Optimizing Production Lines for Soft and Deformable Products with Agile and Flexible Reconfigurable System

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Abstract
Market shifts and changing consumer demands highlight the challenges of traditional mass production techniques. This workshop proposes an Artificial Intelligence-integrated system with a multi-layer Digital Twin for optimized food production, adapting to product characteristics and facilitating real-time monitoring. Traceability services maintain product and process information, complemented by Digital Twin services projecting potential scenarios. Data-driven AI models optimize decision-making, from production layout adjustments to operational enhancements. Throughout it, human oversight is ensured using interactive dashboards, integrating technology with expertise. Implementation involves monitoring variables, managing model complexity, conducting analyses, applying knowledge effectively, interacting with stakeholders, and ensuring interoperability across functionalities.

Keywords
Digitalization, Digital Twin, Machine Learning, Optimization Algorithms, Traceability, Production Line Optimization.

1. Introduction

The evolving market and swift shifts in consumer preferences are signaling the challenges of many traditional mass production methods [1], paving the way for solutions that can rapidly adapt to emerging needs and trends. Thus, a reconfigurable production system – integrated, convertible, scalable, and customizable – is essential and required. There is a growing need to develop new technologies and algorithms for designing and controlling these adaptable production and logistics systems. Smartness and agility are essential qualities for creating a flexible, maintainable, and adaptable system in any business, especially relevant in producing a wide array of low-cost, high-quality products with short lead times for the fresh market [2] [3]. The integration of pervasive computing, advanced software, and sensor technologies has improved the capabilities and reliability of manufacturing systems [4], enabling the production of products with reduced costs, lower energy and resource input, minimizing human errors, and getting more responsiveness to customer demands. However, rapid technological evolution can exceed companies' ability to develop complex digital systems, which raises significant challenges [5]. The communication between production plants and internal logistics handling systems is a key issue that hinders agility, particularly in situations requiring the management of a variety of products with short life cycles. In this context, the AGILEHAND European Project aims to enhance the flexibility, agility, and reconfigurability of European manufacturing companies' production

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and logistic systems through the development of advanced technologies specifically designed for autonomously grading, handling, and packaging soft and deformable products, positioning it as a key strategic tool for these companies. This paper focuses on the AGILEHAND Suite, "Agile, Flexible and Rapid Reconfigurable SUITE". It is structured into several solutions, each addressing a different aspect of reconfigurable systems. The Traceability Solution aims to improve system agility by collecting relevant data across all stages of production and logistics. The Digital Twin Solution explores the development of a data-driven framework for creating simulation models for DTs in smart factories. The Rapid Reconfiguration of Production Solution applies intelligent methods to swiftly reconfigure the production system, aiming to develop algorithms that optimize production layouts and machine setups. The Operations Optimization Solution focuses on optimization algorithms to increase the level of automation of the production line at different management levels, from the strategic to the operational level. A key point is the potential for integrating all these solutions within the suite, creating a cohesive tool that improves several aspects of an industrial lifecycle and which is evaluated by using different Key Performance Indicators (KPIs).

2. The Agile, Flexible, and Rapid Reconfigurable background

Implemented in 2002, the European Union's General Food Law (Regulation No178/2002[6]) mandated traceability for all food and feed businesses, highlighting the importance of tracking products from raw materials to final outputs, a critical aspect for perishable items [7] [8]. Modern technologies, including QR codes, barcodes, radio frequency identification (RFID) and electronic data interchange (EDI), significantly enhace these systems. Additionally, integrating IoT sensors and RFID tags, optimized by Tree-augmented Naive Bayes (TANB) for chronological data management [9] along with temperature and humidity monitoring, are pivotal advancements. RFID systems paired with signal strength and machine learning algorithms offer further improvements. For specific products like fruits and vegetables, spectroscopic methods and chromatographic analysis also provide efficient tracing solutions [10], underscoring the diversity of approaches available for product traceability in production chains. DTs and Discrete Event Simulations (DESs) are influential tools in enhancing productivity, flexibility, and cost efficiency in various industries. DTs, as virtual replicas of physical objects or systems, enable the modelling and simulation of entire processes, including simulating scenarios such as machine breakdowns, maintenance schedules, and changes in production to identify and resolve potential bottlenecks, optimizing production schedules [11]. They significantly enhance system flexibility by enabling real-time testing of various change scenarios, optimizing resource use [12][13]. This proactive management includes optimizing inventory levels to meet demand without excessive costs and exploring different energy usage scenarios to minimize energy consumption without sacrificing productivity. Reconfiguring production systems is essential for staying adaptable and responsive to market changes and customer needs [14]. It aims to assist in strategic production planning, aiding workers in both weekly and monthly planning tasks by incorporating crucial machine parameters [15], and integrating factors like worker availability and product orders to optimize the process [16].

3. The Agile, Flexible, and Rapid Reconfigurable Suite

This section proposes a comprehensive framework improving production and logistics systems in the food industry, with a focus on soft and deformable products. The framework consists of four solutions: Production Traceability, Data-Driven Digital Twin, Intelligent Rapid Reconfiguration of Production and Automated Production Line Operations Optimization (Figure 1). These solutions leverage advanced technologies and strategic innovations to improve the handling of soft and deformable products, aiming to advance production and logistics systems in the food industry, ensuring more efficient, agile, and intelligent handling of such products.

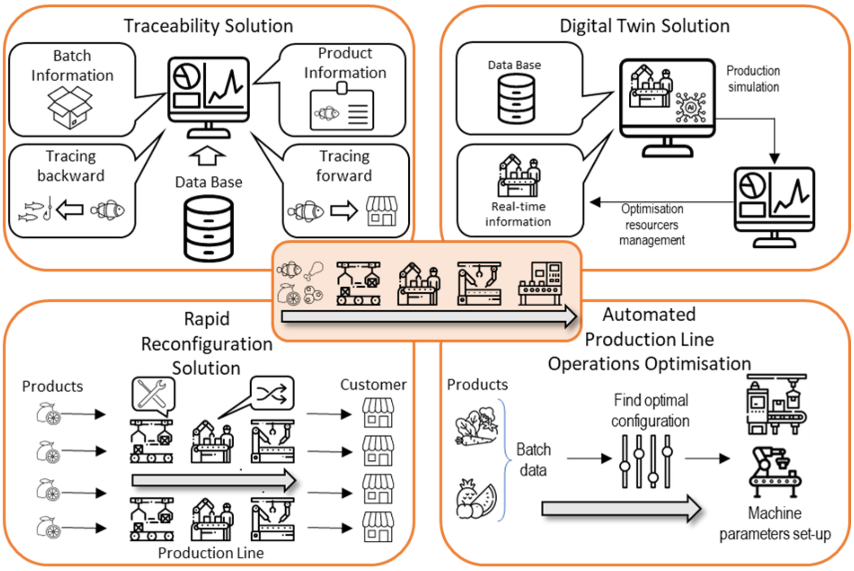

Figure 1. The Agile, Flexible, and Rapid Reconfigurable Suite.

3.1. The Product-Oriented Traceability Solution

Product traceability involves tracking a product throughout its lifecycle, from raw material acquisition to eventual consumption, by documenting and recording information about each stage of the supply chain. It is crucial to ensure product quality and safety, effective response to recalls or defects, compliance with regulatory requirements, and building trust among consumers. A central database serves as an integral component of proposed traceability solution, providing a unified platform for storing, managing, and accessing critical information about the product. Some benefits of having a traceability system with a central database system are data integrity and accuracy, efficient data retrieval, real-time monitoring, improved analytics and decision making. The traceability system stores data in tables within a database, with each table containing product or process specific information. These tables are interlinked through relationships established using keys, including primary and foreign keys. To integrate the database with other production systems, i.e. Enterprise Resource Planning (ERP) or Manufacturing Execution System (MES) a seamless connection for sharing and synchronizing data can be established using standardized communication protocols like Application Programming Interfaces (APIs) or middleware solutions. Additionally, data from machines can be integrated into the database through IoT devices of sensors, enabling real-time monitoring and improved analytics for informed decision-making and further development like DTs or production optimization processes. Through the user interface, users can edit the database by creating or deleting tables, uploading data, and displaying data. The application also allows for forward and backward tracing, enabling users to trace back a batch of products from an order number placed by a consumer. Furthermore, users can see additional product information such as supplier details, origin, and data from sensors at different stations. The system also provides information regarding historical data, tracing back processed products that were already handed over to the customer.

3.2. The Digital Twin Solution for Production and Logistic System Synchronization

The huge data flow produced by a manufacturing facility is the driving force for simulations within a DT, offering a real-time view of the plant functioning.
[14]. With this data, the DT simulation model can accurately replicate the plant dynamics to call the whole system a Data-Driven DT. Therefore, DES stands out as the best approach for this task, given its ability to capture the main features of complex systems where shifts happen at specific moments, a trait typical of industrial operations. The DT can simulate scenarios, predict results,

and optimize operations using the framework, which enables it to mirror the current state of the plant and experiment with hypothetical situations. The real-time data and digital model relationship enhances efficiency, reduces costs, and improves the system performance. The interoperability of DTs in manufacturing is relevant for two main reasons: communication of manufacturing processes with other systems and the interaction between real and cyber aspects of the model [4]. The real-world aspect of the DT relies on physical sensor networks and data processing tools to convey information to its cyber counterpart, while the cyber aspect depends on simulation tools to replicate these states and inform the control of the physical machinery. In addition, the digital model may consider several simulations based on the system complexity and, consequently, underscore the importance of effective interoperability within DTs.

3.3. The Intelligent Rapid Reconfiguration of Production Solution

Rapid reconfiguration in production involves quickly modifying and adapting the production processes and systems to meet changing demands and optimize operations. It aims to minimize downtime, maximize flexibility, and often leverages advanced technologies, such as automation, robotics, and data analytics, to streamline the reconfiguration process. Rapid reconfiguration in production enables businesses to enhance agility, reduce costs, and improve overall productivity. The rapid reconfiguration system for production supports production planning and management using data analytics. It optimizes machine set-up adjustments and frequencies to increase productivity and reduce the number of machine set-ups. The system also provides specific information to support production planners when machine set-ups are needed due to product changes. By using historical production data and feedback, the system gives predictions on delivered product quality by the supplier. It uses different parameters, such as field location, weather conditions, and historical delivered product quality, to create scenarios with profiles. Additionally, if sensor data for identifying the quality of initial products is available, the system can use this data to make predictions and provide recommendations for possible adaptations to fit customer order quantities. This is important as customers want different quality classes of products.

3.4. The Automated Production Line Operations Optimization Solution

The objective of the Automated Production Line Operations Optimization Solution is to enhance manufacturing operations. Machine learning (ML) is used to model the patterns and relationships between process data, manufacturing equipment parameters, and product quality. It involves creating neural networks trained on historical data and predicting product quality based on the input process data and product quality. Once the neural network is trained, it can incorporate optimization techniques to find the optimal manufacturing equipment parameter configuration that optimizes product quality. Given the current process data, the neural network is used to predict the product quality for different configurations of the manufacturing equipment parameters. Then, symbolic reasoning approaches, such as constraint satisfaction or logical inference, or reinforcement learning techniques can be used to find the optimal manufacturing equipment parameter configuration. Adaptive control techniques are then used to iteratively adjust the manufacturing equipment parameter configuration to changing conditions (for instance, product properties or environment variables) to achieve a given target product quality. Note that the characteristics of the product may render it impossible to achieve the target quality. In these situations, advanced rescheduling techniques can be used to trigger a change in the product batch sequence. This AI framework provides improved flexibility and agility to food processing, allowing the maximization of the final product quality.

3.5. The system integration

Integrating data from multiple sources in industrial settings poses challenges such as data quality (accuracy, completeness, consistency, timeliness, and relevance of the data), preprocessing, fusion, and security. The proposal suggests leveraging industry standards for industrial control integration, such as IEC 62264 [16], and state-of-the-art time series database engines like Timescale to create a common data persistence layer for the different solutions. This approach aims to simplify the development of dataset preparation pipelines and increase semantic interoperability among solutions. The common data modelling approach simplifies the development of dataset preparation pipelines by providing a unified and standardized framework for transforming raw data into a clean, structured format that can be readily used for analysis and modelling. This approach is crucial in ensuring data quality, facilitating effective analysis, and maximizing the value derived from data assets. Additionally, using a common data model unifies data into a known form and applies structural and semantic standards, making it easier to share and understand the same data across different solutions. By standardizing the data representation and transformation processes, the common data modelling approach reduces the complexity and effort required for developing dataset preparation pipelines, ultimately leading to more robust and impactful data-driven decision-making processes [17]. Furthermore, the use of APIs allows different solutions to use inner functions as external services, enabling the development of complex interactions, for instance leveraging digital twin simulation models for forecasting future scenarios in operations optimization workflows. APIs allow other solutions to use inner functions as external services by providing a set of defined rules that enable solutions to communicate with each other.

4. Discussion and conclusion

This paper addresses the challenges in delivering advanced digital solutions tailored to the food industry, particularly focusing on soft and deformable products. It introduces a comprehensive framework that includes several critical components: the availability and selection of appropriate sensors for these specific food products, the necessary complexity and capability of modelling systems, the requirements and provision of data analytics tailored to this industry, the understanding and provision of relevant knowledge support, the need for interoperability both within and among various DTs in the food manufacturing process, and the development of intuitive human-computer interactions suited to this sector. This approach aims to revolutionize the way soft and deformable food products are handled and processed, offering a predictive edge in an industry where variability is the norm. It presents strengths in integrating advanced technologies for enhanced traceability, flexibility, and operational optimization, offering significant improvements in efficiency and adaptability. However, it faces challenges with its complexity, reliance on accurate data and technology, and potential scalability and cost issues. Balancing these advanced technological benefits with the practicalities of implementation and maintenance is crucial for its success. Thus, implementing effective solutions across these interconnected areas in the framework will empower food manufacturing businesses to anticipate and tackle production issues that are currently challenging to predict.

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