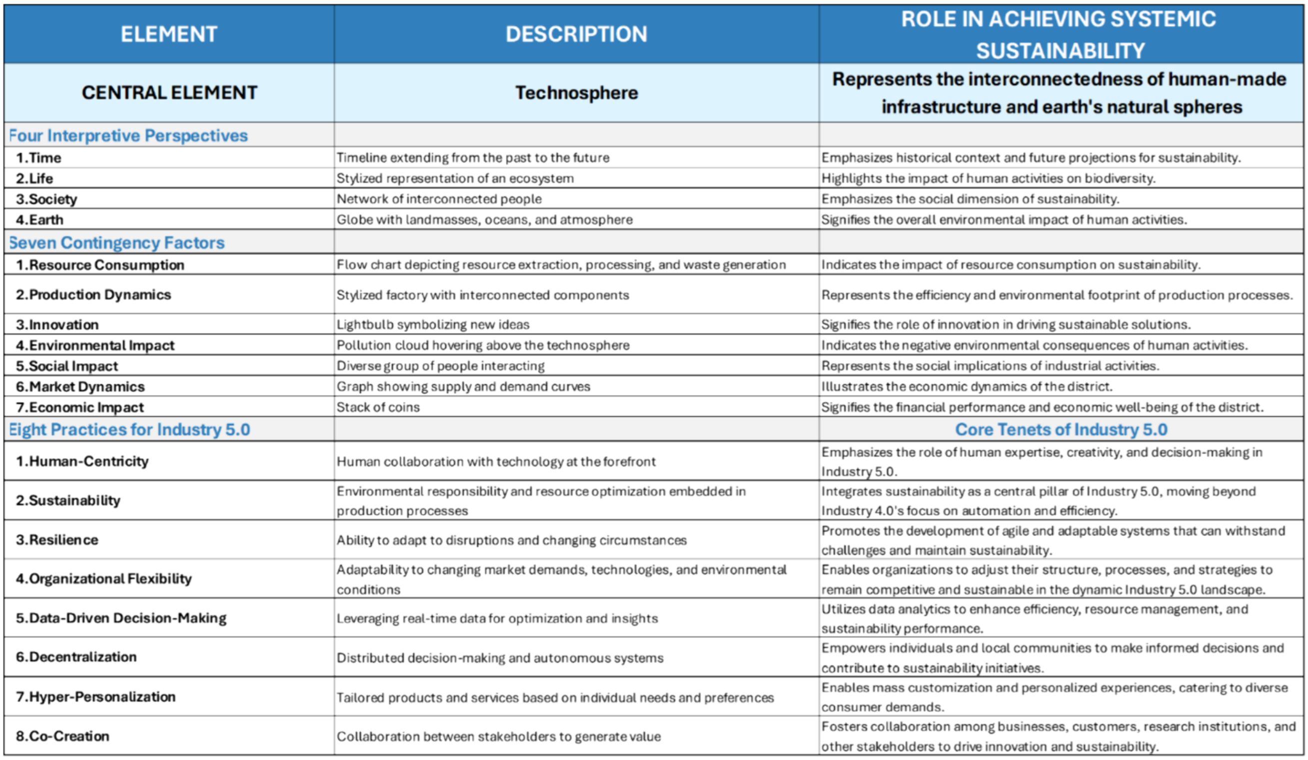
Fig. 3 Geoanthropological framework of contingency factors [Based on the model proposed by the Max Planck Institute for the History of Science (MPIWG)]

external factors such as geopolitics and regulations. If we view geoanthropology as the study of human interaction with the planet, the technosphere emerges as a focal point—a network of human-made technologies interacting with the earth's spheres. Here, systemic sustainability is assessed, and Industry 5.0 practices are implemented, representing the convergence of human activity and the planet. The conceptual framework proposed in Fig. 4 represents an innovative approach that integrates key concepts from systemic sustainability, geoanthropology, and Industry 5.0 and provides a detailed roadmap to guide the transformation to more sustainable industrial practices.

This approach is significant because it recognizes and addresses the complex interactions between human activities and the natural environment, moving beyond traditional sectoral approaches that often ignore these relationships. The four interpretive perspectives—Time, Life, Society, and Earth—each emphasize the importance of considering historical context, ecological balance, social dynamics, and securing resources for the future. These perspectives provide a basic conceptual framework for fully understanding the complexity of systemic sustainability and for directing action toward goals of equity and environmental sustainability. In addition, the framework identifies seven key contingency factors, such as resource use and impacts, market changes, and innovation, that must be carefully evaluated to ensure long-term sustainability. In parallel, the adoption of the Industry 5.0 principles of humanity at the center, decentralization, and co-creation are an important step toward building a more sustainable, human-centered industrial model. These principles incentivize active individual participation, organizational flexibility, and stakeholder collaboration, promoting a more inclusive and sustainability-oriented vision for the future of the industry.

Data Analysis

This section presents the analysis of data from the Italian ceramic industry to understand its evolution and sustainability, as well as the mutual influence between a set of key indicators selected through a multidisciplinary approach. The analysis is based on a data set of 24 metrics collected from 2010 to 2021. These indicators have been grouped



ELEMENT	DESCRIPTION	ROLE IN ACHIEVING SYSTEMIC SUSTAINABILITY
CENTRAL ELEMENT	**Technosphere**	**Represents the interconnectedness of human-made infrastructure and earth's natural spheres**
Four Interpretive Perspectives		
1.Time	Timeline extending from the past to the future	Emphasizes historical context and future projections for sustainability.
2.Life	Stylized representation of an ecosystem	Highlights the impact of human activities on biodiversity.
3.Society	Network of interconnected people	Emphasizes the social dimension of sustainability.
4.Earth	Globe with landmasses, oceans, and atmosphere	Signifies the overall environmental impact of human activities.
Seven Contingency Factors		
1.Resource Consumption	Flow chart depicting resource extraction, processing, and waste generation	Indicates the impact of resource consumption on sustainability.
2.Production Dynamics	Stylized factory with interconnected components	Represents the efficiency and environmental footprint of production processes.
3.Innovation	Lightbulb symbolizing new ideas	Signifies the role of innovation in driving sustainable solutions.
4.Environmental Impact	Pollution cloud hovering above the technosphere	Indicates the negative environmental consequences of human activities.
5.Social Impact	Diverse group of people interacting	Represents the social implications of industrial activities.
6.Market Dynamics	Graph showing supply and demand curves	Illustrates the economic dynamics of the district.
7.Economic Impact	Stack of coins	Signifies the financial performance and economic well-being of the district.
Eight Practices for Industry 5.0		**Core Tenets of Industry 5.0**
1.Human-Centricity	Human collaboration with technology at the forefront	Emphasizes the role of human expertise, creativity, and decision-making in Industry 5.0.
2.Sustainability	Environmental responsibility and resource optimization embedded in production processes	Integrates sustainability as a central pillar of Industry 5.0, moving beyond Industry 4.0's focus on automation and efficiency.
3.Resilience	Ability to adapt to disruptions and changing circumstances	Promotes the development of agile and adaptable systems that can withstand challenges and maintain sustainability.
4.Organizational Flexibility	Adaptability to changing market demands, technologies, and environmental conditions	Enables organizations to adjust their structure, processes, and strategies to remain competitive and sustainable in the dynamic Industry 5.0 landscape.
5.Data-Driven Decision-Making	Leveraging real-time data for optimization and insights	Utilizes data analytics to enhance efficiency, resource management, and sustainability performance.
6.Decentralization	Distributed decision-making and autonomous systems	Empowers individuals and local communities to make informed decisions and contribute to sustainability initiatives.
7.Hyper-Personalization	Tailored products and services based on individual needs and preferences	Enables mass customization and personalized experiences, catering to diverse consumer demands.
8.Co-Creation	Collaboration between stakeholders to generate value	Fosters collaboration among businesses, customers, research institutions, and other stakeholders to drive innovation and sustainability.

Fig. 4 Comprehensive framework for systemic sustainability in industrial districts, integrating geoanthropology and Industry 5.0

into seven main categories known as contingency factors: resource consumption, production dynamics, innovation initiatives, environmental impact, social impact, market dynamics, and overall economic impact.

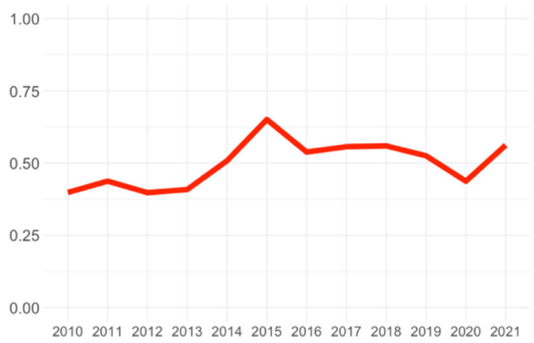
The analysis of these data was done objectively by assigning each indicator a weight proportional to its contribution to the overall set of information. These weights were calculated using the coefficients obtained from Principal Component Analysis (PCA) for each contingency factor. This method made it possible to synthesize the data of 24 individual variables into a more practical set of 7 aggregated variables, allowing a clearer analysis of the evolution of the ceramics sector. The study of the sustainability of the district is based solely on the analysis of internal sector data, without the inclusion of external values. This ensures that the contingency factors accurately reflect the specific characteristics and behaviors of the sector in question. In addition, the implementation of standardization using the sigmoid function mitigates the effect of outliers, ensuring that the interpretation of the results is robust and representative of general trends, without being distorted by extreme values.

However, it is important to recognize that this approach requires that time series be interpreted based on their internal patterns and trends, rather than as absolute values comparable to other sectors or external standards. Therefore, the assessment of sustainability in this context focuses on identifying relative improvements and areas of opportunity within the sector itself, promoting a deep and specific understanding of its sustainability challenges and achievements. The next step is the analysis of the time series, as shown in Figs. 5 and 8. This phase includes the seven contingency factors, the four domains of geoanthropology, and the holistic indicator of systemic sustainability. Emphasis is placed on the trajectory of each time series, identifying dominant trends and key events, as well as the correlation between them. This analysis aims to understand the evolution of the sector in recent years and provide insights that illuminate its future direction.

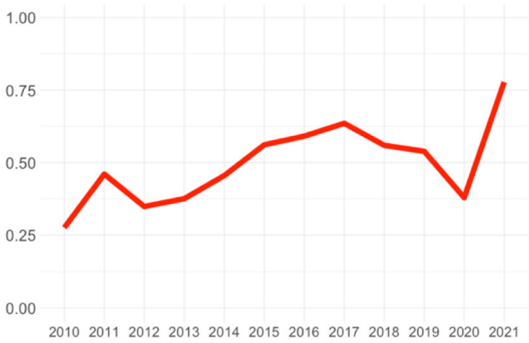
Developing Contingency Indicators

The research on the Italian industrial ceramic district has focused on a detailed analysis of the time series of the seven contingency factors shown in Fig. 3. These factors have been significantly influenced by three historical events.

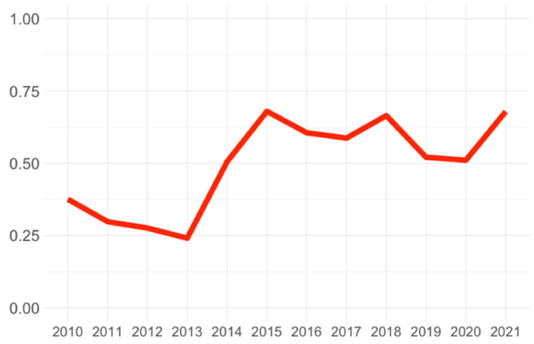
The Italian government's industrial policy, which between 2014 and 2015 spurred investments to modernize production facilities and implement digital technologies in line with Industry 4.0; a market slowdown with a reduction in demand starting in 2016; and the COVID-19 pandemic in 2020 shocked global markets. These events are critical to understanding the variability of each factor. Resource



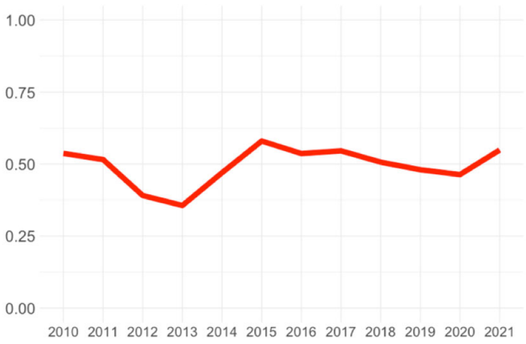
(a) Resource Consumption



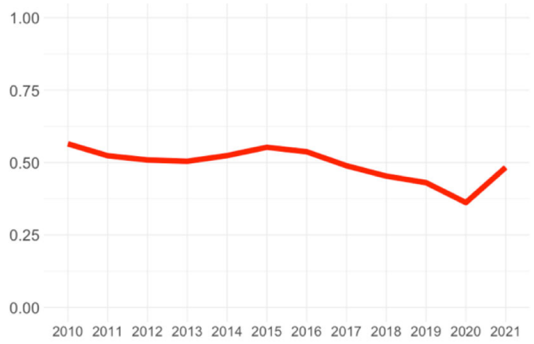
(b) Manufacturing Dynamics



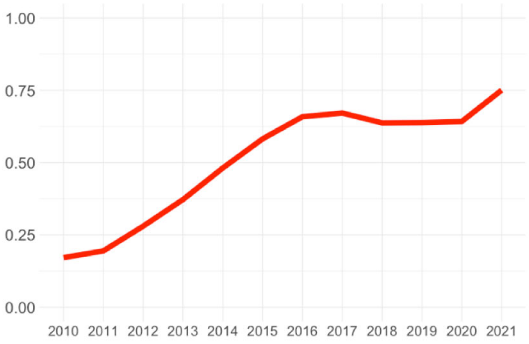
(c) Innovation



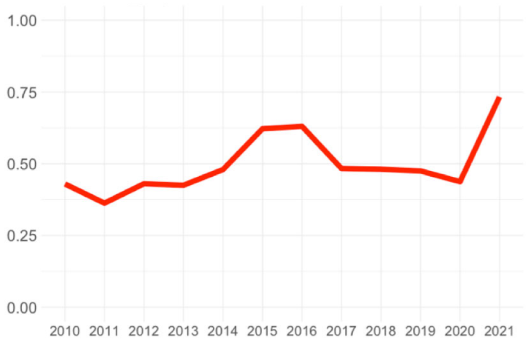
(d) Environmental Impact



(e) Social Impact



(f) Market Dynamics



(g) Economic Impact

◀ **Fig. 5** Trends over time of the seven contingency factors and the sustainability index

consumption (Fig. 5a) shows a stable trend with a slight positive inclination, interrupted by a peak and valley attributable to R&D investment, the fall in demand, and the pandemic. In manufacturing dynamics (Fig. 5b), a generally intermittent improvement is observed, interrupted in 2020 but with increases in production and efficiency indicators. Innovation (Fig. 5c), measured through investment in digitization and fixed assets, showed a notable increase in 2015, aligned with digital transformation and post-COVID-19 recovery. Environmental impact (Fig. 5d), though stable, reflects in its indicators a move toward cleaner and more efficient production. Social impact (Fig. 5e) is marked by the market slowdown in 2016. There is stability with a negative trend in the volume of companies and employees, although with improvements in the quality of human capital, demonstrating the duality of digitization: It increases the value per employee but reduces the total number of workers. Market dynamics (Fig. 5f) stand out for their positive trend despite the market slowdown, due to the sector's commitment to internationalization and digitization, which is reflected in a substantial increase in total billings. Lastly, economic impact (Fig. 5g), although slightly positive, has been marked by significant investments in digitization and post-pandemic recovery efforts.

Therefore, the digitalization process has played a crucial role in the evolution of the industrial district, with a significant impact on production, the market, and the social fabric, as well as the resilience of the sector to the market slowdown and the impact of COVID-19. Government incentives, along with internationalization strategies, have contributed significantly to increasing the competitiveness of companies, as evidenced by the positive trends observed in market dynamics and economic impact. It is important to note, however, that although productive efficiency has increased, this improvement has not directly translated into greater efficiency in resource consumption or environmental impact. In the social sphere, digitization has had a positive impact on the quality of human capital, but this has been accompanied by a reduction in the total number of employees and enterprises.

Developing Geoanthropology Domains

The seven individually analyzed contingency factors are now integrated into the holistic theoretical framework of geoanthropology. This approach, rooted in anthropology, advocates a holistic study of sustainability that integrates the analysis of various scientific disciplines into four main domains: Time, Earth, Life, and Society. The Time domain encompasses the history and evolution of both humans and the planet, reflected here through innovation and time series analysis. Earth focuses on the geological sciences and is represented here by the consumption of natural resources and the dynamics of production. Life encompasses the biological sciences, explored in our study through environmental impacts. Finally, Society encompasses the social and economic sciences, analyzed in our research through social impact, market dynamics, and economic impact.

Examining the time series of each domain (Fig. 8), we observe patterns and trends consistent with the contingency factors analyzed. In particular, the Time domain (Fig. 8a), represented by the Innovation factor, shows a significant jump coinciding with the process of digitization of the industrial district. On the other hand, the Life domain (Fig. 8d) shows a stable and slightly positive trend, corresponding to the Environmental Impact factor. The Society domain (Fig. 8b) stands out for its pronounced positive trend, driven by digitization and interrupted only by the impact of COVID-19. Meanwhile, the Earth domain (Fig. 8c) shows a similar pattern, but with a much more moderate trend.

The correlation matrix in Fig. 6 illustrates the relationships among the four domains, using red hues to indicate high correlation pairs and blue hues for medium correlation pairs. Generally, there is a strong correlation across all domains. The Time domain demonstrates a significant relationship with others, most notably with Society, underscoring the profound influence of innovation across all study indicators. Additionally, the correlation between Earth and Society is evident, reflecting the industrial district's ability to generate social value while enhancing production efficiency and reducing resource use. The Life domain exhibits the lowest correlation, indicating that environmental impacts had minimal effects on the other

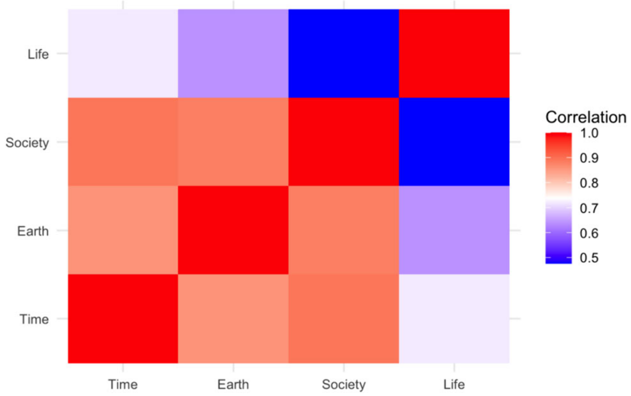


Fig. 6 Correlation matrix of geoanthropology domains

domains during the study period from 2010 to 2021. This period did not provide sufficient data to assess the impact of decarbonization efforts fully. This high level of correlation among the domains underscores the paradoxical nature of sustainability, achieved through a balanced interplay rather than individual domain development.

To visualize the evolution of geoanthropology domains over time, a spider web graph model (Fig. 7) is employed to represent the values for the years 2010 and 2021. This approach facilitates the simultaneous comparison of trends across multiple domains (Earth, Time, Society, and Life) on a single 2D plane. As evident, the domains of Earth, Time, and Society all exhibit a clear upward trend between 2010 and 2021. This suggests an increase in economic and social value, potentially linked to factors such as innovation and improved natural resource management. Conversely, the value for Life remains relatively stable throughout the analyzed period. This stability might indicate that there have been no significant changes in energy resource management practices during this timeframe.

Finally, digitalization has emerged as a powerful driver of change, especially in the social domain, but its interaction with environmental sustainability seems less direct. The resilience and adaptability of the domains to disruptive events such as the COVID-19 pandemic highlight the importance of integrated strategies that strengthen sustainability in all its facets and prepare the industrial ceramics district for future challenges.

Developing Systemic Sustainability Index

Finally, the four geoanthropological domains are combined to formulate a systemic sustainability index. Examining the evolution of the index over time (Fig. 8e) reveals the same tendencies and patterns previously identified in the contingency factors and geoanthropological domains. There is a general slightly positive trend over time, as well as a pronounced peak and trough, reflecting the digitization process and the impact of the COVID-19 pandemic, respectively. This comprehensive index accurately reflects the general evolution of the industrial district throughout the period analyzed from its 24 metrics, indicating that the methodology of analysis and aggregation of elements implemented for this study is appropriate and effective. The comprehensive analysis of the Italian ceramic industry, focusing on seven contingency factors and four geoanthropological areas, highlights the effectiveness of our methodological approach in understanding the evolution and sustainability of the sector. Innovation, promoted by the Italian government's industrial policy between 2014 and 2015, has played a crucial role in positively influencing factors such as production efficiency, market dynamics, economic impact, and social impact, despite the reduction in the number of companies and employees. The resilience to the market slowdown and the COVID-19 pandemic is particularly noteworthy, highlighting the high level of resilience of the sector. The creation of a holistic systemic sustainability index that reflects the patterns of contingency factors confirms the validity of our approach, showing a generally slightly positive trend and highlighting the role of innovation and the sector's adaptability to major challenges. This comprehensive approach not only sheds light on the evolution of the Italian industrial ceramics district but also underlines the importance of multidisciplinary strategies to strengthen sustainability and prepare the sector for future challenges.

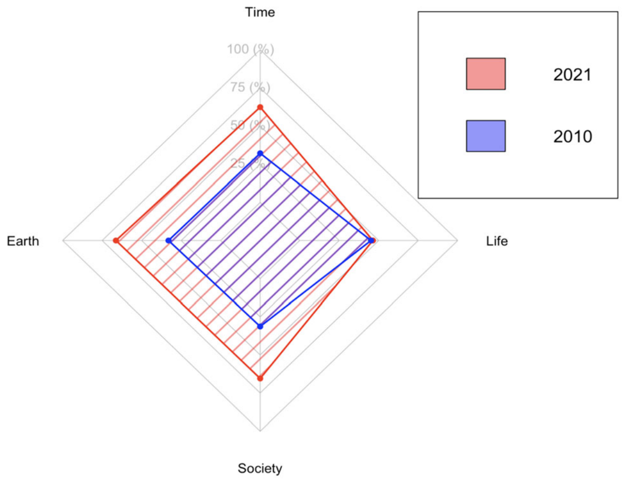


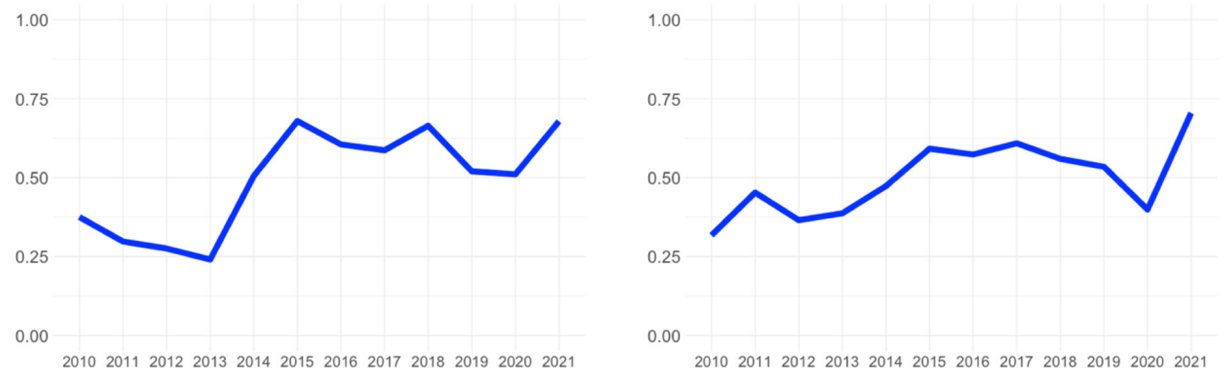
Fig. 7 Spider Web Graph trends in geoanthropology domains between 2010 and 2021

Improving Organizational Flexibility

The proposed methodological approach, using contingency factors and a geoanthropological lens, proves to be a valuable tool for organizations in the ceramic district to improve their flexibility in several dimensions: strategy, structure, systems, people, and culture.

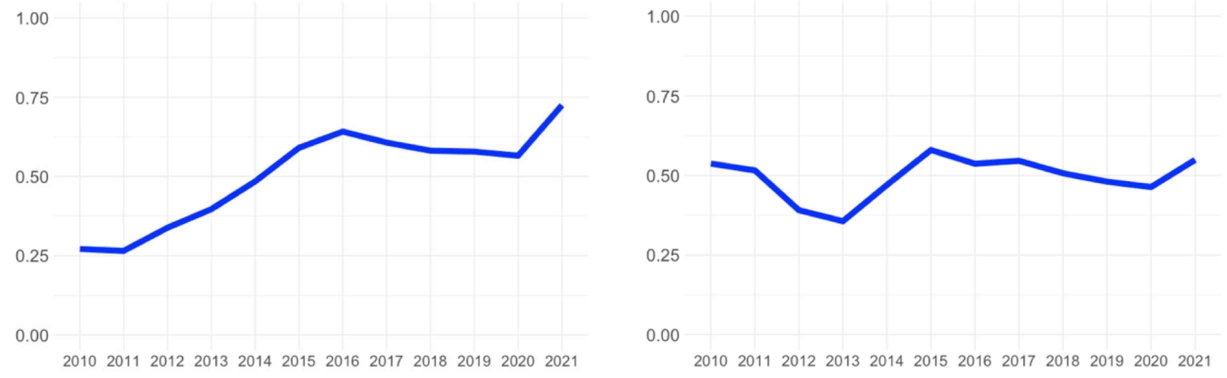
Strategic flexibility contingency factor analysis enables organizations to identify trends and anticipate emerging challenges, thereby informing strategic adjustments in advance. For example, the observed impact of digitization on market dynamics highlights the need for strategic investments in further digital transformation to maintain competitiveness.

Structural flexibility by understanding how different domains (Time, Earth, Life, and Society) interact within the geoanthropological framework, organizations can identify areas where structural changes are needed to improve adaptability. For example, the observed stability



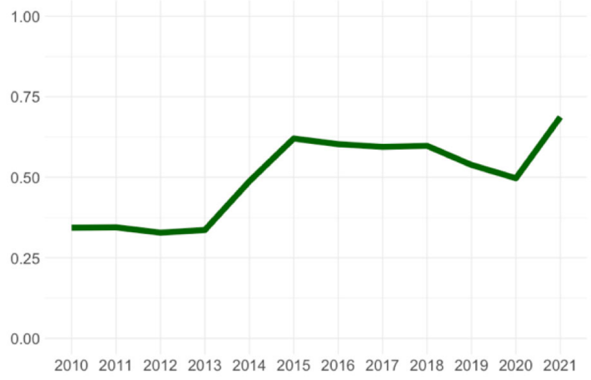
(a) Time Domain

(b) Earth Domain



(c) Society Domain

(d) Life Domain



(e) Systemic Sustainability Intex

Fig. 8 Trends over time of the four domains of Geoanthropology and the systemic sustainability index

of resource consumption despite increasing production efficiency suggests the need for structural changes to promote circular economy practices.

Systemic flexibility the methodology facilitates the assessment of the adaptability of existing systems to changing circumstances. For example, recognizing the limited influence of environmental impacts on other areas could lead to the development of more integrated systems that address environmental issues along with other aspects of sustainability.

Flexibility of people and culture analysis sheds light on the social impact of change, such as the reduction in the workforce due to digitalization. This awareness enables organizations to develop flexible human resource policies and cultivate a culture of lifelong learning to facilitate workforce adaptation.

By integrating the proposed methodology into their operations, organizations within the ceramic district can cultivate a culture of continuous improvement, enabling them to thrive in a rapidly changing and uncertain environment. This enhanced agility will enable them to meet future challenges, capitalize on emerging opportunities, and ultimately achieve long-term success. Finally, the proposed methodology aligns seamlessly with the SAP-LAP framework (Situation, Actor, Process, Learning, Action, Performance) (Singh et al., 2023), which was first pioneered by Sushil (2001). It begins by analyzing the situation through the contingency factors and geoanthropological domains and then identifies the key actors within the organization. By understanding the processes involved and the learning that takes place, the framework guides the development of actions that lead to improved performance and, ultimately, increased organizational agility.

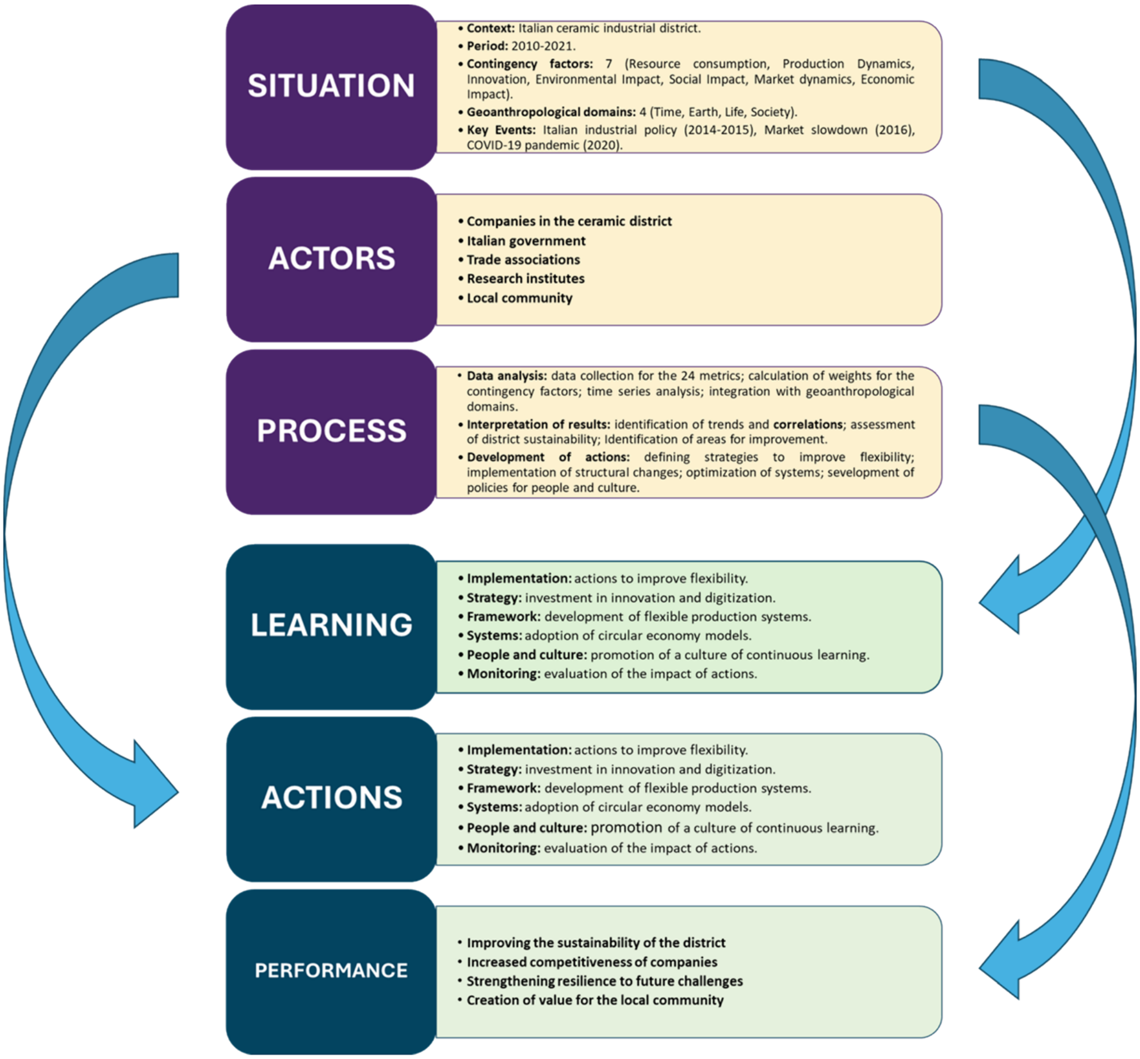
The diagram in Fig. 9 represents a conceptual model for systemic sustainability assessment applied to the case of the Italian ceramic industrial district. It is based on the SAP-LAP (Situation–Actor–Process–Learning–Action–Performance) framework and integrates the geoanthropological lens for a more in-depth and multidimensional analysis that can guide the development of concrete actions to improve the district's flexibility and performance. The arrows in the diagram indicate the flow of information and relationships between various components of the framework.

Industry 6.0: A Symbiotic Future Driven by Geoanthropology and Systemic Sustainability

While the term Industry 6.0 is not widely established or formally defined, it is emerging as the next frontier of industrial transformation beyond Industry 5.0, which emphasizes human centricity, sustainability, and collaboration in manufacturing processes. Industry 6.0, on the other hand, is expected to delve deeper into human augmentation, hyper-intelligence, and human–machine symbiosis. In Industry 5.0, the focus is on human–machine collaboration, using technology to augment human capabilities. In contrast, Industry 6.0 represents a transition to human–machine symbiosis, where humans and machines combine their strengths to achieve higher levels of intelligence and performance. While Industry 5.0 focuses on sustainability and environmental responsibility, Industry 6.0 has the potential to address global challenges such as climate change and resource scarcity through advanced technologies. Industry 5.0 focuses primarily on manufacturing processes, while Industry 6.0 is envisioned to encompass broader aspects of society, including healthcare, education, and urban planning. While Industry 5.0 is still in its early stages of development, Industry 6.0 represents a glimpse into the future of industrial transformation, where humans and machines work in synergy, augmented by cutting-edge technologies, to shape a more sustainable, intelligent, and connected world. It is important to note that Industry 6.0 is still a theoretical concept, and its specific technologies and applications have yet to be fully defined. However, it represents the ongoing evolution of manufacturing toward a future where humans and machines work more closely together, supported by advanced technologies, to achieve even higher levels of productivity, sustainability, and well-being.

Table 2 represents a prospective focus for Industry 6.0, highlighting the critical role of geoanthropology and systemic sustainability in creating an innovative and sustainable industrial future that is responsive to human needs. Geoanthropology provides a deep understanding of the complex dynamics between humans and their environment, informing the development of technologies and industrial practices that are sensitive to socio-environmental interactions. At the same time, systemic sustainability provides a robust conceptual framework for balancing economic, social, and environmental goals, promoting the design of resilient industrial solutions guided by circular economy principles. The synergistic integration of these disciplines creates a powerful framework for the design and implementation of human-centered and sustainable industrial technologies. This approach promotes sustainable innovation by developing solutions that not only optimize operational efficiency but also address human needs and contribute to resource conservation and reduced environmental impact. In addition, attention to ethics in the implementation of advanced industrial solutions is critical to ensure that technological developments are ethically responsible and respectful of fundamental human values.

This transdisciplinary approach reflects a deep understanding of the interrelationships between human, environmental, and social issues and provides valuable guidance for navigating Industry 6.0 toward a sustainable, human-centered future. The transdisciplinary framework in Table 2, by integrating geoanthropology and systemic sustainability, provides a valuable lens for understanding and shaping the emerging concept of Industry 6.0. By embracing these perspectives, Industry 6.0 can become a transformative force for sustainable development, addressing global challenges and improving human well-being.



SITUATION

- **Context:** Italian ceramic industrial district.
- **Period:** 2010-2021.
- **Contingency factors:** 7 (Resource consumption, Production Dynamics, Innovation, Environmental Impact, Social Impact, Market dynamics, Economic Impact).
- **Geoanthropological domains:** 4 (Time, Earth, Life, Society).
- **Key Events:** Italian industrial policy (2014-2015), Market slowdown (2016), COVID-19 pandemic (2020).

ACTORS

- **Companies in the ceramic district**
- **Italian government**
- **Trade associations**
- **Research institutes**
- **Local community**

PROCESS

- **Data analysis:** data collection for the 24 metrics; calculation of weights for the contingency factors; time series analysis; integration with geoanthropological domains.
- **Interpretation of results:** identification of trends and **correlations**; assessment of district sustainability; Identification of areas for improvement.
- **Development of actions:** defining strategies to improve flexibility; implementation of structural changes; optimization of systems; sevelopment of policies for people and culture.

LEARNING

- **Implementation:** actions to improve flexibility.
- **Strategy:** investment in innovation and digitization.
- **Framework:** development of flexible production systems.
- **Systems:** adoption of circular economy models.
- **People and culture:** promotion of a culture of continuous learning.
- **Monitoring:** evaluation of the impact of actions.

ACTIONS

- **Implementation:** actions to improve flexibility.
- **Strategy:** investment in innovation and digitization.
- **Framework:** development of flexible production systems.
- **Systems:** adoption of circular economy models.
- **People and culture:** promotion of a culture of continuous learning.
- **Monitoring:** evaluation of the impact of actions.

PERFORMANCE

- **Improving the sustainability of the district**
- **Increased competitiveness of companies**
- **Strengthening resilience to future challenges**
- **Creation of value for the local community**

Fig. 9 SAP-LAP framework applied to the case study of the Italian ceramic district

Conclusions

The study of the ceramic district has successfully applied a detailed analysis of seven contingency factors and highlighted their evolution over time. Key historical events, including the Italian government's industrial policy, a market downturn, and the COVID-19 pandemic, significantly influenced these factors. The study contributes by filling the knowledge gap in assessing sustainability performance using a contingency approach.

Theoretical Contributions

The theoretical contributions of this research significantly advance the field of sustainability assessment in industrial districts (IDs). The adoption of a contingent approach, integrated with geoanthropology, provides a holistic view of human–environment interactions in industrial settings, representing a departure from traditional sustainability assessment methods. Geoanthropology enriches the understanding of social, cultural, and economic dynamics within IDs, allowing for a more precise identification of relationships between human actions and long-term environmental and social impacts. Moreover, the integration of Industry 6.0 principles provides an additional perspective on how to improve the sustainability performance of IDs, broadening the vision beyond operational efficiency to include the social, environmental, and economic impacts of industrial activities. The transdisciplinary approach proposed in this study, which incorporates key concepts from different disciplines, provides a solid foundation for the development of strategies and policies aimed at improving the systemic sustainability of IDs in the next Industry 6.0 era. Finally, the adoption of flexible management emerges as a key element in the implementation of such strategies,

Table 2 Framework for navigating Industry 6.0 through the transdisciplinary lens of geoanthropology and systemic sustainability

Geoanthropology's role in industry 6.0	Systemic sustainability's foundations for industry 6.0:
Geoanthropology, which studies the complex interactions between humans and their environment, provides valuable insights for shaping Industry 6.0 in a sustainable and human-centered manner: *Understanding human–environment dynamics* Geoanthropology's expertise in analyzing human–environment interactions can inform the development of sustainable technologies and practices within Industry 6.0 *Addressing global challenges* geoanthropology's holistic perspective can guide Industry 6.0 toward addressing global challenges like climate change, resource scarcity, and social inequality *Promoting cultural sensitivity* geoanthropology's emphasis on cultural diversity can ensure that Industry 6.0 technologies and applications are developed and implemented in a culturally sensitive and inclusive manner	*Systemic sustainability*, which focuses on interconnectedness and long-term thinking, provides a solid foundation for Industry 6.0: *Balancing economic, social, and environmental goals* systemic sustainability's emphasis on balancing economic, social, and environmental considerations aligns with Industry 6.0's potential to address global challenges *Designing for long-term resilience* systemic sustainability's focus on long-term thinking can guide the development of Industry 6.0 technologies that are resilient and adaptable to future changes *Promoting circular economy principles* Systemic sustainability's emphasis on circular economy principles, such as resource efficiency and waste reduction, can inform the design of sustainable manufacturing processes within Industry 6.0
Convergence of geoanthropology and systemic sustainability in Industry 6.0	
The integration of geoanthropology and systemic sustainability provides a powerful framework for shaping **Industry 6.0**:	
Human-centered design geoanthropological insights and systemic sustainability principles can guide the development of human-centered technologies that are not only efficient but also socially and environmentally responsible	
Sustainable innovation the combined expertise of geoanthropology and systemic sustainability can foster sustainable innovation within Industry 6.0, ensuring that technological advancements align with long-term sustainability goals	
Ethical considerations	
Geoanthropology's focus on human values and systemic sustainability's emphasis on ethical principles can ensure that Industry 6.0 technologies are developed and implemented in a responsible and ethical manner	

enabling IDs to adapt quickly and effectively to changing environmental, social, and economic conditions.

In addressing the research questions:

- *RQ1* the research establishes that the contingency approach finds its theoretical grounding in geoanthropology. This integration goes beyond conventional sustainability frameworks and demonstrates the adaptability of the contingency approach to different contexts within IDs.
- *RQ2* the study demonstrates that the contingency approach not only enables but also excels in the design of context-adaptive initiatives within industrial districts. The detailed analysis of seven contingency factors provides a multilevel understanding of the specific challenges and opportunities within the ceramic district. Moreover, the proposed systemic sustainability index, derived from geoanthropological domains, serves as a practical tool to guide the development and implementation of adaptive sustainability initiatives tailored to the unique context of IDSs.
- *RQ3* the transdisciplinary approach proposed in this study incorporates the principles of Industry 5.0, which promote humanity at the core of industrial operations, sustainability as a fundamental element of production, and stakeholder collaboration as a driver of innovation. These principles provide an additional perspective on how to improve the systemic sustainability performance of IDs, shifting the focus beyond operational efficiency to the social, environmental, and economic impacts of industrial activities.
- *RQ4* geoanthropology and systemic sustainability are emerging as key enablers of Industry 6.0, fostering sustainable, symbiotic human–machine interactions. These transdisciplinary approaches drive ethical innovation and resilience, address global challenges, and shape a future of hyper-intelligent human–machine symbiosis in Industry 6.0.

The adoption of a transdisciplinary approach stands out as central to advancing the understanding of systemic sustainability in IDs in the context of Industry 5.0. This approach, embodied in the comprehensive framework shown in Fig. 4, combines essential principles from different disciplines, including systemic sustainability, geoanthropology, and Industry 5.0, highlighting the importance of an integrated view to addressing the complex challenges of IDs. Of particular importance is the integration of geoanthropology into the conceptual framework, which provides a holistic perspective on human–environment interactions in IDs. By providing a sound theoretical and methodological foundation, this approach facilitates a nuanced understanding of the social, cultural, and economic dynamics within IDs, allowing for a more precise delineation of the links between human activities and their lasting environmental and social impacts. As a result, geoanthropology enriches the assessment of systemic sustainability by promoting a deeper understanding of the scope and breadth of human–environment interactions.

For an in-depth exploration of systemic sustainability in industrial districts in the Industry 5.0 era, it is essential to adopt a transdisciplinary approach. This approach, outlined in the proposed framework, combines central concepts from different disciplines, including systemic sustainability, geoanthropology, and Industry 5.0 principles. By emphasizing an integrated perspective, it addresses the multifaceted challenges associated with IDs. At the same time, the infusion of Industry 5.0 principles into the framework enhances understanding and guidance. These principles emphasize the centrality of humanity in industrial operations, the indispensability of sustainability in manufacturing, and the catalytic role of stakeholder collaboration for innovation, broadening the scope beyond operational efficiency to include social, environmental, and economic impacts. This integrated approach comprehensively examines the dynamics that influence the sustainability of IDs and provides a solid foundation for developing strategies to improve systemic sustainability. Moreover, from another perspective, the adoption of organizational flexibility emerges as a key element in the implementation of such strategies. Organizational flexibility enables IDs to adapt quickly and skillfully to changing environmental, social, and economic conditions, facilitating the maintenance of a dynamic balance between stakeholder demands and long-term sustainability goals. Consequently, organizational flexibility aligns well with the proposed conceptual framework and contributes to the optimal and responsible management of IDs in the Industry 5.0 era.

Finally, the emerging setting of Industry 6.0 presents a unique set of challenges and opportunities that require a proactive and transdisciplinary approach. Integrating insights from disciplines such as geoanthropology and systemic sustainability with the principles of Industry 6.0 allows us to develop a more nuanced understanding of the complex dynamics at play. By leveraging Industry 6.0 principles, which emphasize factors such as human–machine symbiosis, hyper-intelligence, and sustainable innovation, we can steer industrial development toward more sustainable and resilient paths. In addition, incorporating geoanthropological perspectives provides valuable insights into the complex interactions between humans and the environment in industrial settings. Understanding these dynamics is critical to designing technologies and practices that not only optimize efficiency but also prioritize environmental protection and social well-being. Similarly, systemic sustainability provides a holistic framework for assessing the long-term impacts and interdependencies of industrial activities, ensuring that development strategies are aligned with broader sustainability goals. By adopting a transdisciplinary approach that synthesizes insights from these diverse fields, we can navigate the complexities of Industry 6.0 with greater foresight and effectiveness. This forward-looking perspective allows us to anticipate emerging challenges such as resource scarcity, climate change, and social inequality while identifying innovative solutions that promote sustainable development. Ultimately, by ensuring that sustainability remains at the forefront of the transition to Industry 6.0, we can build a more resilient and equitable industrial landscape for future generations.

Managerial Implications

The research provides key management insights for the ceramic district and broader industrial contexts. The study highlights the influential role of innovation, digitization, and government policies in shaping production efficiency, market dynamics, economic impacts, and social aspects. By dissecting these drivers, managers gain in-depth insights into the mechanisms of sustainability. Of note is the sector's resilience to challenges due to digitization, internationalization, and significant investment. Managers can use these insights to strengthen their businesses against disruptions and promote a proactive approach to sustainability. The interconnected nature of factors such as innovation and market dynamics requires integrated sustainability strategies. Managers are encouraged to take a holistic view of sustainability, fostering comprehensive and interconnected approaches. The introduction of the systemic sustainability index provides a practical tool for managers. Derived from geoanthropological domains, this index provides a comprehensive metric for measuring overall sustainability. It serves as a valuable compass for decision-making and ongoing strategy evaluation. The geoanthropological model for assessing systemic sustainability in industrial districts recognizes that organizational flexibility is essential to effectively manage the complex interactions among environmental, social, and economic factors that influence the adaptive capacity of firms. As a result, it provides practical insights for managers to promote sustainability through innovation, understand resilience mechanisms, support integrated strategies, and use the systemic sustainability index to make informed decisions.

Limitations and Further Research

While this study provides a comprehensive analysis, it is important to recognize its inherent limitations. The exclusive focus on internal data, valuable for insights into the ceramic district, hinders direct comparisons with other sectors and limits broader applicability and benchmarking.

Future research should investigate the complex interplay between geoanthropology, systemic sustainability, and the emerging Industry 6.0 paradigm. This exploration should consider metrics beyond financial metrics to measure the impact of technology in the innovation domain. Exploring these intersections could provide insights into sustainable practices within the Industry 6.0 framework. Extending the contingency approach to different industrial districts and refining methodologies for better comparability across sectors is critical. Strengthening the theoretical foundations of geoanthropology by integrating it with management theories will enhance its applicability in industrial contexts. In addition, a deeper exploration of systemic sustainability is needed for a holistic understanding. These research directions are essential for refining methodologies and theories, advancing sustainability assessment, and aligning it with the evolving Industry 6.0 landscape. By advancing methodologies and theories, researchers can improve sustainability assessments and guide industries toward greater resilience in the face of technological and environmental change.

Acknowledgements The authors thank the Editor, Guest Editors, and anonymous reviewers for their helpful comments on this paper.

Author Contributions Andrés Fernández-Miguel involved in conceptualization, writing original draft. Fernando E. García-Muiña took part in conceptualization, validation. Davide Settembre Blundo carried out conceptualization, review, and editing. Maria Pia Riccardi involved in conceptualization, supervision. Serena Chiara Tarantino took part in methodology, data curation.

Funding Open access funding provided by Università degli Studi di Pavia within the CRUI-CARE Agreement. This research was co-funded by the Italian Ministry of Enterprises and Made in Italy under the measure "Development Contracts" (DM 31/12/2021), grant number: F/310122/01-05/X56 (VOLT—Viability fOr circuLar manufacTuring).

Declarations

Conflict of interest The authors declare no competing interest.

Ethical Approval The authors complied with all ethical norms.

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Key Questions

RQ1. In which specific field of knowledge can the contingency approach for the analysis of the sustainability performance of IDs be embedded?
RQ2. How does the contingency approach to sustainability enable the design of context-adaptive initiatives in IDSs?
RQ3. In the context of Industry 5.0, how can a transdisciplinary approach improve knowledge of the systemic sustainability performance of IDs?
RQ4. How does the emerging paradigm of Industry 6.0 intersect with the principles of a transdisciplinary approach and systemic sustainability?

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