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► To cite this version:

Manuella Germanos, Sihem Mallek-Daclin, Mariane El Kassis, Oussama Ben-Ammar, Nicolas Daclin, et al.. Farming Success: Using Digital Twin Modeling to Assist Smallholders in Decision-Making. 30th ICE IEEE/ITMC Conference - International Conference on Engineering, Technology, and Innovation (ICE), Jun 2024, Madeira, Portugal, Portugal. 10.13039/501100011033 . hal-04734522

HAL Id: hal-04734522

<https://imt-mines-ales.hal.science/hal-04734522v1>

Submitted on 16 Oct 2024

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Farming Success: Using Digital Twin Modeling to Assist Smallholders in Decision-Making

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Abstract—This paper presents a novel Digital Twin architecture to assist different short-food supply chain actors in decision-making. The digital twin provides real-time monitoring and adjustment capabilities, enabling agile responses to supply chain disruptions. We outline the architecture of the digital twin system and discuss its implementation within the context of the SMALLDERS project. Results indicate this approach’s efficiency and ease of use, which would increase the resilience of the short-food supply chain actors.

Index Terms—Digital twin, agri-food supply chain, supplier selection, order allocation, real-time monitoring

I. INTRODUCTION

The agricultural sector, particularly the short food supply chain, is pivotal in global food production and supply chain dynamics. Smallholder farmers constitute a significant portion of the agricultural workforce worldwide, contributing substantially to local economies and food security. However, they often face numerous challenges, including limited market access, financial resources, and technological advancements. In recent years, efforts have been made to address these challenges through various initiatives and projects to enhance smallholder farming systems’ efficiency, sustainability, and resilience.

The SMALLDERS (Smart Models for Agrifood Local vaLue chain based on Digital technologies for Enabling

COVID-19 Resilience and Sustainability) [1] project represents one such initiative to empower smallholder farmers. This collaborative project involves multiple partners with agriculture, information technology, and business management expertise. The project is a collaborative effort encompassing a diverse array of esteemed academic institutions such as the University of Calabria, the University of Parma’s Future Technology Lab, the University of Extremadura, IMT Mines Alès’ Laboratoire des Sciences des Risques, and the University of Tunis El Manar’s Laboratory of Energy Efficiency Applications and Renewable Energies, each contributing unique expertise and resources towards the project’s innovative endeavors. It covers various geographical areas, focusing on regions where smallholder farming is predominant. The project involves diverse partners, including research institutions, agricultural cooperatives, technology providers, and local farmer associations. This multidisciplinary approach ensures that the solutions developed are comprehensive and tailored to the specific needs of smallholder farmers.

The motivation for the SMALLDERS project lies in addressing the specific and significant challenges faced by smallholder farmers in the context of the COVID-19 pandemic and beyond. Critical to global food security, smallholder farmers often lack access to digital tools and technologies that can enhance their productivity, sustainability, and resilience [2], [3]. The pandemic has exacerbated these vulnerabilities, making it even more crucial to develop solutions that can support these farmers in navigating the increased uncertainty and disruptions in the supply chain. The SMALLDERS project aims to fill this

The authors acknowledge the grant *PCI2022*₁₃₂₉₂₄ funded by MCIN/AEI/ 10.13039/501100011033 and by the “European Union NextGenerationEU/PRTR”.

gap by leveraging digital technologies to provide smallholder farmers with the necessary tools to improve their agricultural practices and supply chain management.

By integrating digital technologies, business process optimization, and sustainable agricultural practices, the project brings together researchers, practitioners, and stakeholders from diverse fields such as agriculture, information technology, and business management to develop innovative solutions tailored to smallholder farming communities' specific needs and contexts. The project has involved over 200 smallholder farmers in its test and validation phases, ensuring that the developed solutions are practical, user-friendly, and effective in real-world conditions.

At its core, the SMALLDERS project aims to enhance the digital capabilities of smallholder farmers, optimize agricultural supply chains, and promote sustainable business models. Through innovative technologies, smallholder farmers can access valuable information and resources, assisting them in making informed decisions, improving productivity, and mitigating risks. Moreover, by leveraging optimization models and simulation techniques, stakeholders involved in agricultural supply chains can optimize resource allocation, reduce inefficiencies, and enhance overall performance.

This paper presents the research work conducted as part of the SMALLDERS project, focusing on three key components:

- 1) A methodology for business process simulation,
- 2) Optimization models for agricultural supply chain management and
- 3) The development of a digital twin for smallholder farming systems.

We provide an overview of each component, highlighting its significance, objectives, methodologies, and expected contributions to the broader goals of the SMALLDERS project. Additionally, we discuss the current state of research in relevant domains, identify existing gaps and challenges, and propose novel approaches and methodologies to address them.

The paper is organized as follows: Section II presents the background. Section III presents the problem statement, Section IV presents the proposed approach, and Section V presents the architecture for business process simulation, including transforming BPMN (Business Process Model and Notation) models into simulation models using DEVS (Discrete Event System Specification). It introduces optimization models for agricultural supply chain management, focusing on supplier selection, order allocation, and inventory management. Section VI discusses the development of a digital twin (DT) for smallholder farming systems, outlining its architecture, components, and functionalities, and Section VII specifies different case studies. Finally, Section VIII concludes the paper with a summary of key findings, implications for practice and research, and suggestions for future work.

II. BACKGROUND

The agricultural sector is vital to the global economy, providing food, employment, and livelihoods to billions of people worldwide. Smallholder farming plays a crucial role

within this sector, particularly in developing countries, where it is the primary source of income and sustenance for millions of rural households. Smallholder farmers, typically operating on small plots of land with limited resources and technology, face numerous challenges that hinder their productivity, profitability, and resilience.

Furthermore, smallholder farmers are vulnerable to various environmental and climatic risks, including droughts, floods, pests, and diseases, which can significantly impact crop yields and livelihoods [4]. Climate change aggravates these risks, leading to more frequent and severe weather events that threaten agricultural production and food security.

In recent years, there has been growing recognition of the importance of digital technologies in transforming agriculture and empowering smallholder farmers. Digital innovations, such as mobile applications, sensor networks, and data analytics platforms, can potentially revolutionize agricultural practices [5], [6]. These technologies enable smallholders to access real-time information on weather forecasts, market prices, agronomic practices, and pest management strategies, empowering them to make informed decisions and optimize resource use. Additionally, digital platforms and e-commerce marketplaces connect smallholders directly with buyers, eliminating intermediaries and enabling fairer prices for their produce.

Despite digital technologies' potential benefits, smallholder farmers still face significant barriers to their adoption and use. These include limited access to affordable and reliable internet connectivity, low digital literacy rates, and data privacy and security concerns. Moreover, the digital divide between urban and rural areas exacerbates inequalities and hinders the equitable distribution of benefits from digitalization.

In response to these challenges, various initiatives and projects have been launched to promote the adoption of digital technologies in agriculture and support smallholder farmers in harnessing their potential [7]–[9].

III. PROBLEM STATEMENT

Smallholder farmers face various challenges that hinder their productivity, profitability, and resilience and ultimately threaten their livelihoods. These challenges stem from various factors, including limited access to markets, financial services, information, and resources and vulnerability to environmental and climatic risks.

Smallholders are particularly vulnerable to environmental and climatic risks, which can devastate crop yields, livelihoods, and food security. Additionally, environmental degradation, soil erosion, deforestation, and water scarcity also threaten smallholder agriculture's sustainability, compromising its long-term viability and resilience.

Smallholders' challenges are complex and interconnected, requiring holistic and integrated solutions that address multiple dimensions of vulnerability and resilience. Moreover, smallholder farming systems are characterized by diversity in crops, climates, soils, and socio-economic contexts, making it challenging to develop one-size-fits-all solutions.

Thus, empowering smallholder farmers through innovative, scalable solutions is crucial for sustainable development and resilience. By leveraging digital technologies, sustainable agricultural practices, and participatory approaches, we can address the underlying drivers of vulnerability and create opportunities for smallholder farmers to thrive in a changing climate and globalized economy.

IV. PROPOSED APPROACH

The proposed approach of the SMALLDERS project encompasses a multifaceted strategy that combines technological innovation and stakeholder collaboration to address the complex challenges facing smallholder farmers and enhance their resilience. Integrating digital technologies and sustainable agricultural practices is central to this work to empower smallholders, improve their livelihoods, and foster sustainable development.

By leveraging the power of digital technologies, the project proposes developing tailored solutions to enhance smallholder farmers' access to information and decision-support tools. These solutions include mobile applications, agricultural sensors, and blockchain-based platforms providing farmers with real-time data and personalized recommendations. By harnessing the potential of predictive analytics, smallholders can make more informed decisions, optimize resource use, and mitigate risks associated with weather variability and market fluctuations.

The transformation from BPMN to DEVS is a critical aspect of this approach. The transformation process is semi-automated, involving both automated tools and manual adjustments to ensure accuracy and relevance. Initially developed through participatory workshops with farmers and stakeholders, BPMN models are then converted into DEVS models to enable detailed simulation and analysis. This approach ensures that the models are both user-friendly and technically robust, allowing for effective decision support without requiring extensive technical expertise from the users.

In summary, the proposed approach offers an integrated framework for addressing smallholder farmers' multifaceted challenges and enhancing their resilience to environmental, economic, and social pressures. By combining digital solutions, capacity building, policy support, and stakeholder collaboration, we can unlock the potential of smallholder agriculture to drive inclusive and sustainable development, improve food security, and build resilient communities.

V. ARCHITECTURE OF THE DIGITAL SYSTEM

The proposed platform is a sophisticated framework for monitoring, analyzing, and optimizing agricultural processes. It's built on principles of cyber-physical systems, data-driven decision-making, and simulation-based modeling, comprising interconnected layers and components. The implementation of the digital twin within the SMALLDERS project encompasses the following steps:

- 1) **Data Collection and Integration:** Gathering data from various sources, including sensors, weather stations,

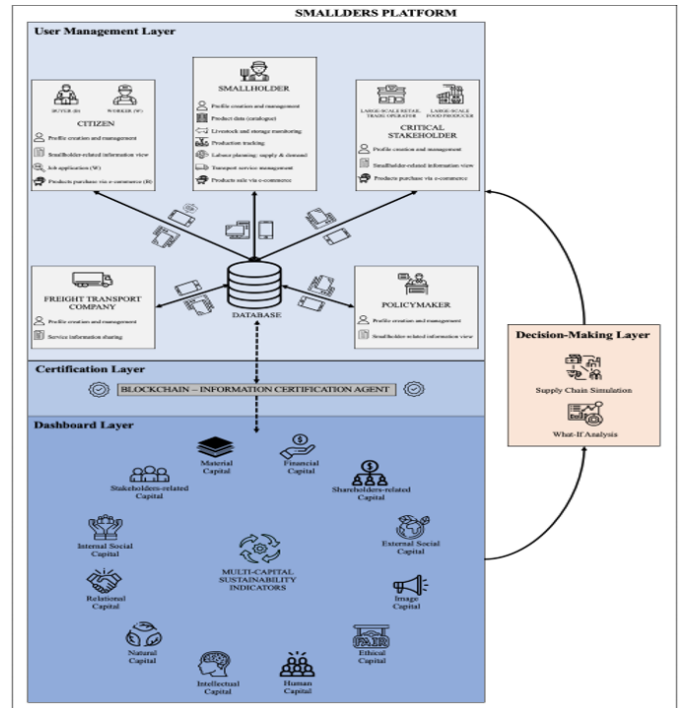


Fig. 1. SMALLDERS Platform

market databases, and stakeholders. This involves developing interfaces and APIs to facilitate seamless data exchange and integration across the system.

- 2) **Model Development and Calibration:** Creating mathematical models and simulation frameworks representing the different aspects of the agricultural system. These models are calibrated using historical data and validated through field trials and stakeholder feedback.
- 3) **Platform Development:** Building the digital twin platform, including the user interface, data processing algorithms, and analytical tools. This involves leveraging cloud computing infrastructure, data storage solutions, and software development frameworks to ensure scalability, reliability, and performance.
- 4) **Stakeholder Engagement and Training:** Conducting workshops, training sessions, and capacity-building activities to engage stakeholders in developing and using the digital twin platform. This ensures that the platform is user-friendly, meets the needs of different user groups, and fosters collaborative decision-making.
- 5) **Pilot Testing and Evaluation:** Implementing pilot projects to test and evaluate the digital twin platform in real-world settings. This involves monitoring the platform's performance, gathering user feedback, and making iterative improvements based on the findings.

Additionally, the implementation considers key performance indicators (KPIs) to evaluate the impact of the digital twin on smallholder farmers. These KPIs include productivity improvements, cost savings, reduction in resource use, and farmer satisfaction. The project aims to demonstrate the tangible

benefits of digital twin solutions for smallholder farmers by measuring these indicators.

The SMALLDERS project aims to develop a robust and scalable digital twin platform that significantly enhances smallholder farming systems' resilience, productivity, and sustainability by adhering to this implementation plan. The platform is designed as a web-based solution, ensuring accessibility for farmers through internet-enabled devices. This accessibility is crucial for smallholder farmers with limited technical resources, enabling them to benefit from the system's capabilities. The platform features a user-friendly interface and comprehensive training materials intended to minimize the need for ongoing technical support. This empowers farmers to independently utilize the tools once they are acquainted with the system.

In summary, the platform's architecture offers a robust, scalable, and adaptive framework for real-time monitoring, analysis, and optimization of agricultural business processes. The platform empowers stakeholders to boost productivity, resilience, and sustainability throughout the agricultural value chain by incorporating data-driven insights, advanced modeling techniques, and decision-support tools. This, in turn, will drive inclusive and sustainable development outcomes, ensuring that smallholder farmers can thrive in an increasingly complex and competitive agricultural landscape.

VI. IMPLEMENTATION OF THE DIGITAL TWIN IN THE SMALLDERS PROJECT

As part of the platform, implementing the Digital Twin system within the SMALLDERS project represents a convergence of cutting-edge M&S technologies, domain expertise models, and stakeholder engagement to address the challenges smallholder farmers face in low-resource settings. The implementation process of the digital twin unfolds in iterative stages in the Modeling and Simulation layer. As described in figure 2, it proposes a build time phase that supports the description of the process models. Then, the system processes will be digitally orchestrated, enhancing forecasting functionality and maximizing anticipation across the agricultural value chain.

A. Co-design and Stakeholder Engagement

Central to the implementation strategy is the active involvement of stakeholders, including smallholder farmers, agronomists, extension workers, policymakers, and technology providers, in designing, developing, and deploying the Digital Twin system. Through workshops, focus group discussions, and participatory design sessions, stakeholders collaborate to identify key requirements, articulate use cases (as described in the section VII), and prioritize features that align with the needs and priorities of end-users. By fostering a sense of ownership, co-creation, and inclusivity, the co-design process ensures that the Digital Twin system is contextually relevant and user-centric, thereby enhancing its usability, acceptability, and sustainability in real-world settings.

B. Technology Infrastructure

The implementation of the Digital Twin system is underpinned by a robust and scalable technology infrastructure that supports data collection both at build time and run time, processing, analysis, and visualization in a distributed and heterogeneous environment. Leveraging cloud computing resources and IoT-enabled sensors, the technology stack provides the computational power, storage capacity, and connectivity required to handle large volumes of data in real-time. It allows to run process simulation and operational research computation. By adopting open-source software frameworks such as Fiware [10], BPMN Modeling, DEVS simulation, containerization technologies, and modular architecture, the technology infrastructure ensures flexibility, interoperability, and scalability, enabling seamless integration with existing IT systems and platforms.

C. Data Acquisition and Integration

A key focus of the implementation process is the development of data acquisition and integration pipelines that facilitate the seamless flow of data from disparate sources to the Digital Twin system [11]. Leveraging standards-based protocols, API integration, and data exchange formats, these pipelines enable the ingestion, transformation, and normalization of data from IoT sensors, weather databases, market platforms, and farmer management systems. By automating data collection, cleansing, and enrichment processes, the data acquisition and integration pipelines ensure the availability of high-quality, reliable, and up-to-date data for analysis and modeling, thereby enhancing the accuracy and robustness of the Digital Twin system.

D. Model Development and Simulation

Another critical aspect of the implementation process is the development of simulation and optimization algorithms that underpin the Digital Twin system. Drawing on domain knowledge, historical data, and expert judgment. Through iterative model training, validation, and refinement cycles, stakeholders collaborate to calibrate model parameters, validate model outputs against ground truth data, and assess model performance under different scenarios and conditions. By incorporating feedback loops, adaptive learning mechanisms, and uncertainty quantification techniques, the model development process ensures that the Digital Twin system delivers accurate, reliable, and actionable insights to end-users, thereby enhancing their capacity to make informed decisions and adapt to changing conditions.

We detail here the methodology for business process simulation, including the transformation of BPMN (Business Process Model and Notation) models [12] into simulation models using DEVS (Discrete Event System Specification).

Business Process Simulation involves representing real-world business processes in a computer-based model to analyze and optimize performance. The methodology includes process modeling, data collection, simulation design, experimentation, and analysis. This methodology will focus on

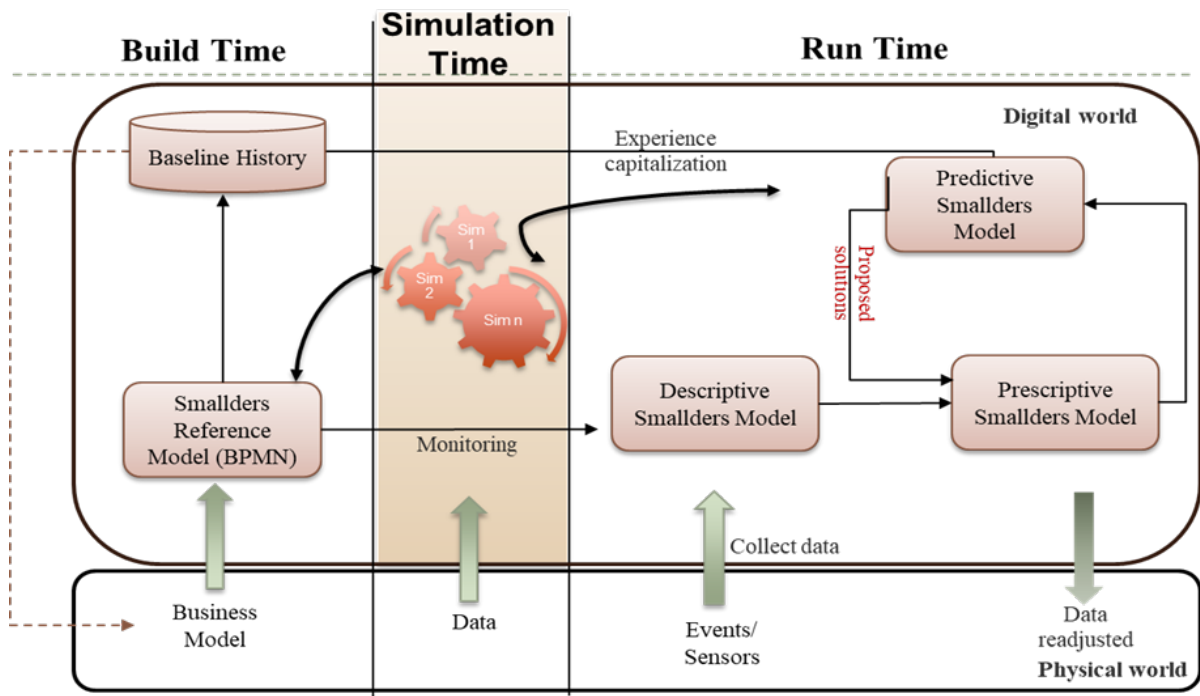


Fig. 2. Digital Twin for Process Modeling & Simulation

transforming BPMN models into simulation models using the DEVS formalism.

1) *Business Process Modeling*: The first step in the methodology is to model the target business process using BPMN (Business Process Modeling and Notation) [13], a widely accepted standard for process modeling. BPMN provides a graphical notation for the activities, events, gateways, and flows that constitute a business process. During this phase, stakeholders collaborate to define the process's scope, objectives, and requirements and map out its activities and interactions.

2) *BPMN to DEVS Transformation*: Once the BPMN model is developed, it is transformed into a simulation model using the DEVS formalism. DEVS (Discrete Event System Specification) [14] is a formal modeling framework for representing and simulating discrete event systems. The transformation involves mapping BPMN elements (activities, gateways, events) to corresponding DEVS constructs (atomic models, triggering conditions, timing constraints), such as atomic and coupled models, states, transitions, and events. All these implementations can be found in [15].

3) *Simulation Design and Experimentation*: Once the BPMN model is transformed into a DEVS simulation model, the next step is to design simulation experiments to evaluate the performance of the business process under different scenarios and conditions. This involves defining simulation parameters, input data sets, performance metrics, simulation controls, and experimental designs.

4) *Simulation Parameters and Inputs*: Simulation parameters include process parameters such as processing times,

resource capacities, queue lengths, and service rates that influence the behavior and performance of the business process. Input data sets represent the initial conditions, input events, and external factors that drive the execution of the business process simulation. These data sets may include demand patterns, arrival rates, order quantities, production schedules, and other relevant variables.

5) *Performance Metrics and Analysis*: Since the proposed Digital Twin would encompass multiple models, each with different objectives, there is a need to define the Key Performance Indicators (KPIs) that will be needed. According to [16], these KPIs would help the models know which solutions offer the best improvement in the area of interest. Correct evaluation of the solutions would help implement the best decisions. The KPIs can be divided into two main categories:

- **Socio-Environmental KPIs**: These KPIs can either focus on minimizing the impact of the supply chain on the environment or consider social factors. For example, one KPI is the amount of water a product would need to grow. The optimization model described in Section VI-E1 attempts to minimize the amount of water used in the farming schedules it generates. Another KPI used by the same model is the hours of labor needed to grow a product. The model attempts to minimize these hours as some areas suffer from scarcity of the agricultural labor force.
- **Economical KPIs**: These KPIs focus on minimizing the costs and maximizing the profits for the different actors of the short food supply chain. For example, the optimization model proposed in Section VI-E2 attempts to

minimize the storage and ordering costs for the retailer while maximizing their profit.

E. Model Validation and Verification

Before conducting simulation experiments, the DEVS simulation model undergoes validation and verification to ensure its accuracy, reliability, and validity. Model validation involves comparing the simulation model's behavior and outputs with real-world observations or data to assess its fidelity and representational adequacy. Model verification involves checking the simulation model's correctness and consistency against its specifications and requirements.

Developing optimization models for agricultural supply chain management requires an approach considering various factors such as supplier selection, order allocation, and inventory management. The following outlines these models.

1) *Demand Selection and Optimization Model*: There has been a recent increase in the demand for smallholder products. This comes in part from the increase in demand in general, but it is also due to the shift in interest from mass-produced sustenance to more locally produced ones [17], [18]. With this shift in demand, some smallholders find themselves unable to meet all the client's needs and are obligated to choose which demands to satisfy. We developed a model to solve this demand selection and planning problem to assist the smallholder in this decision. We consider that a farmer can cultivate multiple products, each with different characteristics (unit price, cultivation time, hours of labor, and cost of storage). We aim to help the farmers choose which farming schedule and product suit them best. To do so, we focus on different criteria, such as the profit that a farmer can make from a farming plan, the amount of water they would need for irrigation, and the total time they would need to spend to take care of the crops, which relates to the size of the workforce they would need.

We develop an asexual variant of the NSGA-II genetic algorithm [19] model that will generate multiple farming plans for the smallholder to choose from [20]. The chromosomes represent feasible farming schedules that the smallholder could follow. The model evaluates the fitness of every chromosome by computing the profit it would generate, the total amount of water the farmer would need to irrigate the plants of the schedule, and the total hours of the workforce that the farmer needs to employ to take care of the plants. The solutions are evolved using different mutation operators while keeping track of the F1 front of the solution space. Once the search is complete, the mode returns all the solutions on the F1 front so that the farmer can choose the solution that best fits their capacity.

2) *Supplier Selection and Optimization Model*: On the other hand, the retailers would have to choose which farmer to buy produce from whenever a client places an order. This issue was discussed with "Le Mas des Agriculteurs", an association that works as a retailer between the small-scale farmers of the Gard department in France and possible buyers. In this scenario, "Le Mas des Agriculteurs" must place monthly

orders at the smallholders to meet the client's demands while considering farmers' lead time to plant and cultivate their produce. To do so, this association employs contract farming, which places the orders months in advance to allow the farmers time to plan and meet the order. Therefore, "Le Mas des Agriculteurs" has to start planning the orders early while considering each of the smallholder's varying prices, production capacities, holding costs, and storage capacities while attempting to minimize the purchasing cost of the demands. To aid "Le Mas des Agriculteurs" in particular and any other retailer facing this problem in general, we developed a linear program presented in [21]. This model takes the clients' demand for a given product for the next 12 months and details an ordering schedule for the retailer to instruct them when and from which producer to buy the product. The model takes into consideration the following parameters:

- Dynamic demand: the clients' demand will change across the year.
- Dynamic production capacity: Each smallholder has their own production capacity, which will vary throughout the year and go through some low and high production phases.
- Dynamic unit holding cost: Each smallholder has their own holding cost, which will vary across the year. During high temperatures, the smallholders might increase their holding costs to account for the increase in energy consumption.
- Dynamic storage capacity: Each smallholder has their own inventory, which they manage. Its capacity to store the products ordered by "Le Mas des Agriculteurs" might change across the year depending on which other products he plans to store in his inventory.
- Ordering cost: Each smallholder has their own ordering cost.
- Unit price: Each smallholder has their own unit price for the product.
- Quantity-dependent pricing: Some smallholders discount the product's unit price when large quantities are ordered.

These optimization models can be integrated into a comprehensive decision support system for short-food supply chain management, enabling decision-makers to make informed choices regarding supplier selection, order allocation, and inventory management to improve overall supply chain performance.

F. Sensitivity Analysis and Optimization

Once the simulation model is validated, sensitivity analysis techniques are applied to identify critical factors and parameters significantly influencing process performance and outcomes. Optimization techniques such as simulation-based optimization, genetic algorithms, and gradient descent are used to find optimal solutions and improve process efficiency, resource utilization, and cost-effectiveness.

Simulation models enable scenario planning and decision support by simulating alternative scenarios, what-if analyses, and sensitivity studies to evaluate the potential impact of

strategic decisions, policy changes, and operational improvements on business performance. Decision-makers can use simulation results to assess risks, explore trade-offs, and make informed decisions to achieve their objectives.

G. Continuous Improvement and Adaptation

Finally, the business process simulation methodology emphasizes continuous improvement and adaptation by iteratively refining the simulation model based on feedback, new data, and changing requirements. As the business environment evolves, the simulation model can be updated, extended, or reconfigured to reflect new realities, emerging trends, and evolving challenges, ensuring its relevance and effectiveness over time.

In summary, the business process simulation methodology provides a systematic approach for modeling, analyzing, and optimizing complex business processes using DEVS-based simulation techniques. By combining BPMN modeling with DEVS simulation, organizations can gain valuable insights into their operations, improve decision-making, and drive performance improvement in a dynamic and competitive business landscape.

H. Deployment and Scaling

The deployment of the Digital Twin system is carried out in a phased and incremental manner, starting with pilot deployments in select geographic areas and scaling up gradually to cover larger regions and populations. Leveraging agile development methodologies, DevOps practices, and continuous integration/continuous deployment (CI/CD) pipelines, the deployment process enables rapid iteration, testing, and rollout of new features and enhancements. By establishing partnerships with local communities, agricultural cooperatives, and extension service providers, the deployment team ensures that the Digital Twin system is accessible, inclusive, and sustainable, thereby maximizing its impact on smallholder farmers' livelihoods and resilience.

I. Monitoring and Evaluation

Throughout the implementation process, rigorous monitoring and evaluation mechanisms are implemented to assess the effectiveness, efficiency, and impact of the Digital Twin system on agricultural outcomes and livelihoods. Leveraging a combination of qualitative and quantitative indicators, including crop yields, income levels, adoption rates, and user satisfaction surveys, monitoring and evaluation efforts track progress against predefined targets and benchmarks. By soliciting feedback from end-users, soliciting feedback from end-users and stakeholders, monitoring and evaluation efforts inform iterative refinements to the Digital Twin system, identify best practices, and generate actionable insights for scaling and replication in other contexts and settings.

In summary, implementing the Digital Twin system within the SMALLDERS project represents a collaborative, iterative, and adaptive process aimed at harnessing the power of digital technologies to enhance the resilience and sustainability

of smallholder farming systems. By engaging stakeholders, leveraging cutting-edge technologies, and fostering a culture of learning and innovation, the implementation process seeks to empower smallholder farmers, improve agricultural productivity, and foster inclusive and sustainable development outcomes in low-resource settings.

VII. CASE STUDIES

One primary goal of this work is to assist the short food supply chain actors in decision-making. Therefore, we present a case study for each of the developed models.

A. Case study: Demand Selection

The demand selection model proposed in Section VI-E1 is carried out as follows.

1) *Implementation*: The implementation of the demand selection model within the Digital Twin involved:

- **Data collection**: The farmer would send a list of orders they received, along with the characteristics of each item. Table I shows some examples of this data.
- **Evaluation**: once the data is received, the proposed model will evolve different solutions and compute their KPIs. Once the model is complete, it will output the best solutions that it has found, i.e., those that belonged to the F1 Pareto front.
- **Decision Support**: after computing the solutions, the farmer is presented with all the possibilities that are returned by the model. Based on the farmer's capacities and objectives, they could select the solution that best suits their needs and get the full farming plan. Figure 3 shows an example of a farming plan returned by the model.

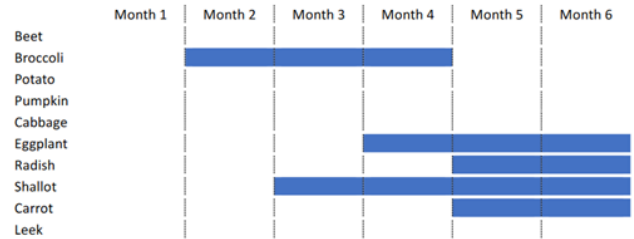


Fig. 3. Example of a generated farming plan.

2) *Results and Benefits*: The demand selection model assists farmers in planning their entire farming schedule with minimal intervention. Additionally, it is a flexible model that accounts for farmers' different needs and limitations and attempts to find the best model for each.

B. Case Study: Supplier selection

The supplier selection model described in Section VI-E2 was applied in the following manner.

TABLE I
LIST OF ITEMS USED AS INPUT TO THE DEMAND SELECTION MODEL

Name	Cultivation period	Land allocation %	Water used (in L)	Hours of labour	Profit (in €)	Cost of storage (in €/month)
Beet	3	45	350	30	125	2
Broccoli	3	30	220	25	187	3
Potato	4	37	300	40	250	2
Pumpkin	4	30	550	42	312	2
Cabbage	3	45	370	28	125	6
Eggplant	3	15	230	31	625	1
Radish	2	22	370	20	187	2
Shallot	4	10	580	44	125	2
Carrot	2	22	420	27	125	2
Leek	5	37	110	51	162	5

1) *Implementation*: The implementation of the supplier selection model within the Digital Twin involved:

- **Data collection**: The retailer would send the demand of their clients along with the list of suppliers they work with and their capacities and prices.
- **Evaluation**: This data received would be passed to the proposed linear program that would compute the optimal time to place orders and their quantities, along with when to store products in inventory. This solution aims to minimize the retailer's costs.
- **Decision Support**: Once the optimal solution is computed, it is returned to the user so that they can plan their orders accordingly.

2) *Results and Benefits*: This model allowed for easy planning for the retailers of the short food supply chain. The model generates a detailed schedule that would facilitate the organization of the orders, inventories, and delivery dates for retailers dealing with multiple suppliers, each with a different pricing and capacity.

VIII. CONCLUSION AND FUTURE DIRECTIONS

In conclusion, the SMALLDERS project presents a comprehensive approach to enhancing smallholder farmers' resilience and productivity by integrating digital technologies and optimization models. The implementation of the digital twin platform, supported by a robust architecture and user-friendly tools, aims to empower smallholder farmers with real-time data and decision-support capabilities. The project's multidisciplinary approach, involving collaboration with various stakeholders and focusing on practical implementation, ensures that the solutions developed are effective and beneficial for the targeted farming communities.

Future work will focus on refining the digital twin platform, expanding its geographical coverage, and enhancing its functionalities based on user feedback and emerging technologies. The ultimate goal is to create a sustainable and scalable solution that can be adopted by smallholder farmers worldwide, contributing to global food security and sustainable agricultural development.

Additionally, the Digital Twin system fosters collaboration of smallholders with supply chain partners by providing a common platform for data sharing, communication,

and decision-making. By breaking down silos and facilitating cross-functional collaboration, organizations can streamline processes, reduce lead times, waste of perishable agro-products and drive value creation throughout the supply chain network.

Looking ahead, several opportunities for future research and development in the field of Digital Twin-enabled supply chain management can be explored:

- 1) **Advanced Analytics and AI**: Continued advancements in analytics, machine learning, and AI technologies hold the potential to enhance the capabilities of Digital Twin systems further [22] and [23]. Future research could focus on developing more sophisticated algorithms for demand forecasting, predictive analytics, and prescriptive decision support to optimize supply chain performance.
- 2) **IoT Integration and Sensor Fusion**: The proliferation of IoT devices and sensor networks presents opportunities to collect real-time data on supply chain operations, such as inventory levels, asset conditions, and environmental parameters [24]. Future research could explore novel approaches for integrating and fusing sensor data within Digital Twin models to improve visibility, traceability, and control.
- 3) **Blockchain and Distributed Ledger Technologies**: Blockchain and distributed ledger technologies offer promising solutions for enhancing transparency, traceability, and trust in supply chain transactions. Future research could investigate the integration of blockchain-based smart contracts and decentralized governance mechanisms within Digital Twin systems to ensure data integrity, security, and compliance [25], [26].
- 4) **Sustainability and Circular Economy**: With growing concerns about environmental sustainability and resource scarcity, there is a pressing need to integrate sustainability principles and circular economy concepts into supply chain management practices. Future research could explore how Digital Twin systems can support sustainable sourcing, green logistics, and circular product lifecycle management to minimize waste and maximize resource efficiency [27].
- 5) **Human-Centric Design and User Experience**: Despite the proliferation of advanced technologies, the success

of Digital Twin implementations ultimately depends on user adoption and engagement. Future research will focus on designing intuitive user interfaces since user requirements [28], interactive visualizations, and personalized decision support tools that empower users to leverage the full potential of Digital Twin systems in their day-to-day operations.

ACKNOWLEDGEMENTS

This work is part of the research project entitled "Smart Models for Agrifood Local vaLue chain based on Digital technologies for Enabling covid-19 Resilience and Sustainability" (SMALLDERS), co-funded by the PRIMA Program - Section 2 Call multi-topics 2021, through the following National Authorities: Ministry of Universities and Research (MUR, Italy), State Research Agency (AEI, Spain), Agence Nationale de la Recherche (ANR, France), Ministry of Higher Education and Scientific Research (Tunisia).

The authors acknowledge the grant PCI2022₁32924 funded by MCIN/AEI/ 10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR".

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