# Smart Bakery: A Digital Twin Framework

**Tsega Y. Melesse[1], Braggio Mattia[1], Federico Briatore[2], Marco Mosca[2], Maria Teresa Pilloni[1], Mohamed Shameer Peer[1], Simone Arena[1], Pier Francesco Orrù[1]**

[1]*Department of Mechanical, Chemical and Material Engineering, University of Cagliari, Via Marengo 2, 09134 Cagliari, Italy (tsegayenew.melesse@unica.it, mattia.braggio@unica.it, mariat.pilloni@unica.it, mohameds.peermohamed@unica.it, simone.arena@unica.it, pierf.orru@unica.it,)*

[2] *Mechanical, Industrial and Transport Engineer Department (D.I.M.E.), University of Genoa, 16126 Genoa, Italy (Federico.Briatore@edu.unige.it, marco.tullio.mosca@unige.it)*

**Abstract**: The integration of digital twin technology with bakery production systems is a key strategy in modernizing traditional food manufacturing techniques. Digital twins are accurate digital models of physical systems or products, always synchronized with real-time data streams from interlinked physical assets. This paper proposes a conceptual framework for embedding digital twin technology in bakery production environments. The framework is built with four interconnected and complementary elements that include a physical product, simulation model, digital twin system, and stakeholder-supported knowledge base. The four elements as a package create an environment that is dynamic and bidirectional, improving the transparency, responsiveness, and efficiency of bakery value chain operations. The physical product includes Internet of Things (IoT) devices that provide real-time input on process variables like temperature, humidity, and gas concentration. This data is then incorporated into a simulation model that predicts production outcomes under different scenarios, thus enabling proactive decision-making. The digital twin integrates real-time process data with simulation output and uses visualization tools and real-time observational capabilities to support management operations. The knowledge base supported by stakeholders guarantees continuous learning and maintains systemic strategic coherence. The integrated system fosters closed-loop decision-making, predictive maintenance, and improved quality while ensuring sustainability and adaptability. The integration of digital intelligence with human expertise equips artisanal as well as industrial bakeries to manage the digital transformation frontier effectively and benefit from smart manufacturing.

**Keywords:** Digital Twin; Industry 4.0; Bakery Operations; Predictive Analytics

## 1. Introduction

The baking industry, traditionally characterized by its artisanal nature and varied production processes, is undergoing a profound technological revolution. This is driven mainly by the compelling need for improved efficiency, higher quality management standards, and greater flexibility (Melesse and Orrù, 2025). Digital development has become a pressing necessity rather than a future aspiration, particularly for those producers who want to enhance the resilience of their businesses to disruptions stemming from global value chains and labor shortages.

The digitalization phenomenon paves the way for developing advanced tools and techniques, summarized under the umbrella of the fourth industrial revolution, also known as Industry 4.0. Of these advances, DT technology is a particularly notable development. A DT is an interactive, virtual representation of a physical system that is synchronized at all times with real-time operational data. This is built on different modeling techniques such as physics-based, agent-based, data-driven, hybrid, and spatial models (Melesse et al., 2024a; Melesse, 2025). Coupling this physical-visual interface allows for simulating operations, predictive control, and better decision-making across the lifecycle of manufacturing. In bakery operations, being subject to intrinsic factors like time, temperature, and humidity, DTs can realistically mimic proofing stages of dough, dough fermentation, baking, and cooling, thus ensuring consistency in terms of quality and eliminating variability (Hassoun et al., 2024; Huang et al., 2024; Zhao et al., 2025).

The benefits offered by DTs in the bakery industry are based on their ability to combine information from connected sensors, simulation equipment, and human input. The integration allows real-time control, prediction of future scenarios, and adjustment of operational procedures. Bakeries can use these features to mimic different operating conditions, determine optimal process parameters, and respond quickly to variations in raw material availability or equipment failures, all with decreased downtime and preserved energy (Abdurrahman and Ferrari, 2025).

The research introduces an original conceptual framework meant to cater to the unique characteristics and needs of bakery production systems. In contrast with hierarchical structures, the proposed model utilizes a bidirectional and integrated framework that encourages two-way feedback among physical products, simulation environments, real-time monitoring systems, and stakeholders' input. The integration with digital and human intelligence is meant to

increase transparency, traceability, and responsiveness in decision-making. Unlike many existing DT implementations that focus on large-scale automated environments or narrow production aspects, the proposed framework integrates artisanal production variability, real-time decision support, and stakeholder-informed learning. Its modular scalability and bidirectional structure allow it to serve both small-scale and industrial bakeries, distinguishing it from conventional, top-down DT models commonly seen in manufacturing.
It is expected that this research will yield significant insights that will find use in both academic research and industrial practice by developing this framework and incorporating it into the larger context of digital manufacturing breakthroughs. The research offers a rational and practical approach for bakeries to embrace digitalization through DT technology to enhance operating efficiency, product quality, and sustainability performance.

## 2. Overview of Digital Twin Applications in the Food Industry

The development of DT technology in the food industry is moving at a fast pace driven by the need for greater operational agility, increased efficiency, and compliance with more stringent food safety requirements. Its early adoption by the meat, dairy, and brewing industries has shown the high value that DTs bring through better traceability, process optimization for improved quality control, and significant waste reduction (Melesse et al., 2022b, 2022a; Zhang et al., 2024).
Essentially, DT functionality makes it possible to create a virtual counterpart that is in real-time synchronization with physical assets, thus having a dynamic model reflecting actual operational performance. This forms the basis for advanced simulation, monitoring, and predictive analysis under industrial operations (Kannapinn et al., 2022; Subahi, 2024; Valero et al., 2023). For industrial food production, DTs act as unobtrusive monitors, with real-time feedback without disruption to the production process (Bottani et al., 2020; Hu and You, 2024). This real-time feedback leads to agile decision-making and encourages continuous process optimization.
The latest developments in digital technology in bakery processes have enabled the development of simulation models that mimic intricate physical processes, such as bread fermentation, dough rheology, and crust formation during baking (Lodi et al., 2021; Purlis, 2012). These simulation models are increasingly being integrated with machine learning algorithms, physics-based modeling, and sensor-derived data, allowing firms to predict results, model new recipe developments, and adjust operational parameters, while ensuring the ongoing operation of real production lines (Krupitzer and Noack, 2022).
The functioning of such advanced functionalities is built on a range of key technologies, including the IoT (Fu et al., 2024), robust wireless communication networks (Meyer et al., 2023), and advanced data analytics, strongly supported by artificial intelligence (AI) (Briatore et al., 2025a), blockchain, and edge computing (Briatore and Braggio, 2025; Guidani et al., 2024; Karadeniz et al., 2019). Such technologies, as a group, support real-time decision-making capabilities and enhance system responsiveness, even in the stringently regulated area of food production (Germanos et al., 2024; Kharchenko et al., 2020; Tasic and Cano, 2024).
Figure 1 shows the four building blocks that make up a DT system in the case of a smart bakery: real-time data collection and integration, simulation and modeling, optimization and predictive analytics, and collaboration between people, processes, and technology. The first building block highlights the need for ongoing data collection from sensors and stock management systems, which provide the vital real-time data necessary for efficient control and surveillance. Then, the data are processed by simulation and modeling software that mimics important scenarios in the bakery, for example, changes in baking time or temperature, thereby allowing predictive assessments and simulated tests of operation strategies.
The third aspect, optimization, and predictive analytics, utilizes advanced data analytical methods to detect inefficiencies, predict equipment failure, and enable improvements in performance in the course of manufacturing. In addition, the inclusion of human resources, business processes, and technological innovations ensures that human knowledge and business practices are in step with technological advancements. This socio-technical vision fosters flexibility, competency, and continuous digital advancement. Together, the components form a unified DT system allowing bakeries to operate in ever-more efficient, responsive, and sustainable ways.

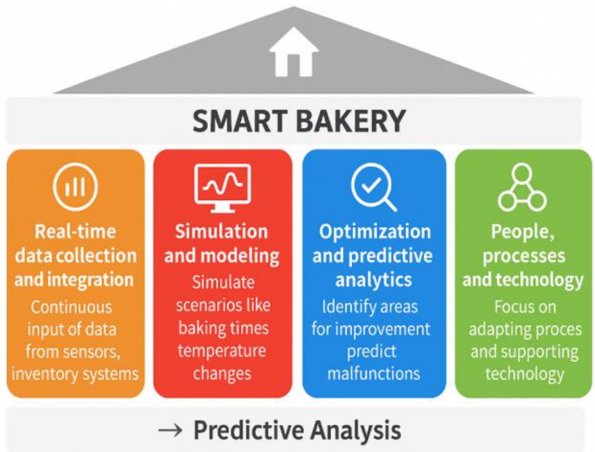


**Figure 1. Core pillars of a digital twin in a bakery**

By accurately tracking production workflows, DTs help create sustainable supply chains reducing operational costs, improving profitability for producers, and lessening environmental footprints, while also offering consumers fresher and healthier products (Vilas-Boas et al., 2023). The need for such technologies is also compounded by global challenges like climate change (Guruswamy et al., 2022), decreased biodiversity, and pollution (Hassoun et al., 2024), making digital transformation an indispensable means for building resilience.
Modern-day bakeries are faced with growing needs to produce an ever-increasing variety of goods that require short lead times, personalized functionality, and low-cost production while meeting sustainability goals. In this context, the use of AI-based DTs is becoming progressively mainstream for real-time detection of anomalies (e.g.,

aberrations in dough consistency), measuring energy expenditure, and enabling flexible control over baking parameters to enable operations to quickly respond to changing conditions.

At more sophisticated levels, the food industry faces constant hurdles in terms of supply chain inefficiencies, traceability gaps, and climate change disturbances. DTs overcome these challenges by offering solid tools for scenario planning, allocation, and logistics optimization. In bakery operations, digital twins in particular narrow down overbaking risks, high ingredient use, and unforeseen operational disruption. In addition, AI-driven digital twins become critical to improving cold chain logistics for perishables thereby ensuring quality and improving shelf-life while simultaneously reducing energy consumption (Braggio and Russo, 2024).

Despite these benefits, the integration of DTs into bakery operations remains in its infancy stages. The major challenges include complexity in integration processes, unavailability of standardized platforms for development, and cultural resistance to replacing manual artisanal practices with data-driven automation (Krupitzer and Noack, 2022; Melesse et al., 2023). Nevertheless, with features like quality control, energy efficiency, and transparency becoming fundamental standards in the industry, DTs are becoming progressively integral to the bakery's digitization process (Purlis, 2012).

## 3. Integrated Digital Twin Framework for Bakery

In this chapter, a holistic Integrated DT Framework is presented that is tailored to bakery production systems. As shown in Figure 2, the framework consists of four basic elements: the physical product, the simulation model, the DT (including visualization and monitoring), and the knowledge base and stakeholders, which are linked by bidirectional data flows. These active connections provide a reactive and intelligent ecosystem in which information is continuously circulated between the physical and virtual worlds. The capability for synchronized real-time enables the system to react, adapt, and evolve, thus enabling continuous improvement in bakery processes.

The key objective of the framework is to incorporate closed-loop decision-making in production operations, thus enabling smart and responsive business processes. By making possible real-time fault detection, adaptability in control capabilities, and direct communication across technical and managerial levels, the framework provides greater visibility and coordination of operations. This integration is critical in maintaining ongoing product quality, regulatory compliance, and strategic alignment.

One of the key highlights of the framework is that it is hierarchical and modular, making it highly scalable and flexible. It is also designed to serve the requirements of small artisanal bakeries starting their digital transformation journey as well as large industrial-scale units pursuing full digital integration. Multi-tiered architecture makes traceability, incremental learning, and continuous improvement possible, permitting stakeholders to pursue focused innovations without losing track of overall operational and strategic objectives.

### 3.1 Framework Components

**Physical layer of the product** – It encompasses all tangible components within the bakery production environment, including but not limited to ovens, mixers, proofers, conveyor systems, and finished baked goods. These components are equipped with sensors that monitor key operational parameters such as temperature, humidity, torque, and weight. Sensor data is transmitted in real-time to a centralized database, where it is stored, organized, and made available for analysis. This continuous flow of high-fidelity information supports the development of accurate digital representations of the physical environment, enabling real-time decision-making, proactive quality control, and optimal resource allocation.

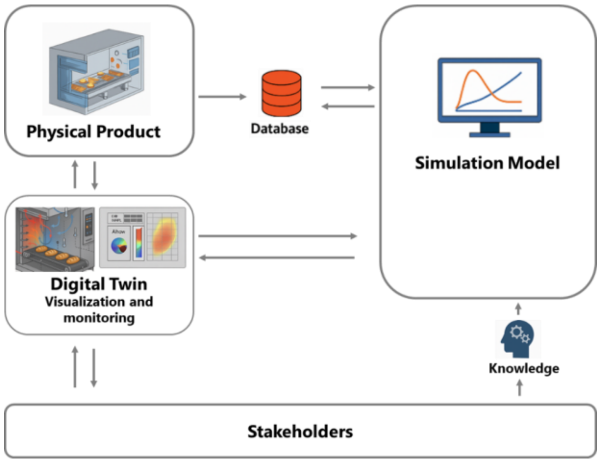


**Figure 2. Digital twin Framework**

**Simulation model** – It is an experimental digital platform intended for bakery operations exploration and optimization under different conditions. Based on software tools like AnyLogic, COMSOL, MATLAB, etc, both data-driven and physics-based algorithms are used in the simulation to model processes such as heat transfer, evaporation of moisture, and changes in dough's structural characteristics. These predictive simulation tests help validate operations as well as conduct stress tests without disrupting current in-production operations. In addition, they provide scenario-based analysis with resultant predictions on how changes in operational parameters, recipe, or energy use would impact overall operations and aid decision-makers in implementing better efficiency and sustainability.

**Digital twin** – Being the virtual equivalent of the physical bakery, integrates real-time information and simulation outcomes into a common monitoring and visualization platform with DT. This module provides operators with an interactive dashboard to monitor baking curves, temperature profiles, energy consumption, and productivity levels. By presenting key operational metrics through intuitive dashboards, the DT facilitates instant anomaly detection and parameter adjustment. By its modular design, the DT can be integrated with incumbent systems, i.e., Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP), thereby establishing a consolidated link between shop-floor operations and top-level business strategy. Most significantly, the DT co-evolves with the manufacturing process by iteratively enhancing its models against real-time deviations, thereby promoting adaptive and agile manufacturing practices.

**Cognitive layer of the system** – It is composed of stakeholders and the knowledge base, including organizational intelligence and human expertise that engage with the digital world. Operators, engineers, analysts, and decision-makers provide contextual information and interpretive comments, thus enhancing the system. This layer builds up knowledge over time from simulations, sensor information, and operational history, thereby facilitating continuous enhancement of the model and strategic planning processes. It promotes collaborative efforts and informed decisions by granting access to past data, compliance reports, and established best practices in processes. This synchronization makes sure that the DT is not just in sync with technical facts but also with overall business objectives and regulatory requirements.

Figure 2 represents the entire integrated framework, highlighting the two-way flow of information and control signals between the physical and digital worlds. The two-way flow provides a guarantee that bakery operations can be optimized through a synergy of automated systems and human intelligence. The framework is scalable, enabling bakeries to begin with fundamental modules and increasingly advance towards fully autonomous smart production. Finally, the system provides a strategic blueprint for future bakery operations, marked by accuracy guided by data, energy efficiency, and environmentally friendly approaches.

### 3.2 Strengths and Limitations

The use of this holistic DT strategy offers several key benefits during bakery operations. Real-time data acquisition and prediction lead to enhancement regarding efficiency through the automation of work processes, minimization of downtime, as well as scheduling (Agrawal et al., 2025). Product quality is maintained through constant adaptive controls in response to baking parameter deviations, i.e., oven temperature or dough viscosity. The goals of sustainability are complemented by advanced algorithms that reduce material waste and lower energy consumption by fine-tuning operational parameters (Peer et al., 2025). Integration with predictive maintenance functions enables the timely detection of machine malfunctions, thus preventing costly breakdowns and ensuring a smooth flow of production (Melesse et al., 2021). The integration with wide traceability in all production stages also ensures compliance with stringent food safety rules and quality standards. Through the provision of decision-making information in the form of real-time dashboards and performance metrics, the system enables operators and managers to make data-driven decisions that enhance both day-to-day operations and long-term planning.

Despite these benefits, there are significant challenges in the implementation of such a system (Attaran and Celik, 2023; Melesse et al., 2024b). The upfront expense of sensors, connectivity infrastructure, and modeling tools can be a huge disincentive, especially for small bakeries with limited capital (Moshood et al., 2024). The convergence of different technologies ranging from IoT devices and AI algorithms to high-end simulation software requires high-level technical expertise and concerted deployment. Data handling is also important, with enormous volumes of data required to be collected, stored securely, and interpreted correctly to yield useful insights. For small and medium-sized enterprises, scalability and cost could further complicate adoption. Furthermore, the effective implementation of the DT model relies extensively on organizational change management, such as large-scale workforce training and establishing a digital-first employee culture. Surpassing cultural resistance towards automation and a data-centric process is key to achieving the full potential of the system.

To overcome these challenges, small bakeries can adopt incremental digitization strategies starting with low-cost sensor kits and open-source analytics platforms. Partnering with local universities or innovation hubs for pilot projects can also lower entry barriers. Additionally, government incentives and shared digital infrastructure models—such as cloud-based digital twins hosted by consortia—can provide affordable access to advanced technologies.

The suggested integrated DT approach offers a sound, scalable, and future-proof solution for bakery operations digitalization. By mapping physical systems onto advanced modeling, real-time monitoring, and cooperative knowledge management, the approach supports continuous improvement, operational excellence, and strategic responsiveness in the rapidly changing context of the food sector.

## 4. Conclusion

This research introduces a strong and holistic DT framework intended particularly to address the growing challenges and transformational opportunities that exist in bakery production systems. By coupling physical operations with sophisticated modeling techniques, real-time surveillance, and data-based decision-making, this framework makes it possible to deploy smart, flexible, and environmentally conscious strategies in the baking industry.

One major benefit is its modular and stratified nature, making it possible for bakeries to incrementally implement DT technologies aligned with different levels of maturity, from artisanal bakeries to industrialized companies with full automation, as per their current levels of preparedness and future strategic goals. The use of bidirectional data flows in conjunction with human-oriented knowledge frameworks allows for real-time feedback, predictive maintenance, as well as constant performance optimization, while at the same time fostering company learning and process transparency.

The model essentially views technology not as solely separate. Instead, it unifies human familiarity and contextually-based cognizance in the digital environment through the integration of the knowledge base module, thus improving not just operational responsiveness but also creating traceability, regulatory compliance, and strategic alignment. The DT thus evolves from a passive monitoring tool to an active collaborative intelligence system that harmonizes automation with human cognition.

Future research should focus on maximizing this model's potential and its real-world application through pilot case studies. Key areas for research include cost-benefit analyses, assessments of opportunities for scalability, as

well as development of modularized implementation frameworks designed to overcome adoption barriers. In addition, interdisciplinary research involving academic institutions, technology creators, and industry experts will also play a key role in setting standards for interoperability, facilitating knowledge transfer, and expediting skill development among staff involved in digitalization.
The DT framework outlined above is a strategic guide that will enable bakeries to attain their digitalization goals. The framework is aligned with the overall mandate to develop smart, robust, and efficient food production systems under whose auspices data-driven precision, human ingenuity, and harmonization with the environment converge to forge new paths in food production. As bakeries evolve to meet the needs of modern markets, volatility in value chains, and the need to remain environmentally conscious, DTs stand as much more than technological facilitators as drivers of organization-level as well as systemic advancement.

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