D6.3
Replication Plan

BBTWINS
Agri-Food Value Chain Digitalisation for Resource Efficiency

Circular Bio-based Europe Joint Undertaking

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1. Introduction

The agri-food sector is at a critical juncture, facing mounting challenges due to climate change, increasing global demand, supply chain vulnerabilities, and the urgent need for sustainability. To tackle these issues, the sector must embrace digital transformation, leveraging cutting-edge technologies such as artificial intelligence, the Internet of Things, blockchain, and Digital Twin systems. These technologies not only optimize resource use and operational efficiency but also enhance traceability, transparency, and decision-making in agricultural production. Among these innovations, Digital Twins have emerged as a game-changer for modern agriculture, providing real-time virtual representations of physical assets that enable continuous monitoring, predictive analytics, and simulation-based optimization. While manufacturing, healthcare, and the automotive industries have successfully integrated digital twin technologies, agriculture remains at an early stage of adoption, facing barriers such as high implementation costs, data acquisition difficulties, and the need for sector-specific adaptations. Overcoming these barriers is essential to unlocking the full potential of digital twins in the agri-food industry.

The BBTWINS project, funded under the Horizon 2020 Bio-Based Industries Joint Undertaking (BBI JU), aims to accelerate digitalization in agri-food value chains through the integration of sensorization, Data-driven analytics, blockchain traceability, and digital twin technologies. The project is structured around two real-world use cases, PORTESA (pig farming) and DIMITRA (peach production), each focusing on critical operational aspects of their respective value chains.

To ensure a comprehensive transformation, these use cases were further divided into key technological and operational areas.

- The project addresses logistics and cooperative operations by developing smart logistics models to optimize transport, supply chain management, and cooperative resource allocation, enhancing efficiency through real-time data analytics.
- Artificial vision and mathematical modeling techniques are employed to monitor and analyze critical factors such as animal health and fruit quality, using Data-driven imaging and computational models to simulate and optimize various subcomponents of the peach and pig production sectors.
- Another crucial pillar of the project is the implementation of a blockchain-based traceability platform, ensuring end-to-end traceability of products throughout the supply chain, from farm to consumer. Blockchain technology enhances food safety, transparency, and regulatory compliance, making it an essential element for modern agri-food systems.
- The project also focuses on by-products valorization, developing strategies to repurpose agricultural waste into bio-based products, thereby enhancing sustainability and resource efficiency. Through data-driven methods, BBTWINS optimizes by-product processing and market integration, contributing to circular economy approaches.
- At the heart of BBTWINS is the construction and implementation of Digital Twins, tailored to each use case. These digital twins integrate sensor data, AI analytics, and blockchain traceability to enable real-time

monitoring, predictive simulations, and automated process optimization. By creating these dynamic virtual models, the project provides agricultural producers with unprecedented control over their operations, enabling them to make data-driven decisions, optimize resource use, and enhance overall efficiency.

Given the advancements and lessons learned throughout the BBTWINS project, it is essential to establish a Replication Plan to ensure that these innovations can be scaled and applied across different agricultural sectors and industrial settings.

This plan serves as a blueprint for the broader adoption of digital transformation strategies in agriculture, outlining methodologies for scaling sensorization and data collection frameworks to other agri-food supply chains, expanding Data-driven feedstock optimization models for diverse bio-based production systems, and adapting logistics and process modeling techniques to different regional and sectoral contexts. Additionally, the replication plan aims to implement blockchain traceability solutions for enhanced transparency in other food industries, deploy digital twins for new agricultural domains beyond pig farming and fruit production, and leverage sustainability impact assessments to support data-driven decision-making for future implementations. By documenting technological advancements, implementation frameworks, and strategic guidelines, the Replication Plan ensures that the BBTWINS approach can be successfully replicated in new settings, fostering resilience, sustainability, and competitiveness in the agri-food sector. Furthermore, the potential for cross-sector application—such as adapting digital twin and blockchain technologies to forestry, fisheries, or bioenergy production—underscores the broader economic and environmental impact of this initiative. As agriculture moves towards fully digital, data-driven, and sustainable production systems, the Replication Plan will play a pivotal role in guiding industry players, policymakers, and researchers toward the next phase of innovation and transformation.

1.1. Executive Summary

The BBTWINS Replication Plan (D6.3) establishes a structured methodology for extending and adapting the digital solutions developed within the BBTWINS project to additional agrifood sectors and value chains. BBTWINS leverages cutting-edge digital twin technologies, sensorization, data-driven analytics, and blockchain-based traceability to optimize production, enhance sustainability, and improve decision-making across agrifood industries.

This document builds upon the implementation of two primary use cases:

- PORTESA (pig farming), which integrates sensor-based monitoring, data-driven decision-making, and blockchain traceability to optimize feedstock usage, logistics, and by-product valorization.
- DIMITRA (peach production), where real-time sensorization and predictive analytics improve crop quality assessment, logistics, and supply chain efficiency.

Recognizing the potential for broader adoption, this Replication Plan outlines:

- Key agrifood sectors and regions suitable for the implementation of BBTWINS technologies.

- A stakeholder power analysis, identifying critical actors in the adoption and replication process.
- Methodologies for scaling digital twins, data-driven optimization, and blockchain traceability across different agrifood contexts.
- Best practices and critical success factors to ensure seamless integration into new operational environments.
- Economic feasibility and sustainability assessments to evaluate the viability of replication.

To demonstrate the real-world application and scalability of BBTWINS solutions, two pilot replication cases have been selected in Spain and Greece. These cases will focus on:

1. **The Olive Oil Industry** addressing inefficiencies in olive harvesting, milling, and logistics while enhancing product traceability and waste valorization.
2. **Agriculture, in particular crop cultivation**, expanding the use of data-driven monitoring, blockchain traceability, and digital twins to optimize resource management and improve production efficiency.

By leveraging data-driven approaches, data analytics, and digital modeling, BBTWINS aims to support the digital transformation of agrifood systems. This document serves as a comprehensive roadmap for policymakers, agrifood industry players, technology providers, and researchers, guiding them toward the scalability, replicability, and long-term sustainability of BBTWINS digital innovations in different agricultural domains.

1.2. Structure

The Replication Plan (D6.3) is structured into six core chapters, followed by an Annex and References section. This document presents a comprehensive strategy for the adaptation and scaling of BBTWINS technologies across various agrifood sectors, emphasizing success factors, stakeholder engagement, and detailed replication scenarios.

- **Chapter 1: Introduction**
  Provides an overview of the replication plan, including an executive summary, purpose and scope, methodology, key services, and contributions. The chapter also outlines the relationships with other deliverables in the BBTWINS project.

- **Chapter 2: Transforming Agri-Food with BBTWINS: Success Factors and Digital Technologies**
  Discusses the core functionalities of BBTWINS digital technologies—sensorization, data-driven analytics, blockchain-based traceability, and digital twins. It highlights the success factors that have enabled the effective application of these technologies in agrifood value chains.

- **Chapter 3: Stakeholder Power Analysis**
  Analyzes the key stakeholders involved in the adoption of BBTWINS technologies in the agrifood sector. This chapter includes stakeholder mapping, power-interest analysis, and engagement strategies, emphasizing the role of BBTWINS partner events in mobilizing and engaging stakeholders for successful technology adoption.

- **Chapter 4: Identification of Replication Sectors and Regions**
  Identifies the most suitable agrifood sectors and regions for replicating BBTWINS solutions, focusing on Spain and Greece. Sector-specific challenges and digital transformation opportunities are analyzed to ensure targeted and effective replication.

- **Chapter 5: Selection of Replication Cases**
  Presents two main replication cases—Olive Oil Production and PORTESA's Agricultural Activities—with a detailed analysis of their value chains, challenges, and tailored BBTWINS solutions. This chapter also includes tailored KPIs, economic feasibility assessments, and a SWOT analysis to evaluate the replication potential.

- **Chapter 6: Scalability and Future Applications**
  Consolidates the replication strategy, focusing on scalability, international expansion potential, and future applications of BBTWINS technologies across sub-sectors. It provides a framework for adapting and expanding BBTWINS solutions beyond the initial replication cases.

1.3. Purpose and Scope

The purpose of this Replication Plan (D6.3) is to outline a structured methodology for extending the digital solutions developed within the BBTWINS project to additional agrifood sectors and value chains. By leveraging the knowledge, tools, and technologies implemented in the project's two primary use cases—PORTESA (pig farming) and DIMITRA (peach production)—this document provides a strategic framework to ensure the scalability, adaptability, and wider adoption of BBTWINS' innovations in different contexts. The replication strategy focuses on the integration of digital twins, blockchain-based traceability, sensorization, and Data-driven analytics into new agricultural applications. The plan aims to evaluate how these technologies can be effectively transferred to different subsectors within the agrifood industry while maintaining their efficiency, economic viability, and sustainability impact. This effort serves as a proof of concept, demonstrating the potential for broad replication before expanding to new geographical regions.

A key component of this deliverable is the identification of two preliminary replication cases within Spain and Greece, ensuring that the proposed methodologies and technological implementations can be tested within similar regulatory and operational environments. These cases will be selected within the same regions as the original use cases but in different agrifood subsectors, allowing for a comparative analysis of digital transformation impacts across different agricultural production systems. To enhance the validity and feasibility of this replication strategy, a preliminary SWOT and power analysis will be conducted for each selected replication case. This will provide insights into the strengths, weaknesses, opportunities, and threats associated with replication, as well as the influence of key stakeholders in shaping the adoption process. By defining clear objectives, identifying key stakeholders, and structuring an evidence-based approach, this document serves as a guide for policymakers, industry players, and researchers to replicate and scale BBTWINS' digital solutions across different sectors of the agrifood industry. The ultimate goal is to foster digital transformation, increase efficiency and transparency, and promote sustainable agricultural practices through the wider adoption of smart technologies.

1.4. Methodology

The replication plan follows a structured approach to ensure the scalability and adaptability of the BBTWINS digital tools across new applications within the agrifood sector. This methodology is designed to demonstrate the feasibility of extending the BBTWINS innovations to different subsectors within the same geographical regions where the original case studies were implemented. The process consists of several key steps, ensuring a systematic analysis of technologies, stakeholders, and feasibility assessments for successful replication.

The first step is to provide a comprehensive description of the core functionalities, technologies, and digital tools developed within the BBTWINS project. These tools include sensorization, Data-driven analytics, blockchain traceability, and digital twins, which together form a holistic digital transformation framework for agrifood value chains. Sensorization enables real-time data collection from agricultural environments, ensuring precise monitoring of parameters affecting production quality and efficiency. Data-based analytics process this data to optimize operations, improving decision-making across the supply chain. Blockchain technology enhances traceability by securing transaction records and ensuring compliance with food safety regulations. Finally, digital twins provide a dynamic virtual representation of physical processes, enabling predictive analytics, simulation, and optimization of operations. Together, these digital solutions form the foundation for the replication strategy.

The second step focuses on the identification of replication sectors, regions, and countries, but within a preliminary scope limited to Spain and Greece, where the original case studies—PORTESA (pig farming) and DIMITRA (peach production)—were conducted. Rather than broad global expansion, this targeted analysis aims to serve as a proof of concept, demonstrating how adaptable the BBTWINS digital tools can be within different agrifood subsectors. The selected regions share similar agri-food industry characteristics, regulatory frameworks, and market dynamics, making them ideal for testing the scalability of the developed technologies. By focusing on these two countries, the study can effectively evaluate the transferability and customization of digital solutions before considering broader applications.

A stakeholder analysis is then conducted to identify and classify the key actors involved in the replication process. This includes food producers, processors, distributors, and regulatory authorities, each of whom plays a crucial role in the adaptation and implementation of digital innovations. Food producers benefit from real-time monitoring and optimized decision-making, processors gain efficiency in production and logistics, distributors leverage blockchain-enhanced traceability systems, and regulatory authorities ensure compliance and policy alignment. A power analysis is also carried out to determine the influence of each stakeholder group in shaping digital transformation efforts. This step ensures that the replication process is inclusive and considers potential barriers faced by less influential stakeholders. Highlighting key practices for success is another essential step. Based on the BBTWINS experience, the replication plan identifies critical success factors, such as stakeholder collaboration, robust data collection frameworks, and the use of flexible and interoperable digital tools. Ensuring that these elements are present in the replication efforts will maximize the likelihood of successful adaptation in new agrifood contexts.

The selection of specific replication cases will be based on feasibility and sectoral relevance, focusing on new agrifood subsectors within Spain and Greece, rather than expanding to different countries. This approach ensures continuity while testing the applicability of BBTWINS solutions in diverse but related production systems. This ensures that the replication strategy remains contextually relevant while showcasing the potential of BBTWINS technologies in different agrifood settings. Additionally, for the two selected replication cases, a preliminary SWOT and power analysis will be conducted to further enhance the validity of the replication plan. This will allow for a deeper understanding of strengths, weaknesses, opportunities, and threats, while also assessing the influence of key stakeholders in driving or hindering the implementation process.

This structured methodology ensures that the BBTWINS replication plan provides a clear, evidence-based framework for scaling up digital transformation into agrifood systems. By demonstrating the adaptability of BBTWINS technologies within different but related subsectors in Spain and Greece, this initiative will provide a scalable model for future applications in broader international contexts. The ultimate goal is to foster a wider adoption of digital innovation in agriculture, driving efficiency, sustainability, and resilience across the entire value chain.

Figure 1: Structure of BBTWINS Replication Plan

1.5. Key Services and contributions

The BBTWINS project's potential replication plan is underscored by the collaboration of a diverse consortium of partners, each bringing unique expertise and capabilities to the table. Within the context of extending the project's impact and innovations to other sectors or geographical areas, several entities emerge as key contributors to a potential replication plan:

Centro Nacional de Tecnología y Seguridad Alimentaria (CNTA)

- **Role in Replication**: As the project coordinator and an RTO specializing in food processes, CNTA is pivotal in the mathematical modeling of food processes. They could lead the replication plan by providing the methodological framework and expertise necessary for adapting the digital twin technology to new sectors or use cases beyond meat and fruit production.

PANOIMAGEN

- **Role in Replication**: PANOIMAGEN's expertise in sensorization and data processing positions it as a key partner in the replication plan, particularly for ensuring real-time monitoring and Data-driven decision-making. Their role involves deploying IoT-based environmental and process sensors, integrating data collection systems into the BBTWINS Data Lake, and developing machine vision models for quality assessment and predictive analytics.

SOLTEC INGENIEROS S.L. (SOLTEC)

- **Role in Replication**: SOLTEC's expertise in digital twin design and implementation positions them as a critical partner for the technological deployment of the replication plan. They can offer the technical know-how to adapt and scale the digital twin models for other agricultural sectors or even for non-agricultural applications where process optimization and sustainability are key concerns.

STELVIO TECH (STELVIO)

- **Role in Replication**: With their specialization in blockchain technology, STELVIO is essential for ensuring that the traceability and security aspects of the digital twins are effectively replicated in new settings. They could provide blockchain solutions that are scalable and adaptable to different regulatory environments or supply chain configurations.

VTT Technical Research Centre of Finland Ltd (VTT), Flemish Institute for Technological Research (VITO)

- **Role in Replication**: VTT's & VITO's involvement in logistics optimization is crucial for the replication plan, especially when considering new geographical areas or sectors with distinct logistical challenges. Their research and technological capabilities can help adapt logistics solutions to maximize efficiency and sustainability in new contexts.

Cluster of Bioeconomy and Environment of Western Macedonia (CluBE)

- **Role in Replication**: CluBE, serving as the use cases coordinator, could play a significant role in identifying new areas for replication, particularly within the bioeconomy sector. Their experience with the multi-actor approach and engagement with various stakeholders can facilitate the identification of new partners and sectors for the project's expansion.

CVRESIDUOS (CVR)

- **Role in Replication**: Given their focus on residual biomass valorization, CVR is vital for ensuring the sustainability aspect of the replication plan. They can offer expertise in converting waste into valuable products in new sectors, thereby promoting circular economy principles across different value chains.

REVOLVE MEDIA (REVOLVE)

- **Role in Replication**: Communication and dissemination are critical for the success of any replication plan. REVOLVE MEDIA's experience in this area could help raise awareness, engage stakeholders, and disseminate the outcomes and best practices learned from BBTWINS to a broader audience, facilitating the adoption of the project's innovations.

Each of these entities brings essential competencies to the table, from technological expertise and research capabilities to logistical optimization and stakeholder engagement. For a successful replication plan, leveraging these strengths in a coordinated manner will be key to achieving broader impact and ensuring the scalability of the BBTWINS project's innovations.

1.6. Relationships with other deliverables

The "Replication Plan" (D6.3) is a cornerstone deliverable within Work Package 6 (WP6), ensuring the scalability and broader application of the BBTWINS project's outcomes. Its development is guided by insights, data, and technologies generated throughout the project, integrating contributions from multiple work packages to create a comprehensive roadmap for replication and adoption in new contexts.

The Replication Plan (D6.3) draws extensively on knowledge and technologies developed across BBTWINS. From WP1 (Data Collection, Sensorization & Data Modeling), deliverables D1.2 and D1.3 provide essential data on sensorization and data processing in the meat and fruit value chains, offering valuable insights into how scalable sensor technologies and data collection methods can be adapted to different agricultural environments. These foundational datasets help define key parameters for effective replication in diverse sectors. Within WP2 (Feedstock Optimization for Bio-based Operations), deliverables D2.1 and D2.4 play a crucial role in informing replication by detailing feedstock optimization and downstream processing strategies. These findings ensure that

BBTWINS' bio-based operations can be effectively adapted to various biomass sources and operational scales, enhancing feasibility and impact in different agricultural and industrial settings.

The process modeling efforts in WP3 contribute directly to the replication strategy. Deliverables D3.4 and D3.5 provide logistics and value chain optimization models, enabling the efficient scaling of BBTWINS solutions across diverse geographical and operational contexts. By identifying bottlenecks and optimization opportunities, these models ensure that replication strategies are economically and operationally viable. A critical component of the Replication Plan is WP4 (Blockchain Implementation for Value Chain Traceability), which introduces blockchain technology for enhanced supply chain transparency and security. Deliverable D4.3 demonstrates how a blockchain network can be deployed for traceability, ensuring that replicated BBTWINS solutions maintain integrity and trust across new markets and industries. The Digital Twin technology from WP5 further strengthens the replication framework. D5.2 (Digital Twin Prototype) provides a blueprint for deploying Digital Twins in agricultural and food production environments, allowing for real-time monitoring, predictive analytics, and enhanced decision-making in new application areas.

From an environmental and economic impact perspective, WP7's D7.3 assesses the sustainability credentials of BBTWINS technologies. This evaluation ensures that replicated solutions align with sustainability goals, providing compelling data to support adoption by industries seeking economically and environmentally viable innovations. Finally, WP8 (Communication and Dissemination) plays a vital role in extending the reach and impact of BBTWINS technologies. WP9 deliverables ensures that key stakeholders, policymakers, and industry leaders are engaged in discussions on replication strategies, fostering greater awareness and adoption of BBTWINS solutions beyond the project's initial scope.

By leveraging the insights from sensorization, feedstock optimization, process modeling, blockchain for traceability, Digital Twins, impact assessment, and dissemination efforts, the Replication Plan (D6.3) establishes a robust, multi-faceted strategy for scaling BBTWINS technologies. This cross-WP collaboration ensures that the project's innovative solutions can be effectively applied in new contexts, contributing to the broader adoption of sustainable agri-food technologies and reinforcing BBTWINS' role as a catalyst for digital transformation in the bioeconomy.

2. Transforming Agri-Food with BBTWINS: Success Factors and Digital Technologies

The BBTWINS project leverages advanced tensorizations, data-driven analytics, and digital twin technologies to optimize operations in agrifood value chains. These solutions improve efficiency, sustainability, and traceability across both the meat and fruit sectors. In the meat value chain, real-time sensor data enables feed monitoring, predictive models for pig weights, and automated quality control at the slaughterhouse. Technologies such as LiDAR, deep learning, and computer vision ensure higher precision and labor efficiency while maintaining compliance with quality standards like PDO for "Jamón de Teruel." In the fruit sector, sensor networks provide continuous environmental monitoring, while data-driven models predict yields and optimize canopy management. Real-time imaging and deep learning algorithms enhance harvest planning and resource management. The data analytics framework integrates predictive modeling and process simulations to optimize logistics, product quality, and resource use. For example, hyperspectral imaging assesses fruit quality, while COMSOL simulations improve ham curing and biogas generation processes. Waste valorization technologies convert by-products into bio-based materials and biofuels, promoting circular economy principles.

BBTWINS implements blockchain technology to provide secure, real-time traceability for both meat and fruit production, ensuring transparency and regulatory compliance. Integrated smart contracts automate quality checks and enable data-driven decisions across the supply chain. The digital twin system replicates agrifood production processes using real-time data from the sensor network and data lake infrastructure. It enables simulation, process optimization, and predictive analytics for key operations such as feed management, slaughterhouse planning, ham curing, and fruit storage. A VR interface enhances user interaction, offering immersive monitoring, training, and scenario testing.

The combination of these advanced technologies forms the backbone of BBTWINS, enhancing decision-making, sustainability, and efficiency across the agrifood value chain. To summarize the key functionalities and their insights, the following table highlights the main features and their impact on operations.

Table 1: Summary of Key Functionalities and Insights

Functionality	Description	Key Insights
Sensorization	Real-time data collection from the meat and fruit value chains for precision monitoring and automation	Enhances resource management, reduces manual labor, and improves operational accuracy
Predictive Analytics	Data-driven models for forecasting logistics, animal growth, fruit yields, and biogas production	Optimizes logistics, minimizes waste, and supports proactive decision-making
Blockchain Traceability	End-to-end traceability using Hyperledger Fabric with integrated smart contracts	Ensures transparency, regulatory compliance, and consumer trust
Digital Twin Technology	Real-time simulations and virtual replicas of production processes	Supports process optimization, scenario testing, and predictive maintenance
VR Interface	Immersive virtual environment for monitoring, training, and process simulation	Enhances stakeholder engagement, operational training, and decision-making
Waste Valorization	Conversion of by-products into high-value bio-based products and biofuels	Promotes circular economy and reduces environmental impact

The success of the BBTWINS project is attributed to a combination of well-defined methodologies, stakeholder collaboration, and the strategic application of digital technologies. The project effectively demonstrated how digital twins, blockchain-based traceability, and Data-driven optimization could transform the agri-food sector by improving efficiency, sustainability, and product quality. A key aspect of this success was the tailored approach in implementing Key Performance Indicators (KPIs) across different industrial cases, ensuring measurable progress towards project goals. Additionally, the integration of adaptable digital tools, stakeholder engagement through events, and robust data collection practices facilitated the successful deployment and validation of BBTWINS technologies. To further detail these key success factors, the following elements were fundamental to the project's achievements:

Implementation of Key Performance Indicators (KPIs)

BBTWINS developed a comprehensive KPI framework to monitor, assess, and optimize industrial processes, ensuring the effectiveness of digital solutions. The hierarchical KPI model categorized basic KPIs (direct performance metrics) and comprehensive KPIs (aggregated strategic indicators), allowing a structured approach to tracking efficiency, sustainability, and quality improvements [1–3].

KPIs in the Pork Sector (Portesa Use Case)

The Portesa digital twin was applied across five key stages of pork production, including feed mills, fattening farms, slaughterhouses, biogas plants, and curing facilities. KPIs were specifically designed to optimize logistics, energy efficiency, and production planning:

- Production KPIs: Meat yield ratio, defective product rates, and production cycle times.
- Energy KPIs: Renewable energy integration in biogas plants, energy consumption in processing, and efficiency gains from waste valorization.
- Logistics KPIs: Transit time variability and vehicle utilization rate in livestock transport.

KPIs in the Fruit Sector (Dimitra Use Case)

Dimitra's use case focused on logistics optimization and energy efficiency in fruit sorting, storage, and transportation:

- Logistics KPIs: Transit time variability, spoilage rates, and efficiency of cold storage management.
- Energy KPIs: Solar power integration in storage facilities, reducing energy dependency and carbon footprint .
- Traceability KPIs: Compliance rates with blockchain tracking and audit scores for fruit batches.

This structured KPI methodology ensured effective benchmarking, enabling data-driven decision-making and continuous optimization of production and logistics workflows.

Marketable Digital tools

The adaptability and market readiness of digital tools played a key role in the project's success. Two primary digital solutions—Blockchain Traceability Platform (developed by StelvioTech) and Digital Twin Simulation (developed by SOLTEC)—were deployed to address industry needs.

Blockchain-Based Traceability Platform (StelvioTech)

- The BBTWINS blockchain system created a tamper-proof, end-to-end traceability network for the meat and fruit supply chains.
- It provided secure, real-time data logging, ensuring regulatory compliance and consumer transparency.
- The user web application allowed stakeholders to track products using EAN codes, verifying the authenticity of food products.

Digital Twin for Process Simulation (SOLTEC)

- The digital twin models simulated energy consumption, logistics workflows, and process efficiency across the Portesa and Dimitra value chains.
- In the Portesa case, feed mill, slaughterhouse, and curing facility models allowed predictive adjustments to feed supply, production schedules, and waste valorization.
- In the Dimitra case, Data-driven logistics route optimization reduced transportation costs and enhanced energy efficiency.

These tools enabled real-time scenario testing and decision support, significantly reducing inefficiencies and improving sustainability.

New Product Development (Dimitra and Portesa)

The BBTWINS project has played a significant role in the development of new bio-based products, contributing to resource efficiency and sustainability through waste valorization, bioenergy production, and high-value compound extraction. To ensure the technical and economic feasibility of these innovations, extensive evaluations were conducted, confirming their potential for industrial application and commercialization.

One of the most impactful innovations was the biogas production system developed for Portesa, utilizing organic waste such as pig manure, bones, and skins to generate bioenergy and fertilizers. The biogas plant model demonstrated high economic feasibility, with annual biogas production reaching 19,701,729 m^3 and a Net Present Value (NPV) exceeding €24 million. Various scenarios confirmed positive profitability indicators, including EBITDA, NPV, and Internal Rate of Return (IRR), with estimated payback periods ranging between 1 and 2.2 years, highlighting its commercial viability. In addition to biogas, Portesa explored phosphorus and nitrogen extraction from manure as a potential valorization pathway. Although phosphorus recovery rates reached 91%, the low elemental concentration in manure resulted in negative cash flows, making it economically unfeasible as a standalone process. However, the project successfully demonstrated the potential of keratin hydrolysates extraction from pig hair, showing an NPV of €907,940, an IRR of 13.07%, and a payback period of 5.41 years, confirming its profitability potential. Similarly, collagen hydrolysates extraction yielded high-purity collagen, but low extraction yields and high processing costs limited its economic viability, resulting in negative cash flows. Another promising valorization approach was the extraction of hydroxyapatite from pig bones, a valuable material used in food, agriculture, and cosmetics industries. This process demonstrated high economic feasibility, with an NPV of €1,274,819, an IRR of 65.43%, and a payback period of just 1.5 years, proving its strong commercial potential.

On the Dimitra side, sustainable composting technologies were developed to convert fruit processing waste and pruning residues into organic fertilizers, supporting the transition to circular and sustainable agriculture. Additionally, the combustion of pruning wastes emerged as a highly profitable bioenergy solution, achieving an NPV of €1,774,220, an IRR of 199.67%, and a payback period of less than one year, confirming its viability as an efficient renewable energy source. Furthermore, Dimitra explored the extraction of polyphenols from peach and nectarine waste, a process with strong potential for functional food and nutraceutical applications. Among the different extraction methods analyzed, Ultrasound-Assisted Extraction (UAE) demonstrated better economic performance than Supercritical Fluid Extraction (SFE). The UAE method delivered an NPV of €441,846 and an IRR of 17.00%, confirming its financial feasibility and making it a promising sustainable valorization strategy.

These results underscore the BBTWINS project's contribution to circular economy principles by transforming waste streams into high-value products, reducing environmental impact, and improving economic sustainability. By leveraging digital twins, Data-driven optimization, and blockchain traceability, these innovations ensure that agri-food industries can transition toward more sustainable and resource-efficient production systems, securing long-term profitability and environmental benefits.

Stakeholder Collaboration and Engagement

The BBTWINS project placed a strong emphasis on stakeholder engagement, recognizing that the acceptance and scalability of its technologies depended on the active participation of industry leaders, policymakers, technology providers, and end-users. By fostering a collaborative ecosystem, BBTWINS ensured that its digital twin and blockchain solutions were aligned with real-world industry needs, facilitating smooth adoption across the agri-food sector. One of the most effective strategies employed by the project was active participation in international agrifood and technology forums. These events provided a platform for BBTWINS to showcase its innovations, allowing key stakeholders—including policymakers, food processors, cooperatives, and research institutions—to directly engage with the project's solutions. Through live demonstrations, expert panels, and networking sessions, these forums helped generate interest, foster industry connections, and establish BBTWINS as a leader in digital transformation for the agri-food industry.

Beyond events, multi-stakeholder collaboration played a crucial role in the co-design and implementation of BBTWINS solutions. The project worked closely with food processors, agricultural cooperatives, regulators, and technology developers to ensure that its digital twins and traceability platforms met sector-specific challenges. This approach enabled the customization of solutions, ensuring they could be seamlessly integrated into existing supply chains, logistics networks, and production workflows. Additionally, BBTWINS leveraged public-private partnerships to enhance the financial viability and scalability of its innovations. By aligning with EU-funded sustainability and digital transformation initiatives, the project positioned itself within broader European policies on circular economy, food traceability, and smart agriculture. This integration not only boosted market expansion opportunities but also facilitated compliance with regulatory frameworks, making it easier for stakeholders to adopt the technology.

Through these engagement strategies, BBTWINS successfully accelerated the adoption of digital twins and blockchain traceability, addressing technical, financial, and regulatory challenges. By ensuring that its innovations were co-developed with industry players, the project laid the groundwork for long-term sustainability, widespread market penetration, and continued advancements in digital transformation within the agri-food sector.

Robust Data Collection and Sensorization

The BBTWINS project employed a data-driven approach that was fundamental to its success, integrating sensor-based monitoring, AI analytics, and a centralized data lake to optimize operations across the agri-food sector. By leveraging real-time data acquisition and machine learning, the project enhanced decision-making, resource efficiency, and predictive analytics, ensuring that its digital twin and blockchain-based traceability solutions were both scalable and adaptable. At the core of this approach was the BBTWINS Data Lake, which functioned as a centralized repository for sensor data, enabling seamless integration with blockchain traceability systems and digital twin simulations. This infrastructure facilitated real-time data processing, ensuring that stakeholders could monitor production parameters, logistics performance, and environmental conditions with high precision. The project also deployed online monitoring and sensorization systems, incorporating IoT-based sensors to track critical environmental variables such as temperature, humidity, and logistics performance metrics. These sensors provided real-time feedback loops, allowing dynamic adjustments in supply chain operations and immediate responses to deviations in production conditions.

In addition to real-time monitoring, BBTWINS leveraged Data-driven machine learning models to enhance logistics optimization, energy efficiency, and predictive maintenance. These advanced analytics tools were applied to forecasting energy demand, optimizing supply chain workflows, and minimizing waste ratios, allowing for proactive decision-making and increased operational efficiency. By integrating sensorization, AI analytics, and machine learning into a robust data collection and processing system, BBTWINS ensured continuous performance monitoring and real-time adaptability. This data-centric infrastructure reinforced the project's industrial viability, supporting predictive decision-making and sustainable digital transformation in the agri-food sector. The BBTWINS project successfully validated digital twin and blockchain technologies in real-world industrial environments, demonstrating measurable efficiency gains, sustainability improvements, and enhanced traceability. By integrating tailored KPIs, adaptable digital tools, new bio-based products, stakeholder engagement, and data-driven decision-making, BBTWINS sets a benchmark for digital transformation in the agri-food industry. With a scalable model and validated industrial applications, BBTWINS is poised to expand into new regions and industrial sectors, fostering a data-driven, transparent, and sustainable agri-food ecosystem.

3. Stakeholders Power analysis

Stakeholder power analysis is a crucial tool for understanding how various stakeholders influence policy development, implementation, and outcomes. It helps determine their relevance to the project's success, ensuring that decision-makers can engage with the right actors effectively. This analysis is particularly useful for identifying who will benefit most from a policy, the potential resistance to change, and the structural barriers that need to be addressed to build capacities and tackle inequalities. By assessing the power and interest of stakeholders, this approach enables policymakers and project teams to prioritize engagement strategies, ensuring that those with significant influence are actively involved while also empowering less influential but critical stakeholders.

Stakeholder analysis begins by addressing key questions (as highlighted in the first figure) to determine dependencies, control over resources, organizational structures, and priority issues. These include:

✓ **Who is dependent on whom?** – Identifying key dependencies helps in understanding which stakeholders hold significant power and which are more vulnerable. This is crucial for ensuring fair policy implementation.

✓ **Which stakeholders are organized? How can that organization be influenced or built upon?** – Recognizing existing networks or institutions allows policymakers to leverage these structures for better communication and implementation.

✓ **Who has control over which resources? Who has control over information?** – Stakeholders who control key financial, technical, or informational resources often have higher decision-making power and must be engaged effectively.

✓ **Which problems, affecting which stakeholders, are the priorities to address or alleviate?** – Helps in defining urgent issues and ensuring that stakeholder concerns are integrated into the policy framework.

✓ **Which stakeholders' needs, interests, and expectations should be given priority attention with respect to the policy in question?** – Ensures that policy actions align with the interests of the most critical stakeholders while addressing potential conflicts.

The Power-Interest Matrix (Figure 2) categorizes stakeholders based on their level of power (influence over decisions) and interest (concern about the policy/project outcomes). This framework helps prioritize engagement efforts, ensuring that key players actively participate while maintaining communication with less influential actors. The matrix also guides engagement strategies, helping decision-makers manage different stakeholder groups effectively.

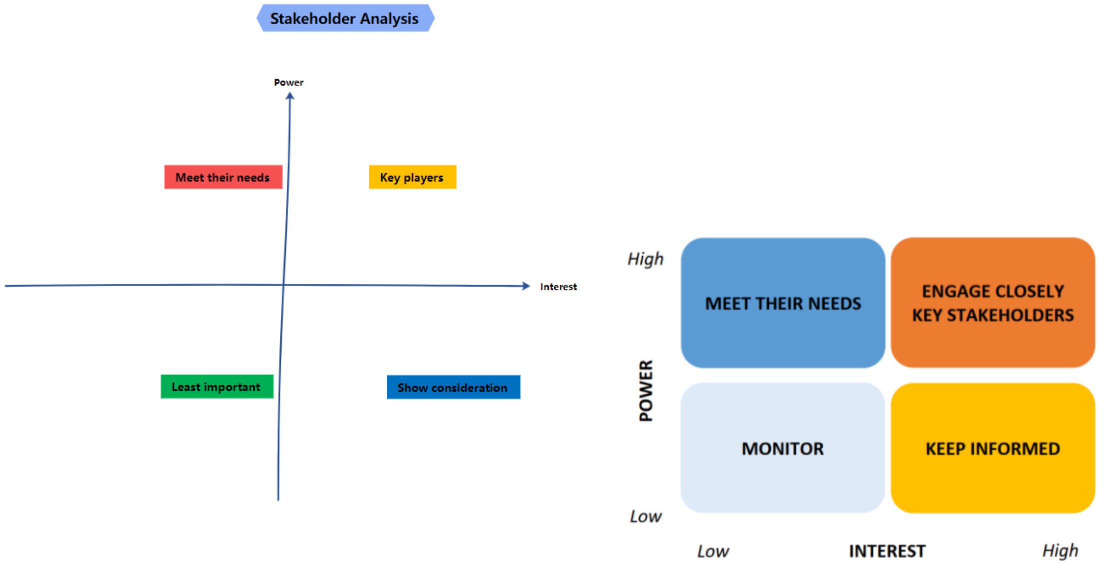

Figure 2: Power interest matrix

Stakeholders are grouped into four key categories based on their power and interest levels, with engagement strategies tailored to each group:

1. **Engage Closely – Key Stakeholders / Key Players (High Power, High Interest)**
    - These stakeholders are both highly interested and highly influential in policy or project outcomes.
    - They must be actively engaged in decision-making and policy design.
    - Requires continuous collaboration, participation in strategy development, and direct communication.
    - Example: Government agencies, industry leaders, regulatory bodies, funding organizations.
2. **Meet Their Needs (High Power, Low Interest)**
    - These stakeholders hold significant influence but may have limited direct interest in the policy or project.
    - Their support is crucial, and their needs and expectations must be proactively managed to ensure smooth policy implementation.
    - Might require incentive structures or tailored engagement strategies to align their interests with policy goals.
    - Example: Investors, trade unions, large corporations indirectly affected by policy changes.
3. **Keep Informed / Show Consideration (Low Power, High Interest)**
    - These stakeholders care about the project but lack influence over decision-making.
    - They must be regularly updated and included in consultations to maintain their support.
    - Their feedback should be integrated into policies to ensure inclusivity and social acceptance.
    - They often serve as advocates or pressure groups, influencing key players indirectly.
    - Example: Local communities, environmental organizations, NGOs, small businesses.
4. **Monitor / Least Important (Low Power, Low Interest)**

- These stakeholders have minimal influence and low interest, requiring only basic updates and monitoring.
- Engagement should be minimal but not ignored, as their role might become more relevant over time due to external factors.
- Example: General public, media, research institutions with indirect interest.

3.1. Stakeholder Power Analysis for the Adoption of BBTWINS Technologies in the Agri-Food Sector

The successful adaptation and replication of BBTWINS digital solutions across different agri-food sectors depend on the engagement and influence of multiple stakeholders. Each stakeholder group has specific interests, incentives, and potential barriers to adopting digital twin technologies, Data-driven analytics, sensorization, and blockchain traceability. Understanding their power dynamics and interest levels is crucial for tailoring strategies that facilitate adoption, minimize resistance, and maximize impact. The following table categorizes key stakeholder groups based on their potential interest in BBTWINS technologies, potential barriers to adoption, and recommended engagement strategies. The classification aligns with the Power-Interest Matrix, which helps prioritize stakeholders based on their influence over decision-making and their level of concern about the technology's impact. Stakeholders with high power and high interest require active engagement, while those with low power but high interest need supportive measures to enhance their participation. Similarly, stakeholders with high power but low interest should be managed to ensure their needs are met, while low power, low interest stakeholders require minimal but consistent monitoring.

Table 2: Key stakeholder groups based on their potential interest in BBTWINS technologies

Stakeholder Group	Potential Interest in BBTWINS Technologies	Potential Barriers to Adoption	Engagement Strategy
Government & Regulatory Bodies (e.g., Ministries of Agriculture, EU regulators, food safety authorities)	- Ensuring compliance with food safety, traceability, and sustainability policies. - Driving digital transformation in agriculture and industry. - Supporting climate action through efficient resource use and waste reduction.	- Regulatory constraints or slow policy adaptation to emerging technologies. - Limited public funding for technological upgrades in the sector.	Engage Closely (High Power, High Interest) - Involve in policy discussions, pilot projects, and strategic collaborations. - Demonstrate compliance benefits and alignment with EU sustainability goals.
Large Agri-Food Corporations & Processors (e.g., meat and dairy processors, olive oil mills, seafood processors, food & beverage manufacturers)	- Improving operational efficiency through Data-driven optimization. - Reducing waste and energy consumption in processing. - Enhancing supply chain traceability with blockchain.	- High investment costs for digital twin implementation. - Resistance to change due to established traditional processes.	Engage Closely (High Power, High Interest) - Provide cost-benefit analyses and pilot projects to demonstrate ROI. - Offer customized implementation strategies to facilitate gradual adoption.
Farmers & Primary Producers (e.g., olive growers, livestock farmers, fruit producers, aquaculture operators)	- Improving crop/livestock monitoring through sensorization and AI analytics. - Optimizing input use (water, feed, fertilizers) and reducing costs. - Gaining higher market value through improved traceability and certification.	- Limited digital literacy and reluctance to adopt new technologies. - High upfront investment costs and uncertain long-term benefits. - Connectivity issues in rural areas.	Keep Informed & Show Consideration (Low Power, High Interest) - Provide training, financial incentives, and easy-to-use interfaces. - Partner with cooperatives and farming associations to facilitate knowledge transfer.
Agricultural Cooperatives & Industry Associations (e.g., olive oil cooperatives, dairy federations, fisheries alliances)	- Ensuring competitiveness of their members by digitizing production and logistics. - Leveraging collective investment strategies to reduce adoption costs. - Facilitating certification and regulatory compliance.	- Heterogeneous stakeholder interests (some members may resist change). - Concerns over data ownership and control when adopting digital twins.	Engage Closely (High Power, High Interest) - Develop sector-specific implementation models. - Promote group funding opportunities and EU subsidies for technology adoption.
Technology Providers & Solution Developers	- Expanding market opportunities for digital twin applications in agriculture.	- Fragmented adoption across different agricultural	Engage Closely (High Power, High Interest) - Foster public-private partnerships to develop

Stakeholder Group	Potential Interest in BBTWINS Technologies	Potential Barriers to Adoption	Engagement Strategy
(e.g., AI developers, IoT sensor companies, blockchain service providers, software firms)	- Collaborating on data-driven innovations in smart farming and logistics. - Driving technological standardization in agri-food digitalization.	subsectors. - Need for customization to fit various production models and supply chains.	tailored solutions. - Provide interoperability and integration tools to ease adoption.
Retailers & Distributors (e.g., supermarkets, wholesale buyers, logistics companies)	- Enhancing supply chain transparency and food safety. - Ensuring sustainability compliance in sourcing and logistics. - Reducing losses through optimized inventory and transport tracking.	- Implementation complexity in integrating new digital traceability systems. - Interoperability issues with existing supply chain management tools.	Meet Their Needs (High Power, Low Interest) - Ensure seamless integration with existing supply chain systems. - Demonstrate benefits in regulatory compliance and cost reduction.

The BBTWINS adaptation strategy recognizes that different stakeholder groups have distinct levels of power and interest in adopting digital twin technologies. Regulatory bodies, industry leaders, and technology providers possess both high power and high interest, meaning they play a critical role in driving policy alignment, funding opportunities, and market uptake. These groups must be actively engaged through direct collaboration, pilot projects, and tailored incentives to facilitate large-scale adoption. Conversely, farmers and small producers, despite being highly interested in improving productivity and sustainability, often have low power in decision-making and face financial and technical barriers. To ensure their inclusion, targeted interventions such as capacity-building programs, financial assistance, and simplified technology interfaces must be implemented. Similarly, retailers and investors, though powerful, may show low interest unless tangible benefits—such as cost savings, compliance advantages, or sustainability incentives—are clearly demonstrated. This makes it essential to provide business case studies and regulatory incentives to encourage their support. By leveraging a tailored stakeholder engagement strategy, BBTWINS can maximize its impact across the agri-food value chain, ensuring broad adoption, operational efficiency, and long-term sustainability.

3.2. The Role of BBTWINS Partner Events in Mobilizing and Engaging Stakeholders for Technology Adoption

The BBTWINS project has actively engaged in a variety of high-profile industry events, conferences, exhibitions, and brokerage meetings to mobilize key stakeholders and facilitate the adoption of BBTWINS digital solutions. These events serve as strategic platforms to communicate the benefits of digital twins, Data-driven analytics, blockchain traceability, and sensorization to different stakeholder groups across the agri-food sector. By participating in these events, BBTWINS plays a crucial role in raising awareness among industry leaders, policymakers, farmers, cooperatives, and technology providers, educating them on the value of digital transformation. Additionally, these engagements help in encouraging adoption by demonstrating how BBTWINS technologies improve efficiency, sustainability, and traceability in various agri-food processes. They also serve as key networking opportunities, building connections between industry stakeholders, research institutions, and policymakers, fostering collaborations that drive innovation and scalability. Furthermore, these events help in aligning with market needs by allowing BBTWINS to understand stakeholder concerns, interests, and barriers, enabling the project to refine its solutions and implementation strategies for broader adoption.

By analyzing the event participation data, we observe several trends that highlight their **strategic importance** in stakeholder mobilization:

1. **Diverse Event Types for Maximum Outreach**
    - Trade fairs and exhibitions (e.g., *FRESKON FAIR, Alimentaria*) provide direct interaction with industry leaders, cooperatives, and food processors, allowing them to experience BBTWINS solutions firsthand.
    - Conferences and workshops (e.g., *XII Congreso Nacional CyTA CESIA*) focus on scientific and policy discussions, engaging regulators, academia, and policymakers.
    - Brokerage and matchmaking events (e.g., *BIC matchmaking event 2024*) facilitate partnerships with technology providers, investors, and funding bodies, helping drive large-scale adoption.
2. **Targeting Key Stakeholder Groups**
    - Government & Regulatory Bodies – Events focusing on policy discussions and EU-funded initiatives help ensure alignment with sustainability policies and digital transformation strategies.
    - Industry Leaders & Processors – Trade fairs and industry-specific events attract food manufacturers, logistics companies, and cooperatives, allowing them to explore BBTWINS solutions in real-world applications.
    - Farmers & Cooperatives – Participation in agritech-focused events helps demonstrate practical benefits of BBTWINS for small and medium producers, addressing their concerns about cost, digital literacy, and scalability.
    - Investors & Financial Institutions – Brokerage events and investor summits provide an opportunity to showcase the economic viability and scalability of digital twin solutions, encouraging investment in smart agriculture.
3. **Maximizing Impact Through Strategic Presentations & Demonstrations**
    - Events such as *BBTWINS Digital Twin Presentation at ANFACO-CECOPESCA* effectively communicate technical advancements and industry applications.
    - Some events include live demonstrations, interactive workshops, and networking opportunities, ensuring stakeholders fully understand the technology's capabilities.
    - Publicly accessible presentations, recordings, and shared materials (e.g., *YouTube recordings, downloadable slides*) allow continued engagement beyond the event.
4. **Expanding BBTWINS Visibility Across Europe**
    - Events have taken place across multiple European regions, strengthening BBTWINS' outreach beyond its initial use cases in Greece and Spain.

- Active participation in EU-funded programs and policy-driven conferences ensures that BBTWINS is well-positioned for future regulatory and funding opportunities.

The engagement strategy of BBTWINS partners through events plays a pivotal role in mobilizing stakeholders for the adoption of digital twin technologies. By participating in high-impact events across industry, research, and policy sectors, BBTWINS effectively strengthens industry connections, accelerating the adoption of digital twins while ensuring alignment with regulatory and market trends to support long-term sustainability. These events also empower stakeholders at all levels, from large corporations to small-scale farmers, fostering inclusivity in digital transformation efforts. Furthermore, they establish a solid foundation for expanding BBTWINS technologies into new regions and industries, driving widespread adoption. By continuously leveraging strategic events, BBTWINS ensures that key stakeholders remain engaged, informed, and motivated to integrate digital twin solutions into the agri-food sector, ultimately paving the way for a more efficient, transparent, and sustainable food supply chain.

4. Identification of Replication Sectors and Regions

The BBTWINS project has demonstrated the effectiveness of digital twins, Data-driven analytics, blockchain traceability, and sensorization in optimizing agrifood value chain processes. However, beyond primary agricultural production, these technological solutions hold immense potential for replication across various industrial processes that require precision, efficiency, and sustainability improvements. To extend the impact of BBTWINS, the focus must shift towards industrial applications where digitalization, process monitoring, predictive analytics, and real-time optimization can enhance manufacturing, processing, logistics, and supply chain management. The replication plan prioritizes sectors with highly structured production processes, significant reliance on real-time monitoring, and a strong need for traceability and optimization.

The following two tables outline the applications of various advanced technologies in both Agri-Food and Non-Agri-Food sectors. They categorize different functionalities—such as sensorization, Data-driven logistics, blockchain-based traceability, mathematical modeling, by-product valorization, and digital twin simulation—and explain how they can be applied to enhance efficiency, sustainability, and innovation across different industries [4–7].

- The Agri-Food Technology Applications table focuses on how these technologies optimize agricultural and food production systems, improving crop yield, livestock health, supply chain efficiency, waste reduction, and product traceability.
- The Non-Agri-Food Technology Applications table highlights the same technological functionalities but applied in industrial settings like manufacturing, logistics, energy, and waste management, where they enhance process optimization, sustainability, compliance, and operational efficiency.

Both tables illustrate the cross-sectoral applicability of emerging technologies, demonstrating how digital tools and advanced analytics can drive innovation, improve resource utilization, and enable sustainable practices across diverse domains.

Table 3: Agri-Food Technology Applications

Functionality	Agri-Food Sectors	Why they can be applied	How they can be applied
Sensorization for real-time monitoring	Dairy farming, greenhouse horticulture, fisheries, olive harvesting	Environmental monitoring improves livestock health, crop yield prediction, and fish farming efficiency.	Deploy IoT sensors to track humidity, temperature, soil nutrients, and water levels for smart irrigation.

Functionality	Agri-Food Sectors	Why they can be applied	How they can be applied
Data-driven logistics optimization	Grain storage, perishable food logistics, seafood distribution, livestock supply chains	Reduces waste, improves route planning, and enhances efficiency in handling perishable food products.	Use predictive modeling for supply chain optimization, inventory control, and demand forecasting.
Blockchain-based traceability	Organic farming, livestock tracking, vineyard management, fresh produce supply chains, , olive oil production	Ensures real-time traceability, regulatory compliance, and fraud prevention in food chains.	Implement blockchain smart contracts to validate organic certifications and prevent counterfeiting.
Mathematical modeling of feedstock	Biogas production, composting facilities, animal feed processing, vertical farming	Enhances process efficiency, optimizes biomass conversion, and supports sustainable farming systems.	Develop Data-driven simulations to optimize anaerobic digestion and bio-processing of organic waste.
Valorization of by-products	Food waste management, nutraceuticals, functional food production, bio-based packaging	Transforms agricultural waste into value-added products, reducing disposal costs and promoting sustainability.	Utilize spectroscopic analysis to extract valuable compounds from by-products for secondary markets.
Digital Twin for process simulation	Meat processing, fruit storage and ripening, aquaculture optimization, olive oil production	Simulates production conditions, optimizes resource allocation, and supports predictive maintenance.	Create digital twins to simulate farm operations, evaluate crop yield scenarios, and predict disease outbreaks.

Table 4: Non-Agri-Food Technology Applications

Functionality	Non-Agri-Food Sectors	Why they can be applied	How they can be applied
Sensorization for real-time monitoring	Pharmaceutical manufacturing, chemical processing, environmental monitoring, energy production	Monitors critical environmental variables, ensuring process efficiency, compliance, and safety.	Install sensor networks for real-time chemical composition monitoring, leak detection, and air quality assessment.
Data-driven logistics optimization	Automotive supply chain, e-commerce warehousing, industrial logistics,	Optimizes logistics efficiency, reduces transport delays, and enhances supply chain	Leverage machine learning models to optimize supply chain routes, stock replenishment, and delivery

Functionality	Non-Agri-Food Sectors	Why they can be applied	How they can be applied
	smart city infrastructure	transparency.	scheduling.
Blockchain-based traceability	Pharmaceutical tracking, aerospace component management, fashion industry supply chains	Ensures authentication, compliance, and tamper-proof tracking of critical high-value assets.	Develop blockchain solutions for secure, auditable records of pharmaceutical and aerospace component transactions.
Mathematical modeling of feedstock	Biorefineries, waste-to-energy plants, circular economy initiatives, water treatment facilities	Supports process optimization, raw material efficiency, and sustainability in industrial operations.	Implement computational simulations for waste-to-energy conversion and carbon footprint reduction strategies.
Valorization of by-products	Plastic and polymer recycling, textile waste upcycling, biofuel production, urban waste management	Reduces waste generation, promotes closed-loop production, and increases material reuse.	Use molecular-level analysis to recover and repurpose industrial by-products into marketable materials.
Digital Twin for process simulation	Smart factories, predictive maintenance in heavy industry, digital modeling of industrial workflows	Simulates production scenarios, enhances operational decision-making, and reduces downtime.	Create industrial digital twins for virtual testing of equipment performance and predictive maintenance scheduling.

The BBTWINS replication plan focuses on Greece and Spain as the initial proof of concept for scaling the project's digital transformation solutions across industrial agrifood sectors. This strategic selection is based on several key factors that ensure effective validation, scalability, and future expansion to other countries.
First, continuity and consistency with existing use cases make Greece and Spain ideal locations for the replication phase. These countries were the primary locations for the original BBTWINS use cases, focusing on peach production (DIMITRA) and pig farming (PORTESA). By remaining within these countries, the replication plan leverages established partnerships, technical knowledge, and infrastructure, reducing deployment risks and ensuring continuity in technology transfer. Testing within a familiar regulatory and operational environment allows for a controlled evaluation of digital twin performance before expansion to different regulatory frameworks.

Additionally, comparable Agri-industrial characteristics between the two countries strengthen the selection. Greece and Spain both have strong agrifood industries and are global leaders in food processing and exports, making them ideal for testing and optimizing digital transformation strategies. They also exhibit common logistics and industrial challenges that can be addressed with Data-driven analytics, digital twins, and blockchain traceability. The selection of olive oil processing, seafood processing, food and beverage production, renewable energy, and logistics for replication ensures that BBTWINS solutions remain adaptable to different industrial challenges while still operating within a recognizable agrifood value chain structure. Moreover, the favorable regulatory and technological landscape of Greece and Spain supports this initiative. Both countries operate under the European Union's regulatory framework, ensuring compliance with EU-wide food traceability, sustainability, and digitalization mandates. They have demonstrated commitment to Industry 4.0, digitalization, and sustainability through various national and EU-funded initiatives, making them receptive environments for innovation adoption. The existing technological ecosystem, including sensorization, AI, and blockchain solutions in agrifood industries, makes them ideal candidates for real-world testing of BBTWINS applications in different industrial sectors. From a logistics and market readiness perspective, both Spain and Greece are major exporters of agrifood products, making supply chain optimization and traceability improvements highly valuable. Digital solutions such as Data-driven logistics, smart warehousing, and blockchain-based traceability have immediate applicability in highly export-oriented food industries. Furthermore, Greece and Spain offer a balanced mix of large industrial processing units and smaller regional producers, allowing the replication plan to evaluate scalability across different business models.

Most importantly, the selection of Greece and Spain serves as a strategic proof of concept before EU-wide expansion. By choosing these two countries as the initial replication sites, BBTWINS can refine its technological models, measure real-world impact, and optimize implementation strategies before expanding to additional countries. A phased approach ensures that potential challenges in adaptation, regulatory compliance, and operational efficiency are resolved before further scaling. Success in these two markets will serve as a benchmark for broader EU-wide and international adoption, enabling BBTWINS to enter new Agri-industrial markets such as Italy, France, Germany, and beyond. In conclusion, the decision to focus the replication plan on Greece and Spain is based on a strategic, evidence-based approach that ensures continuity with original BBTWINS use cases, operational similarities across agrifood processing industries, regulatory alignment within the EU, strong export and logistics-driven market potential, and a structured, phased proof-of-concept strategy for future expansion. This approach maximizes the impact of digital twins, AI, and blockchain solutions in industrial agrifood sectors, ensuring scalability, feasibility, and long-term adoption across Europe and beyond.

The following Table 5 summarizes the Agri-industrial sectors in Greece and Spain are well-suited for the replication of BBTWINS solutions. Each sector faces unique on-field, logistics, and industrial operational challenges that can be addressed through digitalization.

Table 5: Challenges and digital solutions in different agro-industrial sectors

Sector	Specific Challenge	BBTWINS Functionality as a Solution
Olive Oil Processing	Harvesting delays reduce olive quality, affecting oil yield and flavor.	Digital twins optimize harvesting schedules and transport logistics.
	Variable olive ripeness leads to inconsistent extraction efficiency.	Sensorization monitors olive ripeness for better extraction control.
	By-product management of olive pomace poses environmental challenges.	By-product valorization converts olive pomace into bio-based materials.
Cereal & Citrus Processing	Moisture variability in cereals affects storage efficiency and increases spoilage risk.	Sensorization monitors moisture content to optimize storage conditions.
	Weather variability impacts citrus fruit quality, leading to inconsistent juice yield.	Digital twins improve citrus juice extraction and processing efficiency.
	Bulk transportation of cereals often causes product degradation.	Predictive analytics optimize logistics to prevent degradation.
Fisheries & Seafood Processing	Cold-chain failure during transport results in seafood spoilage.	Data-driven logistics enhance cold storage management to reduce spoilage.
	Lack of traceability for seafood origins leads to regulatory compliance risks.	Blockchain-based traceability ensures compliance and authenticates origins.
	High waste generation from fish processing reduces resource efficiency.	By-product valorization converts fish waste into fishmeal and bio-compounds.
Food & Beverage Processing	Temperature fluctuations during wine fermentation impact product quality.	Digital twins monitor fermentation conditions for consistent product quality.
	Inefficient cold-chain logistics increase spoilage risks in dairy production.	Data-driven logistics optimize cold storage to reduce spoilage risks.
	Whey by-product in cheese production remains underutilized.	By-product valorization repurposes whey into functional food ingredients.
Renewable Energy & Bio-Based Processing	Feedstock variability reduces biogas yield and conversion efficiency.	Digital twins predict optimal feedstock composition for biogas production.
	High energy costs in biomass transportation increase operational expenses.	Data-driven process optimization reduces transportation costs and energy use.
	By-product management in bio-based operations remains a challenge.	By-product valorization turns biomass residues into value-added products.

5. Selection of Replication Cases

5.1. Olive Oil Production Industry

The olive oil industry, particularly in Mediterranean countries like Spain and Greece, presents a unique opportunity for the adoption of digital twin technology. As one of the most important agricultural sectors in these countries, the olive oil industry is responsible for a significant portion of global olive oil production. However, despite its importance, the industry faces several challenges that digital twins could help address. One of the primary challenges in olive oil production is the inefficient use of resources, particularly water and fertilizers. Olive trees require careful management of irrigation and nutrient levels to ensure optimal growth and yield, but traditional farming practices often result in over- or under-watering, leading to wasted resources and lower productivity. By implementing digital twins, farmers can monitor real-time data on soil moisture, weather conditions, and tree health, allowing them to optimize their irrigation and fertilization practices [7]. This not only improves yields but also contributes to more sustainable farming practices by reducing water and fertilizer use. Another challenge in the olive oil industry is the time-sensitive nature of olive harvesting and processing. Once olives are harvested, they must be processed quickly to prevent spoilage and preserve oil quality. Delays in processing can lead to fermentation and reduced oil quality, which can negatively impact both the product and the producer's bottom line. Digital twins can help optimize the harvesting and processing schedule by simulating different scenarios and predicting the best time to harvest based on real-time data from the field [5]. This ensures that olives are harvested at their peak and processed as quickly as possible to maintain the highest quality oil. Additionally, digital twins can improve traceability and quality control in the olive oil supply chain. By integrating blockchain technology with digital twins, producers can track every step of the production process, from the olive grove to the bottle. This not only helps prevent fraud and counterfeiting but also provides consumers with the transparency they increasingly demand. Consumers can verify the authenticity and quality of their olive oil, ensuring that they are purchasing a genuine product from a trusted source [4].

The olive oil value chain comprises several stages, from the cultivation of olives to the distribution of the final product. Olive trees are grown in groves, typically in Mediterranean climates with specific soil and weather conditions. Farmers must carefully manage soil quality, irrigation, and pest control to ensure a healthy yield. Proper maintenance, such as pruning, is essential for maximizing production and improving tree longevity. Harvesting is a critical stage where olives are collected either manually or mechanically at the right ripeness to preserve oil quality. Delays in harvesting or using overripe olives can reduce the final product's quality. Once harvested, the olives must be transported efficiently to processing mills to prevent fermentation, which could negatively impact the oil's characteristics. Minimizing transportation time and exposure to environmental factors, such as heat, is essential.

At the mill, olives undergo cleaning, crushing, and processing to extract the oil. This process includes malaxation (mixing of the olive paste) and either cold pressing or centrifugation to separate the oil from the solids. Strict control of temperature and processing time ensures high-quality extra virgin olive oil. After extraction, the oil is filtered and stored in stainless steel tanks at controlled temperatures to prevent oxidation. When ready for distribution, the oil is bottled—often in dark glass containers—to protect it from light, which can degrade its quality. The final step in the value chain is distribution, where bottled olive oil reaches retailers and consumers. Maintaining quality throughout logistics is crucial, as prolonged exposure to heat or light can deteriorate the oil's properties.

Despite the centuries-old tradition of olive oil production, the industry now faces modern challenges that necessitate digitalization. Improving efficiency, ensuring traceability, and valorizing by-products are key areas where digital tools can make a difference. Technologies such as digital twins, Data-based optimization, and blockchain can enhance operational efficiency, reduce waste, and provide consumers with greater transparency. By adopting digital solutions, the olive oil industry can modernize its processes, enhance sustainability, and ensure high-quality products for consumers. The replication of BBTWINS digital tools in the olive oil industry offers a significant opportunity to modernize the sector, improve sustainability, and enhance the quality and traceability of olive oil products. By leveraging digital twins, IoT, and blockchain, the olive oil industry can address its most pressing challenges, ensuring a more efficient, transparent, and sustainable future for producers and consumers alike.

5.1.1. STRUCTURED DIVISION OF THE OLIVE OIL VALUE CHAIN INTO BBTWINS USE CASES

To ensure a methodical approach, the replication plan will follow the same use case framework proposed by BBTWINS. The olive oil value chain will be divided into four core use cases:

Use Case 1: Logistics Optimization

Objective: Enhance the efficiency and sustainability of transporting olives from groves to mills and distributing the final product to markets while ensuring minimal quality degradation.

Challenges Addressed:

- Delays in transportation leading to olive fermentation and reduced oil quality.
- High fuel consumption and carbon footprint from inefficient logistics.
- Lack of real-time monitoring and tracking of olive shipments.

BBTWINS Tools Adaptation:

- Route Optimization: Algorithms will dynamically calculate the most efficient transportation routes, factoring in real-time traffic, weather conditions, and mill processing capacity.
- IoT Sensors for Transport Monitoring: Real-time sensors will monitor transport conditions (temperature, humidity, pressure) to ensure optimal olive preservation.
- Blockchain-Enabled GPS Tracking: Provides transparent, real-time tracking and documentation of olive transport, reducing risks of delays and quality loss.

Use Case 2: Operational Efficiency in Olive Oil Production

Objective: Improve efficiency in olive cultivation, harvesting, processing, and storage using digital tools to enhance yield, minimize losses, and maintain product quality.

Challenges Addressed:

- Inefficient irrigation and pest control leading to variable olive yields.
- Suboptimal processing conditions reducing oil extraction efficiency and quality.
- High energy consumption in oil extraction and storage.

BBTWINS Tools Adaptation:

- Digital Twins for Olive Processing: Simulates crushing, malaxation, and centrifugation processes in real-time, optimizing temperature and extraction parameters.
- AI for Predictive Maintenance: Machine learning models detect wear and tear on milling machinery, minimizing unexpected downtimes and maximizing operational efficiency.
- IoT Sensor Networks for Olive Groves: Sensors monitor soil moisture, climate conditions, and pest activity to optimize irrigation, fertilization, and pest control strategies.

Use Case 3: Bio-Product Valorization

Objective: Optimize the management and utilization of by-products such as olive pomace and wastewater, reducing waste and creating new revenue streams.

Challenges Addressed:

- Large quantities of olive pomace requiring disposal or inefficient use.
- High water usage and pollution from olive mill wastewater (OMW).
- Limited economic incentives for valorization of olive by-products.

BBTWINS Tools Adaptation:

- Data-based Valorization Models: Simulates the most efficient valorization routes, including energy production (biomass), nutraceutical extraction, and animal feed applications.
- OMW Treatment for Biogas Production: Digital models optimize anaerobic digestion for biogas production, providing renewable energy for mill operations.
- Oleuropein Extraction from Olive Leaves: Data-driven chemical analysis determines the best conditions for extracting oleuropein, a valuable antioxidant used in cosmetics and pharmaceuticals.

Use Case 4: Traceability and Quality Assurance

Objective: Ensure complete transparency in olive oil production, from grove to bottle, enforcing quality control.

Challenges Addressed:

- Lack of End-to-End Visibility: Many traditional olive oil supply chains lack centralized tracking, making it difficult to ensure full traceability.
- Counterfeit and Fraudulent Products: Adulteration and mislabeling of olive oil are common issues, requiring robust tracking mechanisms.
- Inconsistent Quality Control: Variations in production processes can lead to inconsistencies in oil quality, requiring stricter enforcement measures.
- Consumer Trust and Transparency: Consumers demand proof of authenticity and quality but often lack reliable means to verify product origin and production standards.

BBTWINS Tools Adaptation:

- Blockchain for Product Traceability: A blockchain system will record every stage of production, ensuring secure and immutable tracking of olive oil batches.
- Smart Contracts for Quality Control: Automated smart contracts will verify that each batch meets extra virgin olive oil standards before being bottled.

- Consumer-Facing QR Codes: Blockchain-linked QR codes on packaging will allow consumers to verify the origin and processing details of the product.

To successfully implement the Digital Twin for Olive Oil Production, a structured approach is required to integrate Data, IoT, blockchain, and logistics optimization across the entire value chain. This implementation plan ensures a seamless transition from traditional practices to a data-driven, efficient, and sustainable system. Its phases are:

Phase 1: Logistics & Inventory Management

- Deploy logistics optimization models.
- Install IoT sensors to monitor inventory conditions (temperature, oxygen levels).
- Establish real-time tracking systems for olive oil batches during storage and transportation.

Phase 2: Sensorization & Data Collection

- Deploy IoT sensors (Milesight EM500-SMTC, EM500-LGT) in olive groves.
- Collect real-time environmental data and integrate it into the Digital Twin platform.
- Use data-driven predictive analytics for crop health and irrigation optimization.

Phase 3: Harvesting & Yield Optimization

- Implement Digital Twins to simulate harvesting conditions.
- Deploy machine vision (Intel RealSense) for olive yield estimation and tree health assessment.
- Optimize harvest timing and resource allocation through data-driven insights.

Phase 4: Processing Optimization & By-Product Management

- Connect mill machinery to the Digital Twin for real-time efficiency monitoring.
- Utilize simulation models to optimize by-product valorization (biogas, cosmetics, nutraceuticals).
- Improve milling efficiency and reduce production waste.

Phase 5: Blockchain for Traceability

- Establish a blockchain system to track olive oil batches from grove to bottle.
- Implement smart contracts for automated quality certification and compliance.
- Enhance supply chain transparency and consumer trust.

The following diagram (Figure 3) visually represents these phases contributing to the Digital Twin.

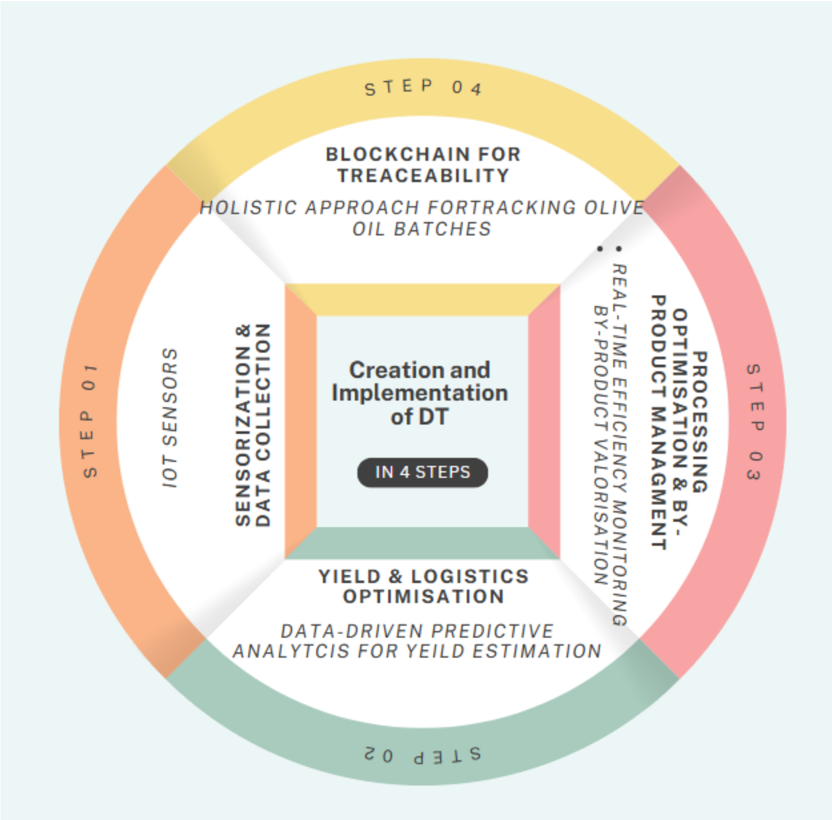

Figure 3: Steps for creation & implementation of DT in the olive oil industry supply chain

5.1.2. STAKEHOLDER POWER ANALYSIS

The adoption of digital tools in the olive oil industry involves a complex network of stakeholders, each with varying levels of power and interest. Understanding these dynamics is essential for effectively implementing technologies like digital twins, IoT sensors, AI, and blockchain. This stakeholder analysis, schematically depicted in Figure 4, categorizes key players based on their influence and engagement, ensuring that digital transformation strategies align with industry needs and regulatory requirements.

Farmers and olive oil producers have low to medium power but high interest in adopting digital tools that optimize productivity, resource use, and costs. While individual farmers have limited influence, cooperatives and associations provide collective bargaining power, particularly in major olive oil-producing regions. Their feedback will be critical in refining digital tools to ensure usability and practical impact on farming operations. **Olive oil mills and processing facilities hold medium to high power and high interest** as they control a critical stage in olive oil production. They seek to optimize operations through Data-driven digital twins to enhance efficiency, reduce energy consumption, and improve product quality. Their role includes adopting advanced processing techniques, ensuring optimal extraction parameters, and managing by-product valorization.

Government agencies and regulatory bodies wield high power with medium to high interest. Institutions such as the Ministry of Agriculture and Rural Development (Spain) and the Greek Ministry of Rural Development and Food influence the sector through policy-making, regulation, and funding. They aim to promote sustainability, productivity, and food traceability by incentivizing digital transformation. Their role includes providing financial incentives, enforcing compliance, and supporting research initiatives.

Technology providers have medium to high power and high interest, given their control over technological infrastructure. Their interest lies in expanding into the agricultural sector and securing long-term partnerships with olive oil producers and mills. They play a key role in customizing technology to industry needs, providing technical support, and integrating Data-driven optimization tools. **Industry associations and trade organizations**, such as the International Olive Council (IOC) and national agricultural associations, **have medium to high power and high interest**. They shape industry standards, advocate for policy changes, and promote best practices. These organizations facilitate technology adoption by organizing training sessions, liaising with regulatory bodies, and disseminating information about technological advancements.

Consumers and market participants hold medium to high power and high interest as their preferences for sustainable, high-quality, and traceable olive oil influence industry trends. Their demand drives transparency initiatives, pushing producers to adopt blockchain and other traceability solutions. Consumers play a role in selecting sustainably produced products, shaping market trends, and influencing producers to comply with ethical sourcing standards. **Local retail outlets and small grocers have low power and low interest** in industry-wide digital transformation. Their primary concern is stocking products that align with consumer demand. While they play a minor role in driving digital transformation, they remain relevant in the distribution of the final product.

This stakeholder analysis aligns with the visual representation shown in the mapping. The implementation of digital technologies in the olive oil industry should be strategically tailored to meet the needs of key players while ensuring buy-in from farmers, industry associations, and government bodies. Recognizing the varying levels of power and interest among stakeholders is crucial for the successful replication of BBTWINS tools in the olive oil sector.

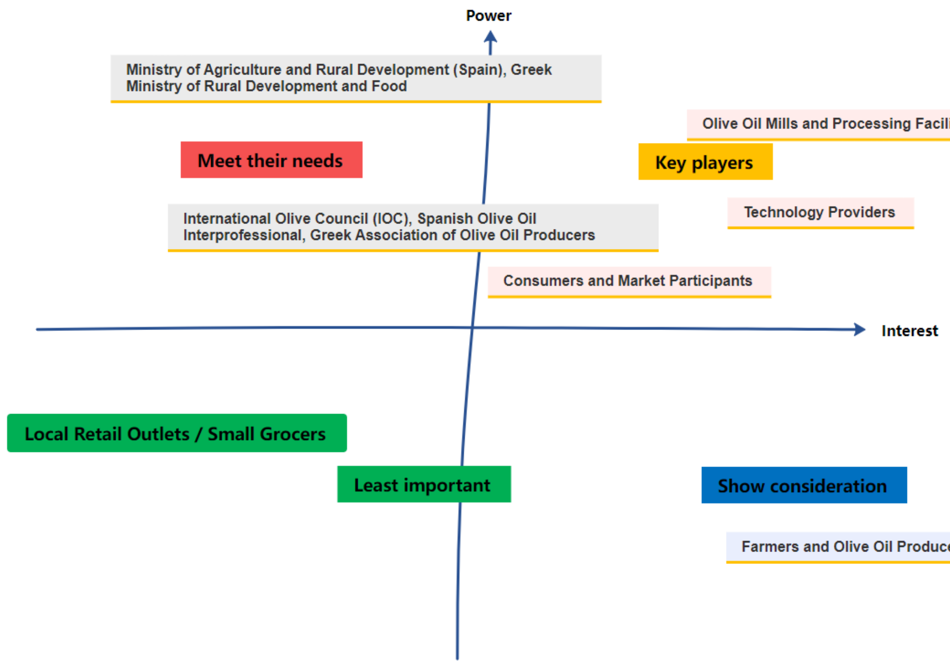

Figure 4: Stakeholder power analysis

5.2. Tailoring BBTWINS Functionalities to Agricultural Operations

For this study, PORTESA's farming activities have been chosen as a model to explore the replication potential of BBTWINS digital technologies in cereal and legume cultivation. These crops share similar farming steps and challenges, making them ideal candidates for the implementation of BBTWINS solutions. The agricultural process at PORTESA involves multiple stages, from crop fertilization and cultivation to harvesting, processing, and distribution. Each stage presents unique challenges and opportunities for digital transformation.

PORTESA's agricultural activities involve multiple stages that contribute to the overall production process. Crop fertilization is the first step in the value chain, where fertilizers are applied to optimize soil quality and nutrient availability. Ensuring the right balance of nutrients in the soil is crucial for healthy crop growth and productivity. Crop cultivation follows, with continuous monitoring of soil conditions and plant development to maintain optimal production levels. This stage often involves interventions such as irrigation, pest control, and disease management to secure high yields. Harvesting is a critical phase, involving the collection of crops at their peak ripeness. Depending on the type of crop, this may be done using traditional manual methods or mechanized harvesting techniques to ensure efficiency and minimal damage to the produce. Once harvested, the crops undergo collection and transportation to processing facilities. Efficient logistics play a crucial role in ensuring minimal delays and maintaining product quality during transit. Proper handling at this stage prevents spoilage and contamination. The processing phase consists of several key steps. First, peeling the grain removes the outer layers to prepare it for milling. This is followed by grain cleaning, which eliminates impurities and unwanted residues to ensure high-quality final products. Next, physicochemical and nutritional analysis is conducted to assess the grain's composition and ensure compliance with industry standards. Chromatic screening, using infrared-based technology, is then applied to classify the grain according to quality parameters. Wet grain conditioning and grinding in a traditional stone mill further refine the product, preserving its natural flavor and texture. After grinding, sieving and classification take place, sorting the grains based on their quality and intended industrial use. Once processing is complete, the next stage is packaging. This step ensures product safety, enhances shelf-life, and prepares the final product for distribution. Proper packaging techniques help maintain freshness and protect the grains from environmental factors. Finally, expedition and distribution ensure that the products reach their intended markets. PORTESA utilizes multiple sales channels, including direct-to-consumer sales, wholesaling, and online marketplace platforms, to make their products accessible to a wide range of customers.

Challenges in Agricultural Operations

The actual process at PORTESA remains quite traditional. The mill is constructed from stone, and the entire structure is made of wood, assembled piece by piece. The most modern technology in use is a chromatic machine with infrared sensors for grain classification. While these traditional methods contribute to product authenticity and quality, they also present significant challenges in scaling and efficiency.

One of the key challenges in PORTESA's agricultural activities is resource optimization. The efficient use of fertilizers and irrigation is critical to reducing both waste and costs, but traditional methods often lead to overuse or uneven distribution. Implementing precision agriculture technologies could help address this inefficiency. Quality control is another significant challenge, particularly in maintaining consistency in grain classification and preventing contamination. Variability in environmental conditions and processing inconsistencies can impact the final product's quality, making standardization difficult without technological intervention.

Processing bottlenecks present an issue due to PORTESA's reliance on traditional milling methods. While stone milling helps preserve the grain's integrity, it may not be scalable for larger production demands, necessitating a balance between traditional techniques and modern efficiencies. Logistics inefficiencies can also disrupt the value chain, leading to transportation delays that affect product freshness and quality. Without proper planning and tracking, inefficiencies can increase costs and reduce customer satisfaction. Finally, limited traceability in the production process poses concerns for consumers who are increasingly interested in knowing the origins and quality of their food. A lack of detailed tracking mechanisms reduces transparency, which could impact trust in the brand and limit market expansion.

Opportunities for Digital Transformation

To address these challenges, several digital transformation opportunities can enhance efficiency, sustainability, and transparency in PORTESA's operations.

IoT-based soil monitoring presents a major opportunity by utilizing sensors to track moisture, nutrients, and weather conditions in real time. This technology allows farmers to make data-driven decisions about irrigation and fertilization, reducing waste and optimizing resource use. Data-Driven grain classification offers a solution for quality control by enabling automated sorting of grains based on defined parameters. Advanced machine learning models can analyze grain attributes to ensure uniformity, reducing human error and increasing production consistency.

Blockchain for traceability can provide an immutable record of each stage of production, enhancing consumer confidence and regulatory compliance. By integrating blockchain, PORTESA can offer full transparency on grain origin, processing, and distribution, improving brand reputation and market competitiveness. Smart logistics can optimize transportation routes, inventory management, and delivery schedules using Data-driven models. Predictive analytics can help minimize delays, reduce spoilage, and enhance supply chain efficiency, ultimately lowering costs and improving service levels. Lastly, by-product valorization represents a sustainability opportunity by converting waste into bio-based products. Instead of discarding grain residues, these can be repurposed into secondary products such as animal feed, compost, or biodegradable packaging, generating additional revenue streams and supporting a circular economy.

5.2.1. TAILORING BBTWINS FUNCTIONALITIES TO PORTESA'S AGRICULTURAL ACTIVITIES

The BBTWINS project provides a suite of digital technologies, including sensorization, Data-driven analytics, blockchain-based traceability, and digital twins, which can be tailored to optimize and digitalize PORTESA's traditional agricultural value chain. Below is a detailed mapping of how each BBTWINS functionality can be applied specifically to PORTESA's agricultural operations, ensuring efficiency, sustainability, and enhanced traceability.

Sensorization for Real-Time Monitoring

- Soil and Crop Monitoring: IoT sensors can be deployed in crop fields to monitor soil moisture, nutrient levels, and weather conditions in real-time. This will allow PORTESA to optimize fertilization and irrigation schedules, reducing resource wastage.
- Grain Processing Control: Sensors placed within grain peeling, cleaning, and classification machines can track temperature, humidity, and impurity levels, ensuring high product quality.
- Storage Conditions: Sensors can be installed in packaging and storage units to continuously monitor temperature and humidity levels, preventing spoilage and ensuring optimal conditions.

Expected Benefits:

☑ Precision agriculture reduces input costs and environmental impact.
☑ Optimized irrigation and fertilization improve crop yield and sustainability.
☑ Real-time alerts prevent spoilage and enhance product consistency.

Data-driven Analytics for Process Optimization

- Predictive Crop Yield Models: AI can process historical weather data, soil conditions, and crop performance metrics to forecast optimal harvest times, reducing waste and improving efficiency.
- Grain Sorting & Quality Control: Data-powered image recognition can automate the chromatic classification of grains, ensuring uniformity in processing.
- Logistics Optimization: AI can analyze transportation routes and supply chain logistics to minimize delays and optimize grain collection and distribution.

Expected Benefits:

☑ Higher product quality through automated grain classification.
☑ Reduced waste by optimizing harvesting and processing schedules.
☑ Improved logistics efficiency, reducing transportation costs.

Blockchain for Supply Chain Traceability

- Product Traceability: Blockchain can be integrated with PORTESA's production and distribution system to provide a fully transparent and tamper-proof record of grain origin, processing stages, and distribution.
- Consumer Confidence & Certification: A blockchain ledger can store nutritional and physicochemical analysis results for each batch, allowing end-users (bakeries, food service companies) to verify product authenticity.
- Compliance & Quality Assurance: Digital records of certifications, regulatory compliance, and quality control checks ensure adherence to industry and environmental standards.

Expected Benefits:

☑ Enhanced transparency and consumer trust.
☑ Streamlined compliance with food safety and ecological labeling regulations.
☑ Fraud prevention by ensuring accurate origin tracking.

Digital Twin Implementation for Operational Efficiency

- Virtual Twin of Crop Fields & Soil Conditions: By integrating sensor data, AI analytics, and historical patterns, a digital twin model can simulate different fertilization and irrigation strategies to determine the most effective approach.
- Simulating Grain Processing Workflows: A digital twin can replicate wet grain conditioning, grinding, and sieving processes, allowing real-time adjustments to optimize output.
- Predictive Maintenance for Processing Equipment: Digital twins can detect anomalies and predict failures in milling, cleaning, and packaging machines, reducing downtime.

Expected Benefits:

☑ Improved decision-making with real-time simulation models.
☑ Lower equipment maintenance costs through predictive diagnostics.
☑ Optimized production output by continuously adjusting processing parameters.

Smart Logistics and Transportation Optimization

- Fleet & Delivery Optimization: Data-based route planning can optimize grain collection and final distribution to bakeries, wholesalers, and retailers.
- Smart Inventory Management: Integrated tracking of stored and packaged grain batches allows for real-time stock monitoring and demand prediction.

- Cold Chain Monitoring (if applicable): Sensors and AI models can monitor temperature and humidity conditions during transportation to prevent grain deterioration.

Expected Benefits:

- ☑ Reduced transportation costs and CO_2 emissions through optimized delivery schedules.
- ☑ Fewer delays in distribution, ensuring fresher, higher-quality products.
- ☑ Minimized waste by preventing stock shortages or excess inventory.

By-Product Valorization for Circular Economy

- Repurposing Waste from Grain Processing: By-products such as grain husks and residues can be converted into bio-based materials (e.g., animal feed, biodegradable packaging).
- Optimized Waste-to-Energy Pathways: Data-driven models can analyze the feasibility of biogas production from agricultural residues, contributing to sustainability goals.
- Sustainable Packaging Solutions: The use of bio-based materials for packaging can reduce dependency on plastics, enhancing PORTESA's eco-friendly brand positioning.

Expected Benefits:

- ☑ New revenue streams from valorized by-products.
- ☑ Reduced environmental impact by minimizing agricultural waste.
- ☑ Compliance with circular economy policies and sustainability targets.

5.2.2. STAKEHOLDER POWER ANALYSIS

The PORTESA agricultural value chain involves a diverse set of stakeholders, each playing a critical role in the production, processing, and distribution of agricultural products. These stakeholders have different levels of power and interest in adopting digital transformation technologies such as sensorization, data-driven analytics, blockchain traceability, and digital twins under the BBTWINS framework. Understanding their influence and engagement level is essential to successfully digitizing and optimizing the PORTESA value chain.

Key Stakeholders and Their Roles

- ✓ Local Farmers and Livestock Producers from Teruel: These stakeholders are responsible for the initial stages of the agricultural value chain, including soil preparation, fertilization, crop cultivation, and livestock production. Their primary concerns include improving productivity, reducing costs, and ensuring product quality.
- ✓ Social Foundations Involving People at Risk of Exclusion: These organizations facilitate social inclusion by involving marginalized individuals in agricultural activities. Their role is essential in ensuring fair labor practices and integrating socially responsible employment within the value chain.
- ✓ Technology Providers (Mill, Chromatic Machine, Packaging Machine Manufacturers): This group includes suppliers of agricultural and processing equipment such as mills, chromatic screening machines, and

packaging automation systems. Their technology innovations play a crucial role in modernizing PORTESA's traditional manual processing methods.

- ✓ Regional and Sectoral Agencies (Ecological Production Label): These regulatory bodies oversee certifications, sustainability labeling, and quality control standards for agricultural products. Their role is pivotal in ensuring that PORTESA's products align with ecological and organic farming regulations, enhancing the company's market position.

The Power-Interest Matrix classifies stakeholders based on their level of influence (power) over decision-making and their interest in digital transformation.

Engage Closely – Key Stakeholders (Medim-High Power, High Interest)

Local Farmers and Livestock Producers /Technology Providers

The integration of digital transformation is crucial for farmers, directly influencing their productivity and financial sustainability. However, to effectively utilize Data-based analytics and sensorization technologies, they require dedicated training programs and financial assistance. Providing these resources ensures that they can leverage innovative solutions to optimize their operations. As the backbone of technological advancements, these stakeholders bring critical expertise and innovation. Their role in digitizing key processing stages such as milling, screening, and packaging is indispensable for the seamless adoption of BBTWINS solutions. Active collaboration with farmers and industry players will facilitate smoother transitions and broader technological acceptance.

To foster successful implementation and adoption of digital tools, the following strategies will be employed:

- Organizing regular training sessions to equip farmers with hands-on experience and theoretical knowledge.
- Providing financial incentives and support mechanisms to encourage the adoption of advanced digital solutions.
- Customizing technological solutions to address the specific operational needs of farmers and livestock producers, ensuring practicality and effectiveness.

By focusing on these strategic engagement efforts, we can drive the widespread adoption of digital transformation within the agricultural sector, ensuring sustained productivity and efficiency for all stakeholders involved.

Meet Their Needs – Regulatory and Certification Bodies (High Power, Low-Medium Interest)

Regional and Sectoral Agencies

These agencies influence market access and certification processes but may not be directly involved in technology adoption. Their interest lies in maintaining regulatory compliance and sustainability standards. To foster successful implementation of BBTWINS tools we should demonstrate how blockchain traceability and data-driven analytics align sustainability goals and simplify compliance reporting.

Keep Informed – Social Foundations (Low Power, High Interest)

Social Foundations Supporting Marginalized Workers

These organizations have a vested interest in ensuring fair labor inclusion in digitized operations. They may lack decision-making power but are essential in maintaining the social responsibility and sustainability aspects of PORTESA's business model. To foster successful implementation of BBTWINS tools we should provide clear communication about the impact of digital transformation on employment and labor conditions, ensuring that automation complements rather than replaces social labor contributions.

Monitor – Least Important (Low Power, Low Interest)

General Public and Local Communities

While they do not have direct influence, their consumer behavior and perception can shape demand for eco-certified products. In terms of successfully adopting BBTWINs tools, public awareness campaigns and eco-labeling initiatives can enhance the acceptance of digitized agricultural practice

5.3. Tailored KPIs for optimization monitoring

The successful replication of digital tools in the Olive Oil Industry and PORTESA Agricultural Activities requires a structured monitoring framework that ensures measurable improvements in efficiency, quality, traceability, and sustainability. To achieve this, a hierarchical KPI approach will be implemented, ensuring that performance metrics are adaptable, sector-specific, and capable of guiding future optimizations. The hierarchical approach [1] is a multi-tiered methodology designed to provide a structured and progressive assessment of digital transformation. It consists of three levels:

Supporting Elements (Raw Data Collection & Process Tracking)

At the foundation of the KPI system are the raw data elements, which are the measurable variables collected through digital tools such as IoT sensors, Data-driven analytics, and blockchain traceability platforms. These elements represent the real-world inputs needed to calculate meaningful performance indicators.

For the Olive Oil Industry:

- Sensor-based monitoring of olive moisture levels, processing temperatures, and milling speed.
- Real-time energy consumption tracking in milling and refining processes.
- Data collection on olive pomace production and reuse strategies (e.g., biofuel conversion).

For PORTESA Agricultural Activities:

- IoT sensors monitoring soil moisture, nutrient levels, and crop health.
- GPS-based tracking of machinery fuel consumption and movement patterns.
- Data capture of pesticide/fertilizer application rates and yield per hectare.

These supporting elements feed into the next level of the framework, where they are processed into actionable KPIs.

Basic KPIs (Directly Measurable Performance Indicators)

Once the raw data is collected, it is processed into basic KPIs that measure individual performance factors. These KPIs provide initial insights into specific aspects of operational performance.

For the Olive Oil Industry:

- Milling efficiency = (Oil yield / Total olives processed) × 100
- Energy efficiency = (kWh consumed / Ton of olives processed)
- Water efficiency = (Liters of water used / Kg of oil produced)

For PORTESA Agricultural Activities:

- Crop yield per hectare = (Total harvested produce / Cultivated land)
- Pesticide efficiency = (kg of pesticide used / Total yield)
- Fuel efficiency of tractors = (L per km traveled)

Comprehensive KPIs are aggregated indicators that provide a higher-level assessment of the overall impact of digital tool implementation. These indicators combine multiple basic KPIs to assess broader business, environmental, and operational trends.

Examples Comprehensive KPIs for the Olive Oil Industry

Sustainability Index (SI)

The Sustainability Index evaluates the environmental efficiency of the olive oil production process by integrating key sustainability-related KPIs:

- Energy Efficiency (EE)
- Water Efficiency (WE)
- Waste Valorization Efficiency (WVE)

Formula:

$$SI = \frac{(EE \times W_{EE}) + (WE \times W_{WE}) + (WVE \times W_{WVE})}{W_{EE} + W_{WE} + W_{WVE}}$$

Where:

- WEE,WWE,WWVEW are weight factors (assigned based on their importance to sustainability).

- Typical weights: WEE=40%, WWWE=30% WWE=30%, WWVE=30%.

Example Calculation:

- EE=85% (Energy efficiency in % based on power usage per ton of olives processed).
- WE=75 (Water efficiency, measuring water consumption per kg of oil).
- WVE=90% (Waste valorization, indicating percentage of by-products utilized).

This 83.5% Sustainability Index indicates strong sustainability performance in olive oil production.

Traceability Compliance Score (TCS)

This KPI measures the percentage of olive oil batches tracked end-to-end using blockchain for quality assurance and fraud prevention.

Formula:

$$TCS = \frac{\text{Number of Blockchain-Tracked Batches}}{\text{Total Batches Produced}} \times 100$$

Example Calculation:

- Blockchain-tracked batches: 4,500
- Total batches produced: 5,000

This 90% traceability score indicates that most olive oil batches are fully tracked, ensuring high product integrity.

Cost-Benefit Ratio of Digitalization (CBRD)

This metric compares operational cost savings from digital tools against pre-digitalization costs to assess financial viability.

Formula:

$$CBRD = \frac{\text{Pre-Digitalization Cost} - \text{Post-Digitalization Cost}}{\text{Pre-Digitalization Cost}} \times 100$$

Example Calculation:

- Pre-Digitalization Cost: €1,500,000
- Post-Digitalization Cost: €1,200,000

A 20% reduction in operational costs shows significant cost efficiency from digitalization.

Comprehensive KPIs for PORTESA Agricultural Activities

Precision Agriculture Optimization Score (PAOS)

This KPI measures the effectiveness of precision farming techniques by combining crop yield efficiency, fertilizer use, and irrigation optimization.

Formula:

$$PAOS = \frac{(Y \times W_Y) + (F \times W_F) + (I \times W_I)}{W_Y + W_F + W_I}$$

Where:

- Y = Crop yield efficiency (% of optimal yield achieved).
- F = Fertilizer efficiency (kg of fertilizer per ton of crop).
- I = Irrigation efficiency (L of water used per ton of crop).
- Typical weights: WY=50%, WF=30%, WI=20%.

Example Calculation:

- Y = 90%, F = 80%, I = 85%

This 86% PAOS score indicates strong optimization in precision agriculture.

Greenhouse Gas (GHG) Reduction Impact

This KPI quantifies the reduction in CO_2 emissions due to optimized machinery usage and lower emissions.

Formula:

$$GHG_{Red} = \frac{\text{Baseline GHG Emissions} - \text{Current GHG Emissions}}{\text{Baseline GHG Emissions}} \times 100$$

Example Calculation:

- Baseline Emissions: 50,000 kg CO_2
- Current Emissions: 40,000 kg CO_2

A 20% GHG reduction indicates improved sustainability from optimized farming techniques.

Logistics Optimization Index (LOI)

This KPI measures transportation and supply chain efficiency improvements in agricultural logistics.

Formula:

$$LOI = \frac{\text{Pre-Digitalization Transport Cost} - \text{Post-Digitalization Transport Cost}}{\text{Pre-Digitalization Transport Cost}} \times 100$$

Example Calculation:

- Pre-Digitalization Transport Cost: €500,000
- Post-Digitalization Transport Cost: €400,000

A 20% improvement in logistics efficiency reduces costs and enhances supply chain sustainability.

By implementing the hierarchical KPI methodology, the Olive Oil Industry and PORTESA Agricultural Activities will gain precise measurement of digital transformation impact, enabling sector-specific KPI tracking for targeted improvements. The structured framework will facilitate real-time monitoring and data-driven decision-making, ensuring that operational adjustments are guided by accurate performance metrics. Additionally, the approach supports the scalability of best practices to other agrifood industries, promoting widespread adoption of digital tools. Ultimately, this methodology will lead to tangible, quantifiable, and sustainable improvements, driving efficiency, traceability, and environmental responsibility across both replication cases.

5.4. Economic feasibility of implementing BBTWINS solutions

AI-Driven Logistics Optimization

The AI-driven logistics optimization tool, developed by VITO, is designed for simulating and optimizing raw material logistics. The capital expenditure (CAPEX) is 0 €, as all investment costs are considered overhead within operational expenses (OPEX), which range between €25,000 and €75,000 per year. These costs cover personnel, software licensing, and data storage. The estimated payback period for the tool is approximately two years. In terms of industry applicability, the suggested industries for replication—olive oil processing and cereal/seeds/wheat processing—are not suitable for this tool, as tools 1 and 2 rely heavily on animal feed consumption, a crucial factor in their optimization. Therefore, only tool 3 (digital twin for process optimization) is considered replicable for these industries. The current technology readiness level (TRL) of this tool is estimated at 5 (technology validated in a relevant environment), as it has been demonstrated by VTT to PORTESA during meetings and validated by CLUBE. To advance the TRL to 7 (system prototype demonstrated in an operational environment) and adapt it to the specific needs of a new industry, an additional development effort of at least €100,000 would be required. The actual cost will depend on the level of modifications and integration needed. Regarding hardware and software requirements, the tool requires only a computer (e.g., a laptop), and no additional software licenses beyond what was developed in the BBTWINS project. From the PORTESA case study, results indicated a 1-2% reduction in truck drive time and distance. However, for the olive oil or cereal/wheat processing industries, the optimization potential is uncertain without specific data on their logistics operations. VITO and VTT were the key partners responsible for optimizing logistics and supply chain processes for the BBTWINS use cases.

Mathematical Modelling for Biomass Processing

The mathematical modelling tool, developed by CTIC CITA, is designed for the characterization of products and biomass processing chains. The initial investment (CAPEX) includes €25,000 for the development and application of the mathematical model, along with an additional €1,000 for acquiring a laptop to install and operate the application. The operational expenses (OPEX) amount to €8,000 per year, covering annual maintenance, updates with new campaign data, model adjustments, and validation. The estimated return period is approximately 5 years, depending on factors such as company size, sales, and specific operational conditions. CTIC CITA was the primary entity responsible for characterizing products and analyzing the biomass supply chain, ensuring the model's accuracy and applicability for industrial use.

Blockchain-Based Traceability Platform

The Stelviotech BBTWINS Farm-to-Fork traceability platform is designed to provide secure and transparent tracking of products along the biomass supply chain. The capital expenditure (CAPEX) required for its implementation amounts to €23,800, covering the onboarding process, which involves 280 hours at a rate of €85/hour. There are no additional CAPEX costs related to hardware or infrastructure, as the platform operates on a cloud-based system. The operational expenditure (OPEX) per year includes €5,000 for cloud services, €5,000 for system maintenance, and an optional €2,100 for a functional and technical support contract, which can be eliminated depending on the company's maturity. This results in a total annual OPEX of €12,100. The platform is expected to deliver significant cost savings, particularly in industrial planning management, where it can reduce workload by three hours per day over 220 working days per year, at an hourly rate of €50, leading to an annual saving of €33,000. Considering the total operational savings, the net annual savings amount to €20,900, resulting in a basic payback period of approximately 1.14 years. This indicates a rapid return on investment, making the traceability platform an economically viable and scalable solution for industries seeking enhanced transparency and efficiency in their supply chains.

Sensor Network and AI-Based Data Processing

The PANOIMAGEN solution provides a comprehensive system for environmental monitoring, predictive analytics, and industrial process optimization through the deployment of IoT sensors, a centralized data lake, and AI-driven forecasting models. This system is particularly valuable for applications in precision agriculture, biomass monitoring, and resource management, enabling real-time data collection and advanced analytics to support decision-making. The capital expenditure (CAPEX) for this solution consists of two main components: the cost of sensor installation, which is calculated per hectare, and the system-wide costs for AI model development and data lake setup. The installation cost per hectare includes hardware such as IoT sensors for measuring moisture, temperature, and light, a LoraWAN station for data transmission, solar-powered infrastructure, technical labor, and cloud-based software implementation, amounting to approximately €27,380 per hectare. However, the AI models and data lake, which are required for processing and analyzing collected data, are implemented at a fixed system-level cost of €58,800, regardless of the number of hectares. The system is designed to support more than 100 hectares of sensors, making it highly scalable as the cost per hectare decreases when deployed on a larger scale.

The operational expenditure (OPEX) of the PANOIMAGEN system is primarily driven by data storage and AI model maintenance, reflecting the large volume of data generated by the sensor network. Recurring costs include telephone data, cloud storage, and regular updates to the AI models and data lake infrastructure, resulting in an estimated annual OPEX of €174,588. This high operational cost is due to the intensive computational requirements needed for processing real-time environmental data, running forecasting algorithms, and ensuring seamless cloud-based data sharing. The economic viability of the PANOIMAGEN system depends on the efficiency gains achieved through data-driven insights. By leveraging AI models and centralized data processing, businesses and agricultural operations can optimize resource utilization, improve production planning, reduce waste, and enhance operational efficiency. The solution's return on investment is largely influenced by the scale of deployment, as fixed costs remain constant while benefits increase with the number of hectares monitored. Furthermore, the integration of digital twins and blockchain-based traceability systems enhances the overall value of the platform, making it a strategic investment for industries seeking to adopt smart, data-driven management approaches.

Digital Twin Tool

The SOLTEC BBTWINS Digital Twin is designed to enhance industrial planning and process optimization, particularly for small to medium-sized industries such as CARTESA's slaughterhouse or DIMITRA's industrial plant. The capital expenditure (CAPEX) for implementing the system amounts to €59,000, including €5,000 for computer hardware and €54,000 for onboarding costs involving two workers for 300 hours at a rate of €90/hour. The operational expenditure (OPEX) per year is estimated at €17,500, comprising €6,000 for cloud services, €6,000 for platform maintenance, and €5,500 for an intermediate-level operator (who works one hour per day, 220 days per year, at €25/hour) to manage the digital twin. The anticipated savings from the tool stem from reducing the workload of an experienced industrial planning manager by six hours per day, over 220 working days per year, at an hourly rate of €35, resulting in annual savings of €46,200. Given these cost and savings estimates, the net annual saving is calculated at €28,700, leading to an estimated payback period of approximately 2.06 years. This analysis indicates that the SOLTEC Digital Twin is a cost-effective investment with a relatively short return on investment, particularly for industries looking to streamline operations, reduce planning time, and optimize production processes.

5.5. SWOT ANALYSIS

A SWOT analysis is a strategic framework used to evaluate an organization's internal strengths and weaknesses while identifying external opportunities and threats. This analysis helps decision-makers understand the key factors influencing their operations and develop strategies to enhance growth, mitigate risks, and maintain a competitive advantage. In this case, the SWOT analysis (Figure 5) is specifically conducted to assess the adaptability and effectiveness of the digital tools provided by BBTWINS in the examined use cases. By analyzing these factors, we can determine how well BBTWINS' digital solutions integrate within the industry, identify potential challenges in implementation, and uncover new opportunities for optimization and scalability. By leveraging strengths and opportunities while addressing weaknesses and mitigating threats, this analysis provides a roadmap for enhancing the adoption, efficiency, and long-term success of BBTWINS' digital innovations in the targeted sectors.

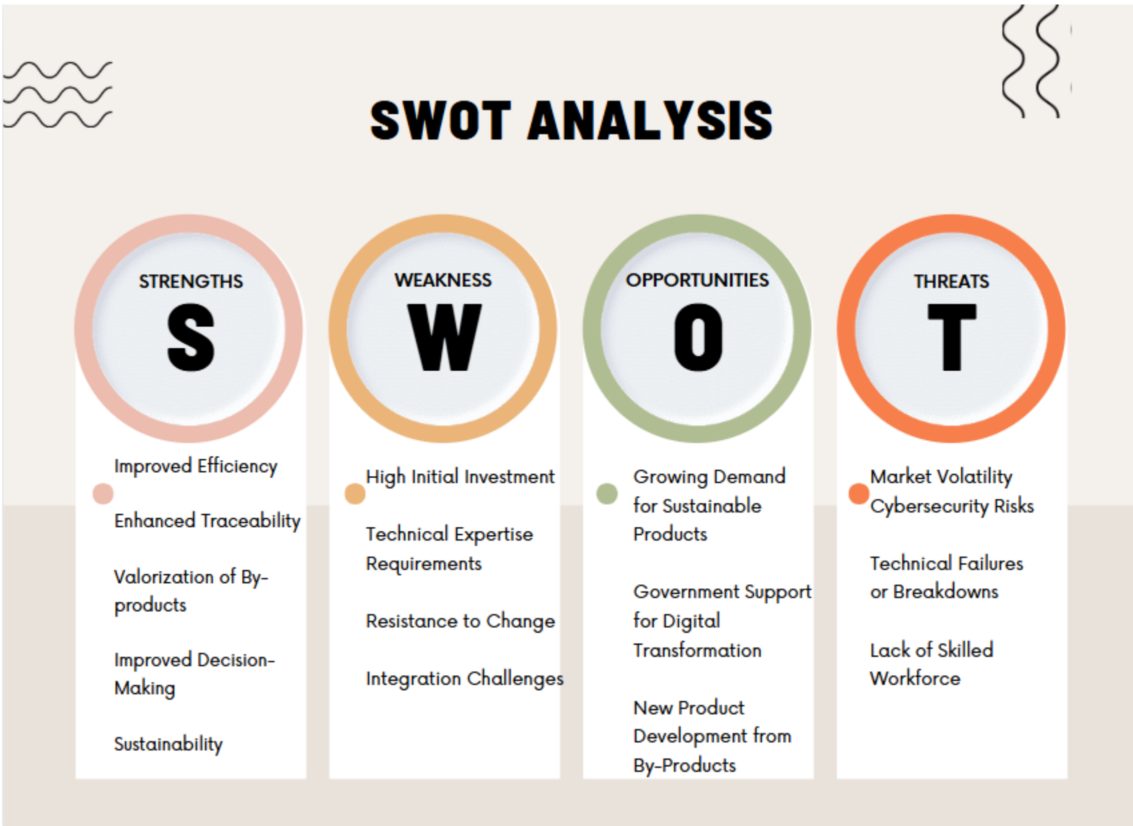

Figure 5: SWOT Analysis

The Strengths represent the key internal capabilities and advantages that set the organization apart and contribute to its success. These strengths may include a highly skilled team, extensive industry experience, cutting-edge technology, a strong brand reputation, financial stability, high customer satisfaction, and efficient operational processes. These factors create a competitive edge, enabling the organization to optimize productivity, enhance decision-making, and maintain customer trust. By leveraging these strengths, the organization can improve its market position, attract new customers, and build long-term resilience. For example, a strong brand reputation combined with high customer satisfaction can lead to increased customer loyalty and positive word-of-mouth marketing. Similarly, technological advancements and financial strength can drive further innovation and expansion. The key to maximizing strengths lies in strategically utilizing them to support growth initiatives, enter new markets, and continuously improve operations.

Table 6: Strengths and implementation plan

Strength	Action Plan
Improved Efficiency	Develop case studies and pilot projects to demonstrate the impact of digital twins on efficiency Provide training and technical support to help producers optimize BBTWINS tools.
Enhanced Traceability	Promote blockchain-based transparency as a market differentiator to attract premium buyers.

	Partner with regulatory bodies to ensure seamless compliance with traceability laws.
Valorization of By-products	Develop business models that leverage OMW for bioenergy, cosmetics, and fertilizers. Engage R&D initiatives to enhance product diversification.
Improved Decision-Making	Use data-driven predictive analytics to assist farmers with precision agriculture.
Sustainability	Partner with certification bodies to obtain eco-labels and sustainability certifications. Develop marketing campaigns focused on sustainability.

The Weaknesses highlight internal limitations that could potentially hinder the organization's performance, efficiency, or growth. These weaknesses might include high upfront investment costs, a lack of technical expertise, inefficient internal processes, dependency on key suppliers, limited financial resources, or resistance to adopting new technologies. If left unaddressed, these weaknesses could create bottlenecks in productivity, slow down decision-making, and reduce overall competitiveness. For instance, if a company relies heavily on a single supplier, any disruption in the supply chain could lead to production delays and increased costs. Similarly, a fragmented industry or lack of technical expertise could make it difficult to implement digital transformation strategies effectively. Addressing these weaknesses requires proactive planning, such as investing in employee training programs, streamlining operations, diversifying suppliers, and implementing change management initiatives to increase adaptability. Mitigation strategies should also focus on financial planning to reduce the impact of high investment costs and integrating scalable technologies that align with the company's long-term vision. Recognizing and improving upon these weaknesses is essential to ensure sustainable growth and operational stability.

Table 7: Weaknesses and Mitigation Strategies

Weaknesses	Mitigation Strategies
High initial investment	Seek government subsidies and investment partnerships
Technical expertise requirements	Provide extensive training programs and easy-to-use interfaces
Fragmented industry	Engage industry groups and cooperatives for shared solutions
Resistance to change	Showcase successful case studies to encourage adoption
Integration challenges	Develop phased integration plans to reduce disruptions
Need for skills development	Offer vocational training to upskill the workforce
Inefficient operational processes	Implement lean management techniques to improve efficiency
Dependency on a single supplier	Diversify supplier base to reduce dependency risk
Financial management challenges	Enhance financial planning and seek alternative funding sources

The Opportunities identify external factors that the organization can leverage to enhance its market position, increase revenue, and stay ahead of industry trends. These opportunities often arise from changing market demands, new technological innovations, strategic partnership possibilities, emerging industry trends, favorable regulatory changes, and expansion into new geographical markets. For example, the growing global demand for sustainable products presents an opportunity for organizations to position themselves as leaders in environmentally friendly solutions. Companies that adopt eco-friendly practices, obtain sustainability certifications, or use digital tools to enhance traceability can gain a competitive advantage. Likewise, favorable regulatory changes, such as government incentives for digital transformation, can be used to secure funding for modernization projects. To capitalize on these opportunities, organizations should actively monitor market trends, build strategic alliances with key industry players, and invest in research and development. Exploring new business models—such as using by-products for alternative revenue streams or expanding into premium markets—can further strengthen market positioning. A clear and actionable plan for leveraging opportunities ensures long-term success and resilience.

Table 8: Opportunities and implementation plan

Opportunities	Action Plan
Growing demand for sustainable products	Develop marketing campaigns emphasizing sustainability
Potential market expansion	Target new geographical markets for expansion
Evolving consumer needs	Adapt product offerings to align with consumer trends
New industry trends	Stay ahead by investing in emerging technologies
Leadership positioning opportunity	Position as an industry leader through advocacy and branding
Strategic partnership possibilities	Form partnerships with key industry players for mutual benefits
Favorable regulatory changes	Leverage regulatory changes to gain competitive advantages

The Threats examine external risks and challenges that could negatively impact the organization's growth, stability, and competitive advantage. These threats may include increasing competition, new market entrants, economic instability, evolving technology, cybersecurity risks, regulatory constraints, and supply chain disruptions. For example, if competitors are rapidly adopting new technologies or expanding into the same market, the organization risks losing market share unless it continuously innovates and differentiates its offerings. Additionally, economic downturns can affect consumer purchasing power, making it necessary for businesses to develop adaptive pricing strategies. Cybersecurity threats are also a growing concern, particularly as digital transformation increases data exposure to cyberattacks. Investing in robust cybersecurity measures, regular risk assessments, and compliance with industry regulations is crucial to protecting sensitive business information. Supply chain vulnerabilities—such as dependencies on a single supplier, raw material shortages, or geopolitical disruptions—can also pose serious risks. Companies should diversify their supplier network and establish contingency plans to prevent operational disruptions. To mitigate these risks, organizations should implement proactive risk management strategies, conduct regular market analysis, build financial buffers, and continuously innovate to stay ahead of evolving challenges. Staying adaptable and resilient will help the organization navigate uncertainties while maintaining a strong market position.

Table 9: Threats and Mitigation Strategies

Threats	Mitigation Strategies
New market entrants	Continuously innovate and improve product offerings
Increasing competition	Enhance competitive intelligence to stay ahead
Economic instability	Develop contingency plans for economic downturns
Evolving technology	Invest in R&D to keep up with technological advancements
Regulatory restrictions	Ensure compliance and proactively adapt to regulations
Cybersecurity risks	Implement robust cybersecurity measures
Supply chain vulnerabilities	Strengthen supply chain diversification and resilience

6. Scalability and Future Applications

The BBTWINS project has demonstrated the potential of digital twins, Data-driven analytics, sensorization, and blockchain traceability in optimizing agri-food value chain processes. However, for these innovations to generate a lasting impact, they must be scalable, adaptable to different subsectors, and expandable to international markets. The replication and expansion of BBTWINS solutions require a structured approach to ensure seamless integration into diverse agricultural and industrial contexts. This section outlines the framework for expansion and adaptability, explores international scaling potential, and highlights the future applications of BBTWINS across different industries.

6.1. Framework for Expansion and Adaptability

The scalability of BBTWINS is rooted in its modular architecture, allowing for flexibility in different operational environments. The project's digital twin models, blockchain-enabled traceability, and Data-driven decision support systems have been designed to accommodate a wide range of agricultural and food-processing industries. To facilitate expansion, BBTWINS follows three core principles:

1. Technological Adaptability: The BBTWINS platform is designed to be customizable for different agricultural sectors, ensuring that digital twin models and algorithms can be adapted to various value chains. For example, the sensorization and data analytics currently used for pig farming can be tailored for livestock management in dairy farms, while the blockchain traceability solution applied to fruit processing can be extended to organic food supply chains. This adaptability enables seamless deployment in new environments without requiring major modifications to the core technology.

2. Interoperability and Integration: To ensure smooth adoption, BBTWINS technologies are developed with open data standards and are designed to integrate seamlessly with existing IT infrastructures, enterprise resource planning (ERP) systems, and sensor networks. Many agricultural businesses operate legacy systems that may not easily support new digital solutions. To overcome this barrier, BBTWINS promotes compatibility with commonly used platforms, making it easier for businesses to transition towards data-driven decision-making without overhauling their existing workflows.

3. User-Centric Deployment and Training: Digital transformation in agriculture requires capacity building and workforce adaptation. Many stakeholders, particularly small and medium-sized enterprises (SMEs) and individual farmers, may lack the necessary digital skills to fully utilize advanced analytics and digital twins. To address this challenge, BBTWINS includes comprehensive training modules, ensuring that all users—

farmers, cooperatives, agribusinesses, and policymakers—are equipped with the knowledge needed to integrate the solutions effectively.

The expansion framework is structured to support technology transfer across subsectors while ensuring scalability and ease of adoption. By maintaining flexibility, ensuring interoperability, and prioritizing user training, BBTWINS creates an ecosystem where digital solutions can be adapted and expanded efficiently across different agricultural and food-processing industries.

6.2. International Scaling Potential

Beyond its initial applications in Spain and Greece, BBTWINS aims to expand internationally by building on EU regulatory frameworks, cross-border collaborations, and market-driven adaptation strategies. The international scalability plan focuses on the following key areas:

1. Leveraging Cross-Border Collaboration: The European Union provides an ideal platform for international scalability due to its harmonized food safety, traceability, and sustainability regulations. BBTWINS is actively engaging with agricultural cooperatives, research institutions, and industry partners in other EU countries to expand its impact. Additionally, the project is aligned with EU-funded initiatives supporting digital transformation in agriculture, making it well-positioned for further funding and collaboration opportunities.

2. Market-Specific Customization: Each agricultural sector operates under unique environmental, economic, and regulatory conditions. For international expansion to be successful, BBTWINS will tailor its digital tools to match regional needs. For example, while in Southern Europe, the focus may be on olive oil production and precision irrigation, in Northern Europe, the emphasis may shift to dairy farm management and cold chain logistics for perishable foods. By conducting regional feasibility studies, BBTWINS ensures that each implementation is contextually relevant and industry-specific.

3. Economic Feasibility and ROI Assessments: To encourage widespread adoption, BBTWINS will conduct detailed economic feasibility studies in new markets. These studies will focus on factors such as:
    - Cost of implementation versus long-term savings
    - Operational efficiency improvements achieved through automation and Data-driven optimization
    - Regulatory benefits related to food traceability and sustainability compliance
    - Environmental impact reductions, including energy and resource savings

By demonstrating clear return on investment (ROI), these assessments will lower financial barriers to adoption and help industry stakeholders make informed decisions about integrating BBTWINS solutions into their operations.

4. Strategic Public-Private Partnerships: Scaling BBTWINS technologies internationally requires cooperation with policymakers, financial institutions, and industry leaders. Public-private partnerships (PPPs) will be crucial in securing funding for pilot programs, developing digital infrastructure, and ensuring regulatory

compliance in different countries. Additionally, collaboration with international agritech companies and digital innovation hubs will accelerate market penetration and technological deployment.

By strategically addressing cross-border collaboration, market-specific adaptation, economic feasibility, and public-private partnerships, BBTWINS is positioned for successful international expansion, ensuring that its digital solutions drive global transformation in agri-food value chains.

6.3. Future Applications Across Sub-Sectors

While BBTWINS has been implemented in pig farming and fruit production, its core technologies hold vast potential for application in other agri-food sectors and industrial domains. Some of the key future applications include:

1. Forestry and Sustainable Logging: Digital twins can be used to monitor forest health, optimize harvesting schedules, and improve resource management. Data-driven predictive models can help assess forest carbon sequestration potential, ensuring sustainable logging practices.
2. Fisheries and Aquaculture: The seafood industry faces significant challenges in supply chain transparency and sustainability. BBTWINS blockchain technology can enhance traceability in seafood logistics, ensuring compliance with sustainability standards and reducing illegal fishing practices. Data-driven monitoring can optimize feeding schedules, water quality, and fish health in aquaculture settings.
3. Bioenergy and Waste Valorization: The circular economy presents opportunities for transforming agricultural and food waste into biofuels, fertilizers, and high-value bio-based materials. BBTWINS technologies can optimize waste processing plants, predict biogas yields, and improve energy efficiency in bio-based industries.
4. Dairy and Livestock Management: The dairy sector can benefit from BBTWINS digital twins in milk production monitoring, feed optimization, and disease detection. data-driven analytics can help dairy farms optimize energy consumption, automate milking processes, and ensure higher-quality dairy production.
5. Food and Beverage Processing: Data-driven analytics and digital twins can improve efficiency in wine, olive oil, and beverage production, optimizing fermentation, storage conditions, and logistics. Blockchain traceability can be used to verify product authenticity and sustainability claims in premium agri-food products.

By applying BBTWINS technologies across these additional sectors, the project can drive digital transformation, increase sustainability, and enhance efficiency in industries beyond traditional agriculture.

BBTWINS has laid the groundwork for a scalable, adaptable, and globally replicable digital transformation framework in agriculture and related industries. By ensuring technological flexibility, promoting international scalability strategies, and identifying new cross-sector applications, the project is well-positioned to expand its impact and drive sustainable innovation. Future growth will depend on continued partnerships, financial support mechanisms, and ongoing technological refinements, ensuring that BBTWINS remains at the forefront of smart agriculture and industrial digitalization.

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