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Defining a Methodology for Digital Supply Chain Twin in the Ceramic Industry

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Abstract. The current industrial environment requires companies to develop innovative solutions to adapt production processes and procurement strategies to the challenges of global supply chains. The Italian ceramic industry, characterized by high resource consumption and a complex supply chain, demonstrates vulnerabilities in ensuring the continuity of its operations. To address these challenges and mitigate supply chain risks, the circular economy paradigm has been adopted, tailored to the specific context, and implemented with an innovative perspective. In this context, this paper proposes a transdisciplinary methodological approach, integrating knowledge from supply chain management, digitalization, and sustainability science, and leveraging digital technologies in a real-world setting. The research focuses on defining a methodology finally aimed at developing a Digital Supply Chain Twin (DSCT): a dynamic virtual representation of a real supply chain that predicts its behaviour. Achieving this goal requires building a robust benchmark of data and objective functions to represent supply chain components, performance metrics, and flows. Indeed, only a validated and reliable DSCT can enable accelerated and automated "what-if" analyses related to sustainability performance. Procurement decision-making will thus benefit from an intuitive, fast, and automated tool to evaluate supply chain performance and potential modifications, integrating economic, environmental, and social sustainability perspectives.

Keywords. Digital Supply Chain Twin, Circular Economy, Sustainability, Supply Chain Management, Transdisciplinary Engineering.

1. Introduction

In today's rapidly evolving industrial landscape, supply chains have become increasingly complex and must address numerous challenges [1]. Industries worldwide are grappling with economic, political, and environmental fluctuations that disrupt the flow of materials and products [2]. These challenges necessitate innovative solutions to enhance resilience and sustainability. Thus, there is a growing need to strengthen supply chains, particularly in strategic sectors driving the green and digital transition [3]. As part of its Open Strategic Autonomy objective, the European Commission has initiated a study on supply chain vulnerabilities to develop targeted industrial policies [4]. Expanding on this

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analysis, the Centro Studi Confindustria has identified critical dependencies—or vulnerabilities—of EU countries on foreign supplies, with a high level of sectoral detail, comparing them with those of the United States and China [5]. The selection criteria for critical products include geographical diversification of imports, substitutability through exports, and, for European countries, intra-area trade substitutability. The ceramic industry, renowned for its rich tradition and high resource consumption, is particularly susceptible to these disruptions. The Italian ceramic sector, a cornerstone of the nation's manufacturing excellence, faces specific challenges such as dependence on imported raw materials and the necessity of sustainable production practices [6]. Recent studies have highlighted the industry's efforts to optimize its green supply chain to mitigate environmental impacts. Several regulations govern goods purchased from outside national borders, particularly concerning extra-EU imports within the European Union [7]. Mechanisms like the Carbon Border Adjustment Mechanism (CBAM) should support, not replace, existing carbon leakage measures, ensuring EU industry competitiveness through features like an export adjustment within the ETS Directive. Despite its global strength, the Italian ceramic industry faces inefficiencies in resource use and supply chain vulnerabilities, worsened by the pandemic and geopolitical instability. These issues underscore the need for resilient, multidisciplinary sustainability strategies tailored to stakeholders and supported by effective communication tools [6][8]. This study introduces a transdisciplinary approach combining Circular Economy (CE) principles and Industry 4.0 technologies, especially Digital Twins (DT) [9], to develop a Digital Supply Chain Twin (DSCT)—a virtual model simulating supply chain dynamics and sustainability impacts [10]. Aimed at improving efficiency and resilience, this framework highlights DT's role in advancing CE within supply chains [11], offering a comprehensive solution for sustainable transformation in the ceramic sector.

2. Methodology for Digital Supply Chain Twin

The proposed methodology has been developed using a transdisciplinary approach, integrating knowledge from multiple disciplines, including supply chain management, digital technology (such as DT), and sustainability. The objective is to apply a comprehensive framework that combines technological, economic, environmental, and social aspects to address supply chain challenges in the ceramic industry.
The methodology, as outlined in Figure 1, consists of several steps:

1. Definition of the phases of the ceramic industry supply chain,
2. Definition of the nodes and connection arcs that make up the supply chain,
3. Defining evaluation metrics for social, environmental and economic impacts,
4. Evaluation of possible scenarios identified by the combination of different characteristics of each element (Digital Supply Chain Twin),
5. Simulation software to compare different scenarios (graph/radar chart).

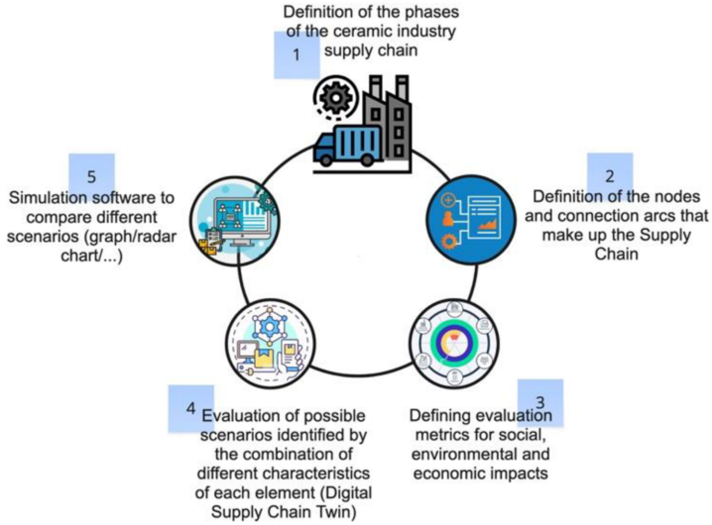

Figure 1. Methodology for the definition of the Digital Supply Chain Twin.

The first step involved defining each supply chain actor and segmenting the network into “upstream”, “core” and “downstream" sections. Within each section, stakeholders, resources, and material flows were identified. At this stage, the modeling approach was structured into three macro-categories:

1. Selection of the system components: it defines how to characterize the entities involved in the supply chain. Each entity can be represented by two main items, as depicted in Figure 2:
    - Node: it represents a specific entity, such as a factory, supplier, or production facility - essentially all actors within the supply chain;
    - Arc: it represents the mode of transport connecting these entities (e.g., air, sea, or land transport).
2. Definition of the operational flows: it establishes how the arcs are represented and quantified, capturing logistical attributes such as volume transferred, transport distance, and mode of transportation.
3. Performance assessment: it assigns specific weighting factors to evaluate the performance of each actor within the supply chain. Performance indicators provide insights into efficiency, environmental impact, and overall supply chain sustainability.

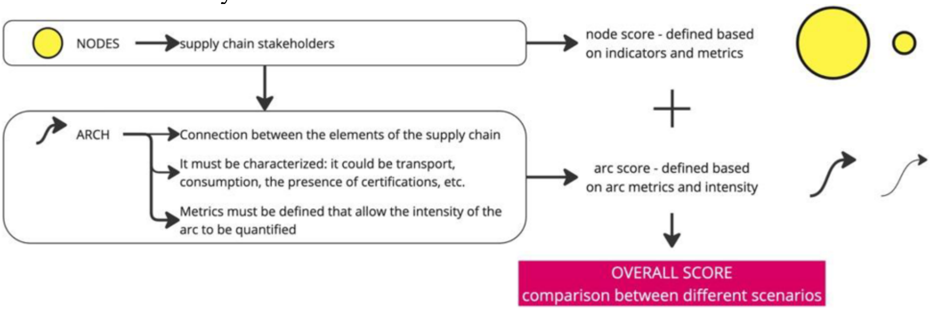

Figure 2. System components for the Digital Supply Chain Twin.

Such an approach ensures a systematic assessment of sustainability performance within the ceramic sector, leveraging DT technology to model, monitor, and optimize supply chain operations [12].

The first step involves identifying supply chain components and evaluating them using sustainability indices across environmental, economic, and social dimensions. These indices are assigned to both nodes and arcs, culminating in a comprehensive, weighted sustainability index for the entire supply chain. Scenario analysis is conducted through benchmarking and combining different node and arc characteristics, producing indices that guide evaluation. Dedicated software then visualizes alternative scenarios, using a DT to replicate supply chain actors and enable real-time sustainability assessments. The final goal is to develop a DSCT tool that supports performance monitoring, predictive analysis, and scenario comparison to optimize sustainability across the ceramic supply chain.

As illustrated in Figure 3, a set of evaluation metrics for supply chain nodes was selected through a literature review and an analysis of relevant regulatory frameworks. The proposed method is flexible enough to add additional evaluation parameters; in fact, the metrics presented below do not represent all the parameters to be evaluated.

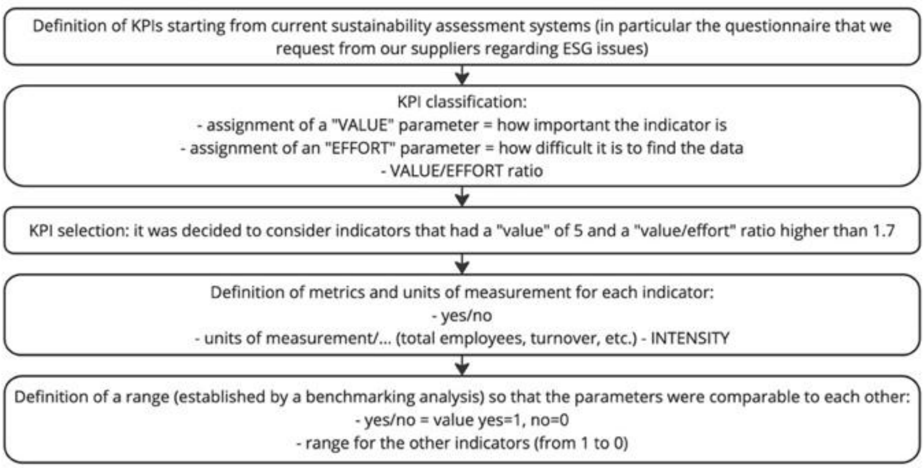

Figure 3. Supply chain node assessment.

To establish the sustainability index for assessing supply chain nodes, the following procedure was adopted: 1) Identification and selection of key parameters, 2) Definition of parameters, 3) Normalization of parameters, and 4) Index calculation.

Regarding the definition of KPIs, the process started with an analysis of existing ESG assessment systems, with particular attention to supplier evaluation questionnaires related to these themes. Once the full list of KPIs had been compiled, a panel of sector experts – including technical specialists and managerial figures drawn from the supply-chain companies involved – reviewed the indicators. Based on this expert judgement, different weights were assigned to individual indicators to ensure a balanced assessment and to enable a more accurate selection. The experts scored each KPI against two parameters: "Value" (representing the importance of a specific indicator) and "Effort" (indicating the ease of data retrieval). The relationship between these two parameters was then defined through a value/effort ratio. To avoid an excessively large number of indicators, only those with a value of 5 and a value/effort ratio greater than 1.7 were considered. Once the key indicators were identified, the next step was the normalization of metrics for KPI calculation and unit standardization. This ensured that each metric could be compared with others and assigned the same weight in the evaluation. For quantitative indicators, a recognized and widely used unit of measurement was assigned to define the indicator's intensity (e.g., total employees, revenue in euros). For qualitative indicators, a binary approach (Yes/No) was used to indicate whether the data was available.

To ensure comparability among different stakeholders and competitors, a benchmarking analysis was conducted to define an appropriate range for each parameter. This analysis involved various supply chain actors, allowing for the definition of normalization factors tailored to each major supply chain segment (e.g., raw material procurement, machinery manufacturers, ceramic tile producers).

Once all normalized metrics were defined, the final sustainability index calculation (SIC) for each node was performed. Equation 1 determines the sustainability intensity of each node by the Sustainability Index Calculation (SIC) as the sum of the normalized parameters:

$$SIC = \sum_{n=1}^{x} I_n \tag{1}$$

where I_n is the weight of node n, with n from 1 to x. Table 1 below summarizes all the indicators, units of measurement, and "value" and "effort" parameters assigned to each one.

Table 1. Selected indicators and metrics with respective parameters "value" and "effort" assigned.

Area	Measure	Response	Value (1-5)	Effort (1-5)	Value/Effort	UM	Intensity
BUSINESS	Does the company monitor its sustainability performance with specific quantitative indicators?	Y/N	5	3	1,7	Y/N	
	The company publishes its results regarding environmental, social and economic sustainability in a specific report	Y/N	5	3	1,7	Y/N	
GOVERNANCE	Presence of women	n.	5	1	5,0	n.	n./turnover
	Community Investments	€	5	3	1,7	€	€/turnover
	Privacy and Data Security Policy	Y/N	5	2	2,5	Y/N	
SOCIAL	N° of accidents occurred in the current year	n.	5	3	1,7	n.	n./turnover
	N° of deaths in the company over the last 3 years	n.	5	3	1,7	n.	n./turnover
	N° of training hours provided during the year	n.	5	3	1,7	n.	n./turnover
	Does the company have gender equality as its mission?	Y/N	5	2	2,5	Y/N	

	Sustainable Procurement Policy covering environmental aspects, labour practices and human rights	Y/N	5	3	1,7	Y/N	
	Supplier Code of Conduct	Y/N	5	3	1,7	Y/N	
INNOVATION	Investments in Research and Development with a focus on sustainability	€	5	3	1,7	€	€/turnover
	N° of patents owned in the field of sustainable innovation and/or digitalisation	n.	5	2	2,5	n.	n./turnover
SAFETY	Non-compliant products/services are identified and appropriately managed	Y/N	5	2	2,5	Y/N	
	Documented analyses of customer complaints are available	Y/N	5	1	5,0	Y/N	
CIRCULAR ECONOMY	Raw materials recycled as part of its activities	tons	5	3	1,7	tons, kg	tons/turnover
	Has an analysis been carried out to assess the increase in resource productivity and reduction of waste along the value chain?	Y/N	5	3	1,7	Y/N	
	Certified origin of raw materials	Y/N	5	3	1,7	Y/N	
WATER, ENERGY AND WASTE	% of electricity from renewable sources	kWh_green	5	3	1,7	kWh_green	kWh_green/turnover
	Total waste produced	tons	5	3	1,7	tons, kg	tons/turnover
	Water consumed (in one year by all company offices)	m3	5	2	2,5	m3	m3/turnover
ORGANIZATION CERTIFICATIONS	ISO 14001	n.emp/total n.emp	5	2	2,5	n.emp/total n.emp	(n.emp/total n. emp)/turnover
	ISO 45001	n.emp/total n.emp	5	2	2,5	n.emp/total n.emp	(n.emp/total n. emp)/turnover
	ISO 9001	n.emp/total n.emp	5	2	2,5	n.emp/total n.emp	(n.emp/total n. emp)/turnover

The second key element of the proposed model is the arc. To evaluate each arc, the first step involved defining the type of transport mode used (e.g., airplane, ship, truck). Next, the operational flow was determined, using specific metrics to assess the intensity of the flow. The metrics for calculating the "weight" of arcs are outlined below:

1. Distance to be covered (km): the total distance each transport mode must travel to transfer goods.
2. Energy source: the type of fuel used by each transport mode (e.g., diesel, electric).
3. Intensity factor:
    - Average volume (kg or €): measures the average volume of transported goods, which can be normalized based on either economic value or weight.
    - Number of trips within the timeframe considered: the total number of transport movements occurring within a specific period.

Additional possible metrics are:
1. CO_2 emissions per km (gCO_2/km): measures the carbon footprint per kilometer traveled, enabling a comparison of the environmental efficiency of different transport modes.
2. Transport cost per unit of volume/weight (€ per kg or m^3): the cost associated with transporting one unit of weight or volume of goods.
3. Vehicle utilization index (%): the percentage of utilization relative to the total capacity of the vehicle (e.g., how full a truck is).
4. Transport safety (accidents/km or % of secure deliveries): the incident rate per kilometer or the percentage of goods delivered without damage.

To evaluate possible scenarios resulting from the combination of different characteristics of each element, evaluation parameters have been defined for both nodes and arcs. Specifically, objective functions have been established to accurately represent the supply chain, focusing on its components, performance, and operational flows. The graph score will be determined primarily by the weight of the arcs, as the weight of the nodes is always normalized to 1. Equation 2 is the general equation that will enable the assessment and comparison of various stakeholders and competitors within the ceramic supply chain. The Overall Score equation (OS) is based on the comparison between different scenarios:

$$OS = \sum_{n=1}^{x} I_n + \sum_{a=1}^{y} P_a \tag{2}$$

where P_a is the weight of arch a, with a from 1 to y. The possible scenarios may vary depending on the type of indicators and metrics identified, so they depend on the type of selection made.

3. Case study: application to the Italian ceramic industry

The Italian ceramic industry is a strategic sector within the national manufacturing system, known for its high-quality standards, advanced production processes, and global competitiveness. However, it is also characterized by high resource consumption and supply chain complexity, making it particularly vulnerable to fluctuations in raw material availability, logistics disruptions, and evolving sustainability regulations. The industry heavily depends on imported raw materials, which expose companies to geopolitical risks, transportation delays, and price volatility. Additionally, the sector is subject to strict environmental policies, including the CBAM and the Corporate Sustainability Reporting Directive (CSRD), requiring businesses to enhance traceability, transparency, and sustainability compliance in their operations. To address these challenges, the CE paradigm has emerged as a key strategy for increasing supply chain resilience, reducing waste generation, and optimizing resource use. While CE principles have been widely discussed in literature, their practical implementation in industrial supply chains, particularly in ceramics, remains limited. In response to the increasing complexity and unpredictability of global supply chains, digital technologies have been introduced to improve decision-making and operational efficiency. Among these, DT represents a transformative tool for monitoring, analyzing, and simulating supply chain performance in real time. The research applies a DSCT to the ceramic industry, creating a dynamic, data-driven simulation environment that captures technological, environmental, and socio-economic factors affecting supply chain performance. The methodological framework for DSCT development consists of:

1. Supply chain mapping: identifying key stakeholders, resource flows, and logistics networks, segmented into upstream, core, and downstream sections.
2. Data benchmarking and objective function definition: establishing quantitative metrics to evaluate economic, environmental, and social performance based on CE principles.
3. Real-time data integration: incorporating operational and sustainability metrics from industry databases.
4. Scenario analysis and predictive modeling: running what-if simulations to assess the impact of supply chain modifications on sustainability KPIs.

3.1. Results and discussion

This study presents a transdisciplinary methodological approach that integrates I4.0 technologies to design and validate an integrated solution for sustainability monitoring within the Italian ceramic supply chain. The proposed methodology enables real-time monitoring of environmental, social, and economic sustainability performance through the implementation of DT technology. The research focuses on the development of a DSCT, a dynamic virtual representation of the supply chain that can simulate and predict its behavior in terms of sustainability impacts. To achieve this goal, a robust dataset and a set of objective functions were established to model the supply chain's key components, performance metrics, and operational flows. A validated and reliable DSCT enables automated and accelerated "what-if" analyses, supporting companies in assessing sustainability scenarios and optimizing procurement strategies. The structure of the DSCT is built on three fundamental elements: constitutive components, operational flows, and performance metrics. The constitutive components include nodes, representing the different stakeholders in the supply chain, and arcs, which define the logistics connections between them. Nodes correspond to actors such as raw material suppliers, machinery manufacturers, ceramic tile producers, and distributors, each characterized by specific sustainability indicators. Arcs, on the other hand, represent transportation links and are evaluated based on key metrics such as transport distance, energy consumption and CO_2 emissions. This structure allows for a detailed assessment of supply chain inefficiencies, highlighting opportunities for sustainability improvements. Operational flows define the movement of materials, energy, and resources between nodes, incorporating real-time data from supply chain operations. By leveraging the DSCT model, companies can simulate and optimize these flows, identifying alternative logistics routes, reducing environmental impact, and improving resource efficiency. The performance of each supply chain element is assessed through sustainability KPIs derived from a benchmarking analysis. These indicators provide a structured and comparable evaluation of the environmental, economic, and social sustainability of each node and arc within the supply chain (a first representation of the graph is presented in Figure 4).

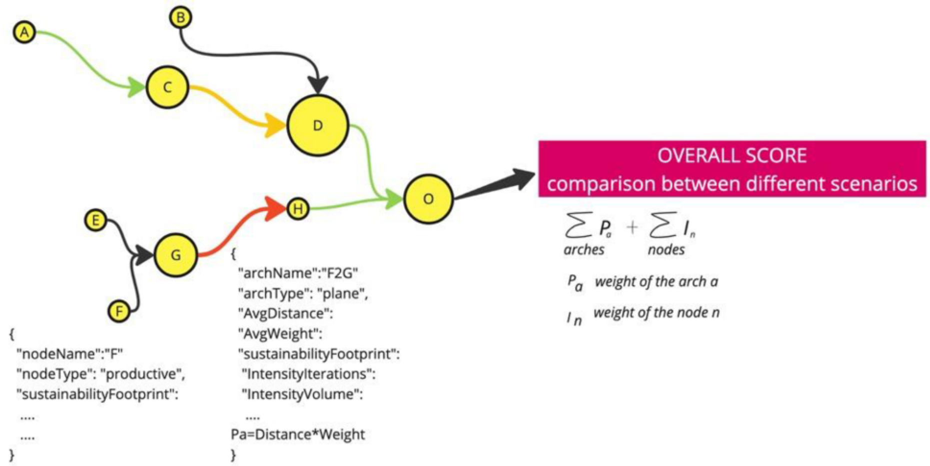

Figure 4. Example of the representation of the supply chain as a graph.

Integrating the Digital Supply Chain Twin (DSCT) into the Italian ceramic sector has shown promise for informed decision-making by visualizing sustainability metrics, inefficiencies, and risks. It supports scenario optimization and strengthens resilience by enabling proactive stakeholder selection based on sustainability. However, challenges persist, particularly regarding data availability, quality, and the integration of diverse datasets across stakeholders. Maintaining alignment with evolving sustainability regulations also requires ongoing updates and standardization. The study underscores the role of digitalization in enabling circular supply chains, improving ESG compliance, predictive modelling, and real-time collaboration. The DSCT framework offers a scalable model for enhancing sustainability in other resource-intensive sectors.

4. Conclusions and future perspectives

The research proposed a novel framework that combines digitalization and sustainability principles to support decision-making in complex supply chains. By integrating DT technology with CE strategies, the study presented a methodological approach that enables real-time monitoring and optimization of environmental, economic, and social sustainability performance. The proposed DSCT framework offers a comprehensive and data-driven perspective, providing companies with the ability to simulate sustainability scenarios and assess the impact of procurement strategies on overall supply chain resilience. The study demonstrated that adopting a DSCT model can lead to tangible improvements in supply chain sustainability. Through real-time visualization of sustainability KPIs, companies are guided to identify inefficiencies, reduce emissions, optimize logistics routes, and improve social responsibility practices. The integration of predictive scenario analysis further supports the development of proactive strategies, enabling companies to mitigate risks and enhance their competitive positioning in global markets. However, several challenges must be addressed to ensure the effective implementation of the DSCT framework. Data availability and accuracy are fundamental issues, as well as the effectiveness of real-time simulations and the input data quality. Additionally, as sustainability regulations continue to evolve, ensuring compliance with ESG standards necessitates continuous updates to the model. While the methodology has been tested within the ceramic industry, its applicability to other manufacturing sectors requires further adaptation to sector-specific challenges and supply chain structures. Future developments should focus on expanding the DSCT framework to other resource-intensive industries, tailoring its application to diverse supply chain configurations. Enhancing predictive capabilities through machine learning algorithms could further improve the tool's ability to anticipate sustainability risks and optimize resource allocation.

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