Wine Economics and Policy

Firenze University Press
www.fupress.com/wep

OPEN ACCESS

Citation: Zironi, A., Danese, P., Romano, P., & Zironi, R. (2024). A Lean Six Sigma, Industry 4.0 and Circular Economy-driven methodology for wine supply chain process improvement. *Wine Economics and Policy* 13(2): 75-88. doi: 10.36253/wep-15803

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

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A Lean Six Sigma, Industry 4.0 and Circular Economy-driven methodology for wine supply chain process improvement

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Abstract. Scientific literature recognizes that Lean Six Sigma (LSS), Industry 4.0 (I4.0) and Circular Economy (CE) offer significant opportunities to improve operational performance and decrease the environmental impact. Wine supply chains represent a strategic asset for the world economy and an ideal setting for the implementation of LSS, I4.0 and CE, but studies that integrate these three approaches to improve wine supply chain processes are lacking. The present research intends to demonstrate how wine supply chain processes (SCPs) can be improved by deploying the synergies between LSS, I4.0 and CE, so as to face the quality, efficiency and sustainability challenges modern competition poses to wine companies. To this aim, this study proposes an original methodology that adopts a step-by-step procedure inspired by the Define-Measure-Analyze-Improve-Control (DMAIC) cycle to systematically improve SCPs throughout the different phases of wine supply chains (i.e., vineyard, cellar, distribution). The methodology has been conceptualized starting from three sources - review of scientific literature, interviews with experts and personal contribution – and assembles in an original way some concepts and tools referring to different bodies of literature such as strategic decision making, data-driven process improvement, lean management, industry 4.0 and circular economy. The methodology has been tested in a real case to evaluate its utility for practice and relevance.

Keywords: Lean Six Sigma, circular economy, winemaking.

1. INTRODUCTION

In recent years, wine supply chains have faced new and demanding challenges. The traditional problems of controlling variability in winemaking processes to guarantee the homogeneity of wine quality, alongside cost savings and waste elimination to pursue efficiency, have recently been complemented by the digitization and automation of production processes and the design of new products and processes with a low environmental impact [1,2,3]. In this context, wineries must be prepared to analyze and modify their supply chains to make them more efficient and sustainable by increasing their capacity for innovation and improving performance using available resources [4,5].

The digital and sustainable transitions represent the perfect playground in which wineries can prove their ability to change their processes at an accelerated pace to face growing competition challenges, new customer expectations, and regulatory compliance. The journey toward such transitions depends not only on technology availability but also on the company's ability to identify the right actions to implement. There is a broad consensus in the scientific literature that Lean Six Sigma (LSS), Industry 4.0 (I4.0), and Circular Economy (CE) can offer companies several opportunities to reduce variability, increase efficiency, improve process control, and decrease the environmental impact.

The concept behind the LSS model is quite recent and was first mentioned in the book "Lean Six Sigma: Combining Six Sigma with Lean Speed" [6]. By combining the principles and tools of Lean and Six Sigma into a single solution, the authors demonstrate how companies can achieve better results than implementing the two approaches separately. LSS focuses on what the consumer really expects from the product or service they purchase (i.e., the value for the customer) and relies on data collection and analysis to identify opportunities to reduce waste and increase the quality of the product or service offered. LSS requires the adoption of specific tools, inspired by Lean Management and Statistical Process Control, within a formalized problem-solving approach following the Define, Measure, Analyze, Improve, and Control (DMAIC) cycle, which is an evolution of Edward Deming's Plan-Do-Check-Act cycle for continuous process improvement [7].

I4.0 has developed more recently to promote the use of digital technologies to optimize production processes and lays its foundation on information and communication technology [8]. The main tools of I4.0 are based on advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, cloud computing, sensors, and smart devices [9]. I4.0 technologies enable the connection and monitoring of machinery, production, and information flows with the goal of providing strategic guidance to managers so as to create production systems (and supply chains) that are not only more efficient, reactive, and reliable, but also more sustainable [10, 11].

CE refers to an economic production and consumption model pursuing the reduction of environmental impact that proposes practical solutions to waste and pollution problems caused by the linear economic model [12]. With a focus on sustainability, modern wineries are committed to implementing strategies that enable them to achieve cost savings to gain a competitive advantage over time through proper management of internal resources [13]. Specifically, through new approaches to design, production, and delivery of products and services, CE can support companies in extending the value of the resources they use over time [14]. According to literature, the main methods to achieve this goal are reuse, remanufacturing, and recycling [12].

Generally, the LSS, I4.0, and CE domains are addressed separately or in pairs [15, 16, 17]. Focusing on wine supply chains, the lack of studies integrating these three views of process improvement is even more evident. I4.0 represents a significant stream of studies, often related to the Agriculture 4.0 framework, which is an evolution of precision agriculture [18], or Viticulture 4.0 and Oenology regarding the winemaking phase in wine supply chains. A recent study [19] explored the potential of applying an I4.0-based decision support tools (DSS) to simulate different scenarios in the wine industry and aid decision makers in choosing the most appropriate strategy to achieve business objectives, but without integrating it with LSS or CE tools.

CE is a rich and promising field of research in the wine supply chain context, but studies exploring the connections with LSS and I4.0 are lacking. As for the literature specifically related to LSS concepts in wine supply chains, it is very limited, mainly focused on the winery and bottling areas, and not related to CE and I4.0 issues.

This research aims to demonstrate how wine supply chain processes (SCPs) can be improved by deploying the synergies between LSS, I4.0, and CE to face the quality, efficiency, and sustainability challenges of modern competition. To this end, this study proposes an original methodology that enables the systematic improvement of SCPs throughout the different phases of wine supply chains, integrating LSS, I4.0, and CE. The methodology has been tested in a real case to evaluate its relevance and utility.

The paper is structured as follows: The next section describes the conceptual and implementation frameworks of the proposed methodology. It is followed by the application to a real winery. In the following section, we discuss and evaluate the Decision Support System (DSS) and derive some conclusions. The final sections report the theoretical and practical implications and the conclusions and future developments.

2. PROPOSED METHODOLOGY

The methodology proposed by this study has been conceptualized based on three sources: a review of the

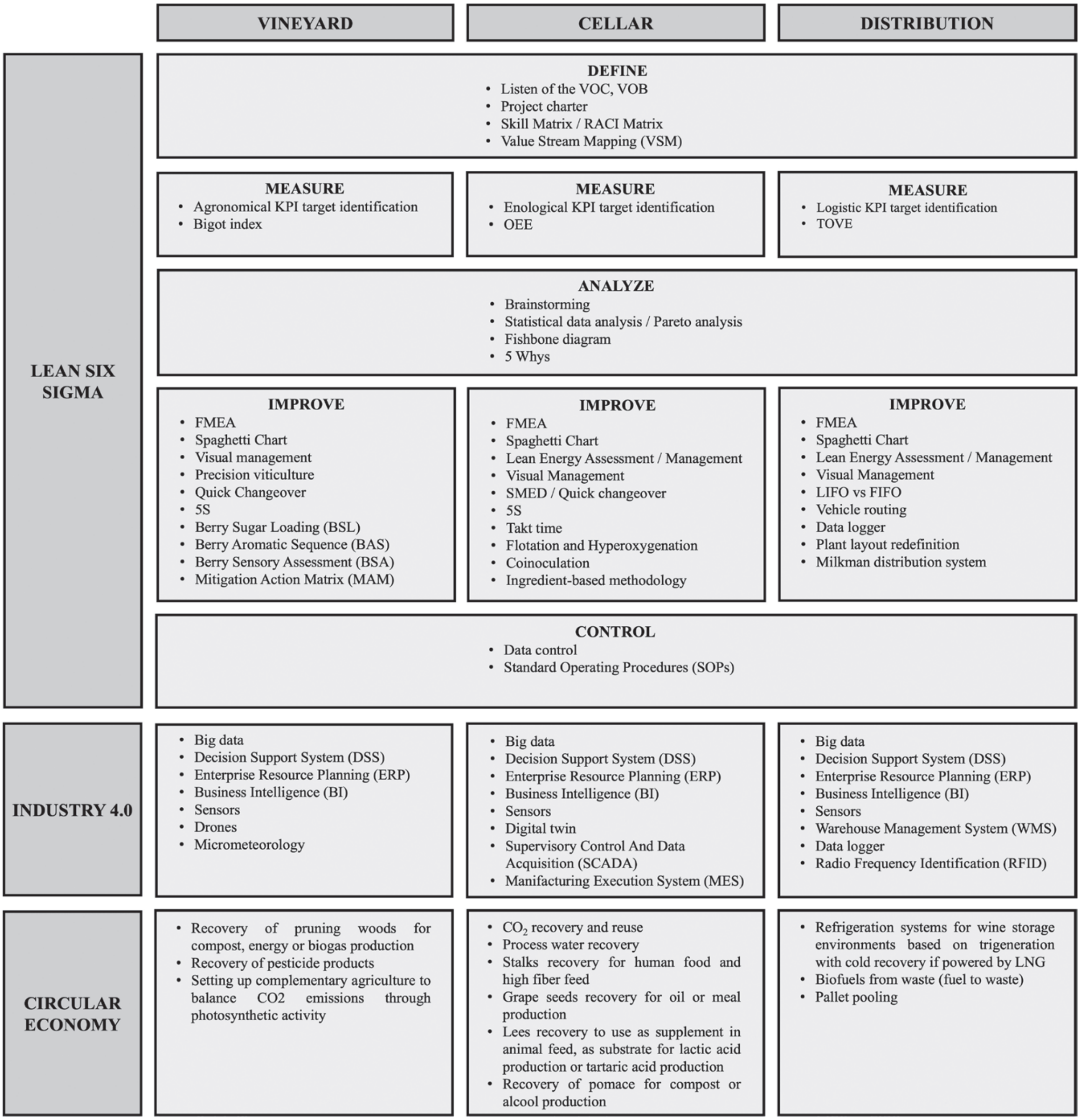

Figure 1. The conceptual framework ("What").

scientific literature, interviews with experts, and personal contributions. The literature review on Lean Six Sigma (LSS), Industry 4.0 (I4.0), and Circular Economy (CE) in the wine sector was conducted on the combination of keywords "Wine supply chain", "Lean Six Sigma", "Industry 4.0", "Circular Economy", "Waste reduction strategies" using the Scopus and Science Direct databases, and with the supports of books and grey literature. The research focused on the three main areas of the wine supply chain: the vineyard, the cellar, and distribution.

Since two co-authors possess extensive consulting expertise in the wine supply chain, their knowledge supplemented the literature with practical insights into

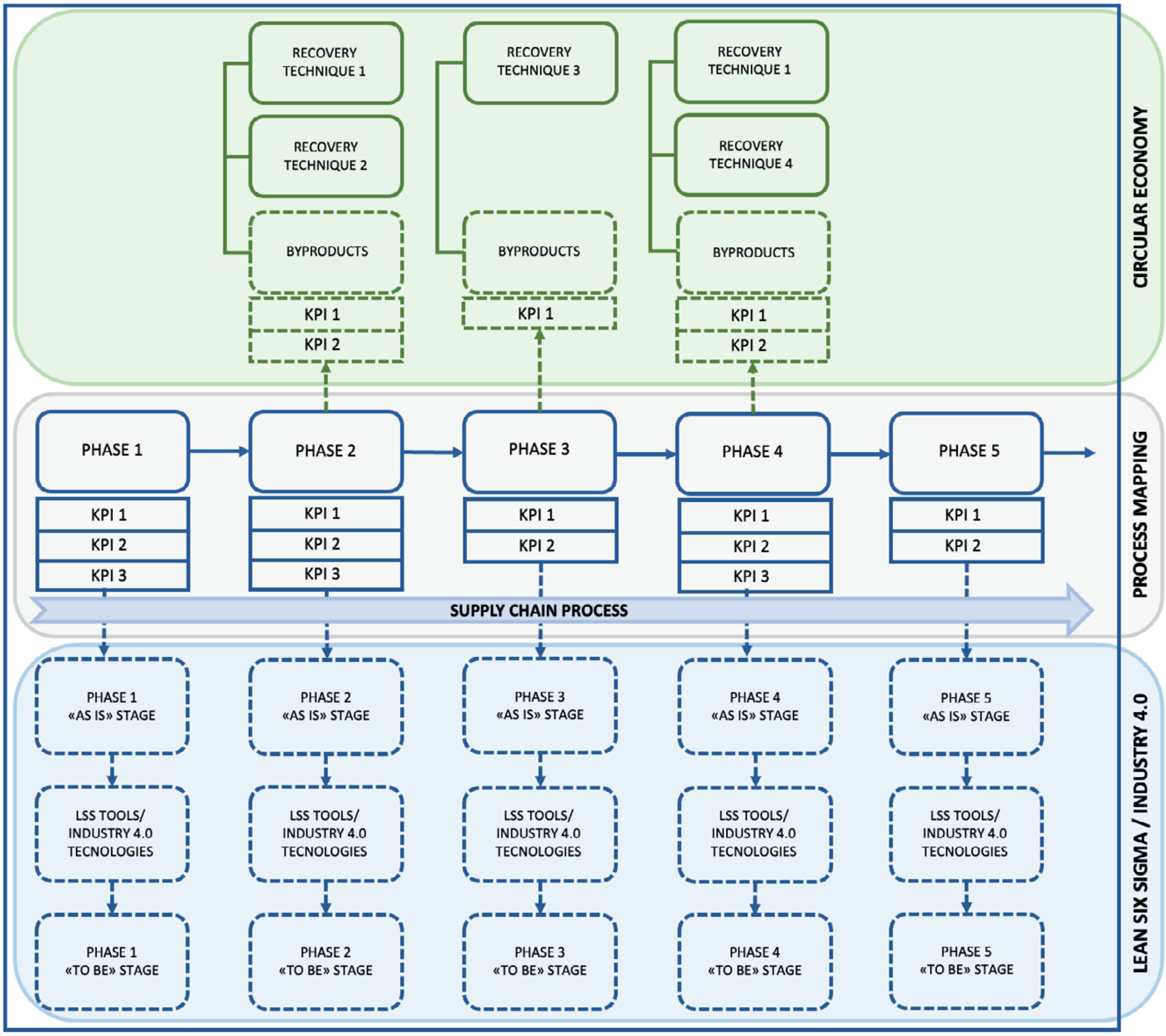

Figure 2. The implementation framework ("How").

solutions for winemaking, waste reduction, and waste by-product recovery. Before testing the model's validity through application in a real case study, we discussed and refined it with three professionals, one from each of the main areas of the wine supply chain. The resulting conceptual framework is synthesized in Figure 1, which presents the main LSS, I4.0, and CE decision-supporting tools for each stage of the wine supply chain.

While Figure 1 reports the conceptual framework and indicates *what* can be done, Figure 2 highlights the implementation framework and suggests *how* to deploy new supply chain processes that use decision supporting tools included in the conceptual framework.

The core of Figure 2 is the SCP, namely the supply chain macro-process that contains all the phases from the vineyard to the final consumer (from vine to dine). Each SCP phase is associated to a set KPIs essential to measure the improvement actions. The upper part of Figure 2 integrates the SCP with circular economy, as it highlights the phases where by-products are generated as well as possible recovery and valorization actions. The lower part integrates the SCP with LSS and I4.0, as it highlights the phases where lean tools and/or I4.0 technologies can be used to reduce waste.

Implementation requires a preliminary phase, called target definition, followed by the iterative repetition of the five phases of the DMAIC cycle.

2.1. Target definition

The aim of this phase is to make explicit the "oenological objective", which consists in the performance target of the SCP, in terms of quality, cost, environmental impact and/or resource consumption, etc. The clarification of the Voice of the Customer (VOC) and the Voice of the Business (VOB) is a prerequisite for properly identifying the oenological objective. The VOC represents the needs and expectations of end customers, which are gathered using questionnaires inspired by the Quality Function Deployment (QFD) methodology. The VOB represents the perspective and expectations of the management, collected through interviews.

2.2. Define

This phase focuses on the governance of the project aimed at achieving the oenological objective. The initial step involves forming a multidisciplinary work team equipped with the necessary skills. The team typically comprises agronomists, oenologists, bottling technicians, sales personnel, IT experts, plant engineers, and external consultants. The Skill Matrix, a tool recommended by the LSS approach, is used to ensure that team members have all the required skills. The team plans the main steps of the project and defines roles and responsibilities. The Gantt Chart and the RACI (Responsible, Accountable, Consulted, Informed) matrix are two project management tools that are utilized at this stage. The team is also tasked with the detailed mapping of the Supply Chain Process (SCP), which forms the foundation of all implementation actions (refer to the central part of Figure 2).

2.3. Measure

This phase is dedicated to collecting data on the SCP and conducting preliminary assessments. Taking the oenological objective into account, the multidisciplinary team initially identifies the strategic KPIs for each phase of the SCP and defines their target values or ranges. The adoption of I4.0 technologies, such as Viticulture 4.0 and Oenology 4.0, can facilitate data collection by simplifying the activities of operators and enhancing the effectiveness, speed, and reliability of data gathering. Furthermore, I4.0 technologies provide company databases with a continuous flow of real-time data, which is crucial for monitoring KPIs. Data collection should also cover by-products, enabling data-driven decision-making on the CE actions to be implemented (see dotted arrows in the upper part of Figure 2).

2.4. Analyze

In this phase, the collected data are analyzed to identify hotspots and areas for improvement. At this stage, investigating the root causes of problems is important. To this aim, the availability of accurate data and the multidisciplinary expertise of the team are crucial. Data collected by sensors and other digital systems must be organized in databases and processed using statistical techniques and DSS, which make extensive use of visual management tools (e.g., dashboards and maps representing the variability of the production process based on the monitored parameters). During data-driven brainstorming sessions, the multidisciplinary team identifies those KPIs that are not aligned with the target ranges defined in the Measure phase and investigates the root causes of this misalignment, also using LSS cause-and-effect analysis tools (e.g., the Ishikawa diagram or the 5 Whys model).

2.5. Improve

In this phase, the team identifies the corrective actions to address the root causes of problems identified in the analysis phase. The conceptual framework (Figure 1) aids the brainstorming process by proposing for each stage of the wine supply chain a structured set of LSS solutions specifically dedicated to the "improve phase," along with CE practices and I4.0 technologies. In line with the learning-by-doing logic, this set can be updated and enriched with the knowledge the team acquires and develops over time. During the brainstorming, the team assesses the suitability of the solutions, practices, and technologies listed in Figure 1 in terms of their impact, costs, time, and resources required. The final outcome is the reconfiguration of the SCP in alignment with the oenological objective, and an implementation plan that defines for each phase how to transition from the current state to the to-be state.

2.6. Control

In this phase the team evaluates if the actions launched in the previous phase (i.e., the new SCP) effectively improve the KPIs identified in the Measure phase and if further improvement cycles are needed. Through data-driven decision-making, the team verifies whether the oenological objective has been achieved. Interviews with customers and assessments of manager satisfaction can be used to ascertain that the VOC and the VOB have been satisfied. The Control phase also includes formalizing the new SCP with the creation of the Best Practice Manual and Standard Operating Procedures (SOPs).

3. TESTING AND EVALUATION

The proposed methodology was applied in a real setting of a winery with 100 hectares of vineyards located in Apulia, in the Taranto area, specialized in the production of organic wines. The company's product portfolio includes a dozen labels, most of which are Primitivo red wine. In addition to the winery, the company has a wine resort where it organizes guided tastings, special events and gourmet dinners. All these activities allowed the company to establish direct channels with its customers over time and to collect their feedback.

3.1. Target definition

The research team initially met with the company owner and the winery manager. From the interviews, it emerged that a general idea of the oenological objective was already present. Considering the winery's medium-term strategy to enter new international market segments, one of the main concerns was the variability in the quality of Primitivo wines in the product portfolio.

The VOB was clear: to increase customization (i.e., to tailor wines in the portfolio to the needs of the market segment) and to produce Primitivo wines that consistently meet customer expectations (i.e., to reduce supply chain process variability).

Regarding the VOC, reports from tasting sessions confirmed that consumers had noted the high variability of Primitivo wines from different vintages. This problem also affected other wine varieties within the company's portfolio. Feedback data also indicated consumer preferences for wines with balanced aromas, limited alcohol content, and produced with practices that have a low environmental impact.

After a brainstorming session, the research team converged on the following oenological objective: "to improve the quality of the company's wines over time by targeting wine customization, reduced variability, and increased environmental sustainability of supply chain processes". The research was conducted in the 2020 vintage, choosing Primitivo as the test grape variety.

3.2. Define

The research team together with the winery manager identified the set of skills required to address the oenological objective and filled the Skill Matrix reported in Figure 3 to create the multidisciplinary team. In addition to specific technical competences, such as agronomic, oenological and sensorial analysis skills, transversal competences related to problem solving, digital technologies and circular economy were included.

The matrix in Figure 3 shows how the internal staff's skills in sensory analysis, digitalization and circular economy were rated low. The involvement of three university experts and an external consultant enabled the complementation of the internal staff's competencies and the acquisition of a proper level of expertise in all key skills for the project.

As first step, the multidisciplinary team identified the main phases of the supply chain process of the Primitivo wines and the currently generated by-products, and used the BPMN software to map the SCP as reported in Figure 4. Due to space constraints, Figure 4 and the subsequent discussion focus on wine fermentation and aging, two significant phases of the overall SCP. Then, the team created a Gantt chart (project charter) that outlined the main steps of the macro project aimed at achieving the oenological objective, including milestones, timing, roles, and responsibilities.

3.3. Measure

The multidisciplinary team collected data on the Supply Chain Process (SCP) and conducted preliminary assessments deemed essential for pursuing the oenological objective. Agronomists, winemakers, and technicians gathered information on production protocols; the winery manager retrieved data on product and process costs; and the sales manager organized a tasting session with the team to determine the "as-is" sensory profile of the Primitivo wines. As illustrated in Figure 5, for each phase of the SCP, the team identified KPIs and mapped the by-product management practices already in use (indicated by a dotted line).

For each KPI, the team established the optimal target ranges in alignment with the oenological objective and compared them with the "as-is" values. To better measure the fermentation process performance, the team introduced a specific KPI named Production Lead Time (PLT).

The Measure phase also presented a significant opportunity for brainstorming, during which the team identified and evaluated alternative solutions that could be implemented to improve the current process. For instance, cellar and vineyard technicians discussed with the winery manager the possibility of adopting digital technologies to support data collection and monitoring.

	STAFF	ROLE	PROBLEM SOLVING	PROJECT MANAGEMENT / TEAMWORKING	VINEYARD	WINEMAKING	SENSORY ANALYSIS / BLENDING	DIGITAL TECHNOLOGIES	CIRCULAR ECONOMY	CUSTOMER BEHAVIOUR	INDIVIDUAL SCORE
			SKILLS								
INTERNAL STAFF	ID1_FB	Agronomist	2	1	3	2	3	2	1	1	15
	ID3_GS	Director	3	3	2	2	2	2	1	3	18
	ID4_TN	Winemaker	2	2	3	3	2	2	2	1	17
	ID5_ML	Agronomist	2	2	2	1	0	0	0	1	8
	ID6_FD	Intern	1	1	2	2	1	3	0	1	11
	ID7_PA	Technician	2	1	2	3	1	0	2	0	11
	ID8_ML	Technician	0	2	3	2	1	0	1	0	9
	ID9_CF	Technician	1	0	2	2	1	0	1	1	8
	ID10_FD	Marketing	2	2	1	1	0	1	0	3	10
	ID11_EG	Sales	1	2	1	1	2	2	0	3	12
	Total skill score		16	16	21	19	13	12	8	14	
	Average score		1.6	1.6	2.1	1.9	1.3	1.2	0.8	1.4	
EXTERNAL STAFF	ID12_RZ	University expert	3	3	2	3	3	2	3	2	21
	ID13_GB	University expert	3	2	3	2	3	3	2	3	21
	ID14_PR	University expert	3	3	2	2	2	2	3	3	20
	ID15_AZ	Consultant	2	2	2	3	3	3	2	2	19
	Total skill score		27	26	30	29	24	22	18	24	
	Average score		2.5	2.3	2.2	2.4	2.5	2.2	2.2	2.3	

LEGENDA	
0	No skills
1	Basic skills
2	Medium skills
3	Advanced skills

Figure 3. Skill matrix.

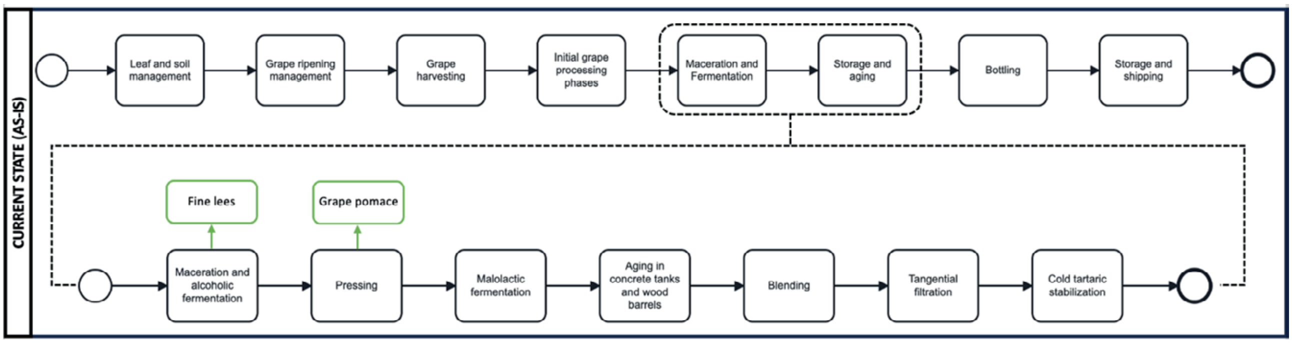

Figure 4. Primitivo wines SCP mapping.

This would potentially reduce the workload, improve the quality of the data collected, and, in turn, more effectively pursue the oenological objective.

3.4. Analyze

The team analyzed the data, work protocols, and KPIs to identify problems and their causes. As illustrated in Figure 6, it was discovered that the most signifi-

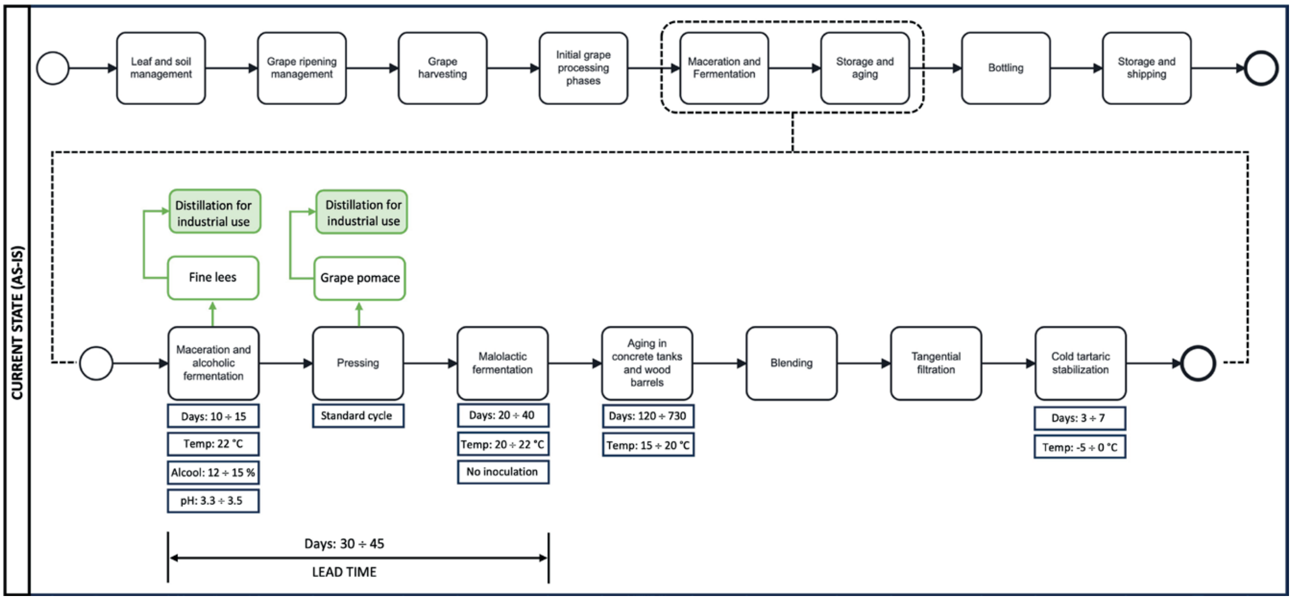

Figure 5. As-is SCP map with KPIs and by-products.

cant discrepancies between the KPI values and the oenological objective pertained to three phases of the SCP: grape ripening, maceration and alcoholic fermentation, and malolactic fermentation.

The 5-Why method, a lean tool commonly used to identify the root cause of problems, revealed the presence of obsolete work protocols and incorrect procedures in both the vineyard and the cellar. These protocols had been established many years prior and had not been updated over time. Due to variations in soil type, microclimate, and other factors, the Primitivo wines had developed different qualitative potentials, which were not being adequately leveraged by the current work procedures. Sensory tasting sessions with the team members confirmed these findings. Another root cause identified was the winery's low level of digitization, especially in data collection, and the complete absence of real-time control over some critical parameters of the production process, such as irrigation water consumption, vineyard micro-meteorological variables, and the temperatures during maceration and fermentation. These two root causes led to numerous errors and misunderstandings among employees, negatively affecting not only the SCP's performance but also the quality of the grapes and wines produced, and consequently, the achievement of the oenological objective.

3.5. Improve

Firstly, the team classified the problems into categories: digitalization problems and production process formalization problems. As a second step, the team was involved in several brainstorming sessions during which the members consulted the conceptual framework (see Figure 1) to address the problems and identified the following improvement actions:

1. Introduction of smartphones and tablets connected to the ERP system for data collection.
2. Installation of I4.0 sensors and technologies to monitor fermentation temperatures and irrigation system water consumption.
3. Modification of grape harvesting and production protocols to improve the quality and sustainability of the winemaking process by introducing an "ingredient-based" production methodology.

As a third step, the team evaluated the economic impact and time required to implement the identified solutions, producing a report that was submitted to the winery director for approval. Finally, as the fourth and final step, the team proceeded to implement the identified solutions.

Regarding digitalization issues, the paper-based tools previously used by vineyard and cellar technicians were replaced with tablets wirelessly connected to the winery's ERP system, enabling synchronized data uploads and making the information accessible to all staff. Digital temperature sensors were installed in all fermentation and maceration tanks. The outdated irrigation system was replaced with a more modern one equipped with Industry 4.0 technology, allowing for real-time data analysis and remote control.

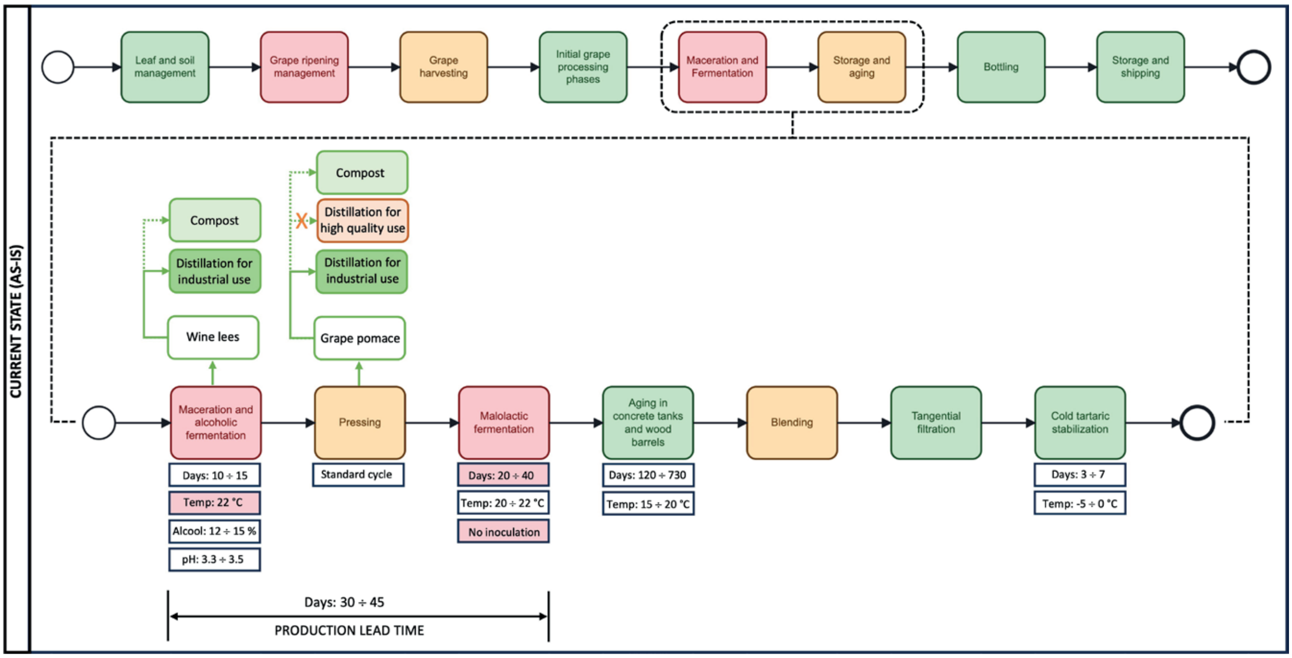

Figure 6. Critical points in the SCP.

Regarding the production process formalization issues, before modifying the current protocols, the team decided to conduct a vineyard potential quality analysis to ensure that the changes aligned with the oenological objective. This methodology revealed the presence of vineyard areas with significantly different quality potentials, leading to their division into quality clusters. Based on these clusters, the team decided to introduce the ingredient-based production methodology. Consequently, the protocols were modified with the goal of producing three distinct ingredients:

– Ingredient 1 (I-1): limited alcohol content but significant acid content.
– Ingredient 2 (I-2): good balance between phenolic and aromatic components.
– Ingredient 3 (I-3): structure, high alcohol and sugar potential obtained by over-ripening grapes.

Once the ingredients were identified, the key parameters (KPIs) to be monitored in the vineyard during the growing season were determined (see upper part of Figure 7).

The team formalized new harvesting protocols by integrating the analysis of grape analytical parameters already in use with the Berry Sensory Assessment (BSA) and Berry Sugar Loading (BSL) procedures [20]. Through BSA, BSL, and periodic monitoring of grape parameters (sugars, acids, and pH), the optimal times for harvesting the grapes needed to produce the three ingredients were identified.

Accordingly, the team defined a specific winemaking protocol for each ingredient (see the lower part of Figure 7). To achieve the oenological objective, the team decided to introduce co-inoculation of yeasts and lactic acid bacteria during alcoholic fermentation. Each ingredient underwent a different fermentation and aging cycle, and at the end of the aging period, the three ingredients were blended in varying proportions to obtain the final wines.

The adoption of an ingredient-based production methodology necessitated modifications to the existing protocols for managing by-products. Compared with the initial SCP, where all winery by-products were sent to the distillery (see Figure 6), in the new SCP (see Figure 8), the wet pomace from I-1 and I-2 can also be used to produce compost for vineyard use. Instead, the wet pomace from I-3 is sent to the distillery for high-quality utilization.

Finally, during implementation, it became apparent that there was a need to organize specific training sessions on blending and sensory tasting of wines and grapes for continuous evaluation of the achievement of the oenological objective. Indeed, the Skill Matrix revealed low scores among the internal company staff in blending and sensory analysis phases. To effectively implement the ingredient-based production methodology, the staff's ability to blend various ingredients to produce final wines with desired sensory profiles is crucial.

VINEYARD	I-1	I-2	I-3
GRAPE MATURITY LEVEL	Phenolic maturity of the skin but not of the seeds	Complete phenolic maturity of the skin and seeds	Complete phenolic maturity of the skin and seeds
TOTAL ACIDITY (g/L)	> 7	5 ÷ 7	< 5
pH	< 3.3	3.3 ÷ 3.5	> 3.5
SUGAR CONTENT (Brix)	20 ÷ 22	22 ÷ 24	> 24

BSA Indicators for I-1

Pulp: film of pulp only slightly visible on skins but juice is released from skins when squashed. Sweet taste, moderately acid and fruity aromas predominate over herbaceous aromas.

Skin: fairly easy disintegration, mixture almost homogeneous. At the taste the tannins are medium size grains.

Seed: Brown-green seeds color. At the taste the seeds crushes under pressure like a fresh almond. Astringent when chewed.

BSA Indicators for I-2

Pulp: film of pulp only slightly visible on skins but juice is released from skins when squashed. Sweet taste, moderately acid and fruity aromas predominate over herbaceous aromas.

Skin: fairly easy disintegration, mixture almost homogeneous. At the taste the tannins are medium size grains.

Seed: Grey brown seeds color, no green traces. At the taste most seeds are hard and crack easily. Moderately astringent when chewed.

BSA Indicators for I-3

Pulp: no film of pulp on skin and seeds and no release of juice when squashed. Very sweet taste, low acid and intense fruity aromas.

Skin: easy disintegration, homogeneous mixture. At the taste the tannins are soft, fine and silky grain.

Seed: Dark-brown seeds color. At the taste all seeds are hard, crack quickly and are crunchy. No astringency.

CELLAR	I-1	I-2	I-3
SEEDS EXTRACTION	no	yes	yes
PRE-FERMENTATIVE MACERATION	no	no	yes Temperature: 8 ÷ 10°C Duration: 3 ÷ 4 days
MACERATION WITH ALCOHOLIC FERMENTATION	Temperature: 22 ÷ 23°C Duration: 6 ÷ 8 days	Temperature: 23°C Duration: 8 ÷10 days	Temperature: 20 ÷ 21°C Duration: 8 ÷ 10 days
POST-FERMENTATIVE MACERATION	no	no	Temperature > 20°C Duration > 21 days
MALOLACTIC FERMENTATION	With alcoholic fermentation (Co-inoculation of yeasts and bacteria during alcholic fermentation)	With alcoholic fermentation (Co-inoculation of yeasts and bacteria during alcholic fermentation)	With alcoholic fermentation (Co-inoculation of yeasts and bacteria during alcholic fermentation)

Figure 7. Production process formalization according to the ingredient-based methodology.

Consequently, the team recognized the need to enhance these specific skills of the company personnel.

3.6. Control

At the end of the harvest, the team organized a meeting with the company owner and the winery manager to taste the wines obtained. Subsequently, tastings were held during international fairs and events to collect consumer and importer judgments. The tasting involved a blind comparison between the previous year's wine (wine A) and the one obtained with the new protocols (wine B). The company proceeded with the collection and processing of tasting data for a period of approximately six months. Over 70% of customers indicated a preference for wine B. At the end of the period the winery director was interviewed, expressing satisfaction for the result achieved.

From the 2022 harvest the company has also extended the experimentation to other varieties. All staff have been trained on the new procedures and a company

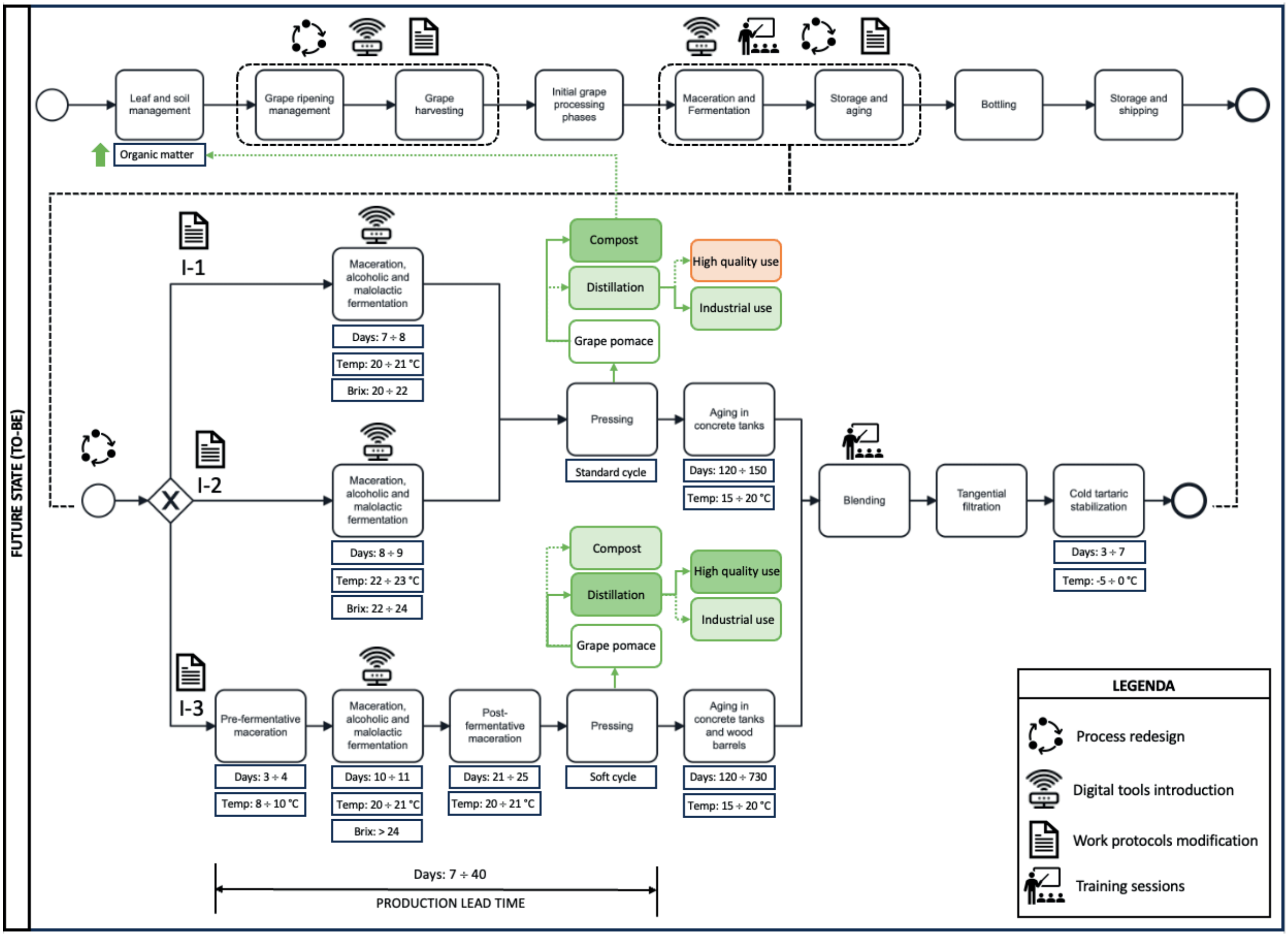

Figure 8. To be SCP map.

best practice manual has been created by the team. The experimentation is still ongoing.

4. DISCUSSION

The aim of this research was to demonstrate how supply chain processes can be improved by deploying the synergies between LSS, I4.0 and CE, so as to face the quality, efficiency and sustainability challenges modern competition poses to wine companies. To this aim, this study proposed an original methodology for systematically improving SCPs throughout the different phases of wine supply chains by integrating LSS, I4.0, and CE. Our findings and evaluation in a real case corroborated that the proposed methodology addresses the gaps identified in the literature concerning the lack of a systemic approach that connects process improvement decision-making to LSS, I4.0, and CE.

The Design Science Research Methodology suggests evaluating decision-support systems considering their novelty, practical usefulness, and relevancy [21]. As justified below, the contribution of the methodology this study proposes is considered novel, practical, and relevant, indicating that it supports decision-making to improve wine SCPs by synergistically exploiting LSS, I4.0, and CE.

Regarding novelty, the methodology uniquely assembles concepts and tools from different bodies of literature such as strategic decision-making, data-driven process improvement, lean management, industry 4.0, and circular economy. It is framed according to the strategic decision-making premise that achieving a goal (i.e., the oenological objective in our case) requires a series of decisions and actions concerning both the conceptualization (i.e., what the strategy entails) and the implementation of the strategy (i.e., how to realize the strategy) [22]. The conceptual framework (Figure 1) aids decision-makers in identifying what can be done in each phase of wine supply chains to achieve the oenological objective, integrating the concepts of LSS, I4.0, and CE, while the implementation framework (Figure 2) provides guidelines on how to improve each phase of SCPs by following the DMAIC cycle—a data-driven process improvement approach based on the scientific method—and considering the LSS, I4.0, and CE solutions of the conceptual framework.

As for usefulness and ease of use, the case study presented in the testing and evaluation section demonstrates the methodology's applicability and utility. The adoption of a step-by-step procedure inspired by the DMAIC cycle facilitated implementation. The addition of the "Target definition" phase with clear elucidation of the VOB and VOC supported convergence toward the oenological objective, avoiding time and resource losses. Wine companies often prioritize the former, as identifying the latter—which is a pillar of lean management representing the value for the customer—is more complex, costly, and time-consuming. The use of the Skill Matrix in the "Define phase" allowed the company to assess internal staff skills, identifying strengths and weaknesses, and to form a well-balanced multidisciplinary team by incorporating qualified external personnel, bringing new ideas and skills that complement those existing within the company. This blend of external competencies and internal staff experience was crucial during the "Analyze phase" for identifying critical issues and during the "Improve phase" for proposing solutions.

Regarding relevance, the use of the proposed methodology led to several solutions of practical significance that synergistically exploit LSS, I4.0, and CE. One of the goals set by the oenological objective was to enhance the quality of the wines produced, aligning them with consumer expectations. To this end, the team created and implemented an original, flexible, customer-oriented production process, based on the adoption of BSL, BSA, and the ingredient-based production methodology (see Figure 7). Inspired by a key concept in lean literature—product modularity [23]—the team considered that wine could be seen as a complex product made up of interchangeable components each characterized by well-defined standardized functionalities (i.e., the ingredients).

The oenological objective also required an increase in environmental sustainability. Comparing Figures 5 and 8 demonstrates how the methodology enabled the mapping and modification of the company's by-product management strategy. Initially, all cellar by-products were sent directly to the distillery. The team identified two weaknesses in this approach: a high carbon footprint due to the transportation and disposal of the transferred product, and a missed opportunity to capitalize on the by-product rich in organic matter. Figure 8 highlights alternatives identified by the team for recovering and reusing by-products from the pressing phase.

The adoption of the ingredient-based production methodology altered the quality of the pressing phase by-products. The pomace from ingredients 1 and 2 was used to create company compost, thereby reducing the carbon footprint associated with distillery disposal. Conversely, the high-quality pomace from ingredient 3 was sent to the distillery to produce a company distillate (Grappa), sold as a complementary product at the company's retail points.

A further relevant contribution suggested by the lean management approach concerned time compression. Longer lead times imply higher resource utilization/waste. SCP mapping identified maceration and fermentation, pressing, and malolactic fermentation as critical phases in terms of Production Lead Time (PLT). Work protocol analysis allowed the calculation of a PLT ranging between 30 and 45 days. This parameter is directly connected to the energy consumption for cooling and/or heating the tanks and the cellar, thereby indirectly influencing the associated carbon footprint. Therefore, reducing the PLT was essential for decreasing the carbon footprint of the process. The team decided to modify work protocols and adopt co-inoculation, bringing the PLT to a range of 7 to 40 days. Fermentation temperatures were adjusted in the work protocol to enhance the quality of the resulting wines and to lower the energy consumption associated with fermentation.

The outcomes mentioned above were made possible by the increased digitalization of SCPs. As highlighted in Figure 8, specific points in the supply chain were equipped with sensors and other I4.0 technologies for real-time monitoring and analysis of process data. This advancement not only significantly reduced the workload for both vineyard and cellar operators but also enhanced the reliability of the data collected by minimizing the redundancy associated with paper-based systems. The decision on which technologies to implement was guided by the recommendations outlined in the conceptual framework.

5. CONCLUSIONS

Although the agri-food sector represents a strategic asset for the world economy [24] and an ideal setting for the implementation of LSS, I4.0 and CE practices, studies that integrate these three approaches to improve wine supply chain processes are lacking. The present study proposes a methodology to support decision makers in improving SCPs and demonstrates that synergies between LSS, I4.0 and CE can be exploited to make wine supply chains more competitive and sustainable. The methodology is novel, usable in practice and relevant, but there are also some obstacles that decision makers should consider as they can limit the adoption in wine supply chain, such as the need for highly skilled personnel, the resistance to change, the short-termism and the lack of resources. Furthermore, the framework presented in this article is versatile and could be applicable beyond the context of wine, such as in the food and beverage sector, and, with appropriate adaptations, in the manufacturing sector in general. To ensure maximum effectiveness, it is essential to integrate the LSS techniques, I4.0 technologies, and CE principles outlined in this research with additional methodologies tailored to the specific application context.

It is precisely these limitations and this improvement opportunities that could guide future research: the methodology could be integrated into a DSS that could support decision makers in a more structured and easier way. In addition, it could be explored how the Artificial Intelligence could contribute to propose alternative solutions to decision makers starting from the conceptual framework from the critical points identified in the SCP map.

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