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RESEARCH ARTICLE

OPEN ACCESS

INTELLIGENT MODEL FOR PRODUCTIVE PLANNING OF ELECTRONIC METERS WITH INDUSTRY 4.0 TECHNOLOGICAL RESOURCES

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ABSTRACT

The advancement of digital technologies has significantly transformed industrial processes, shaping the Industry 4.0 scenario, in which cyber-physical systems, IoT, Big Data, and Artificial Intelligence (AI) enhance productivity efficiency and flexibility. In this context, the manufacturing of electronic meters faces challenges such as operational complexity, demand variability, the need for traceability, and data integration across the production chain. Therefore, the adoption of intelligent solutions that support production planning and control in an agile and precise manner becomes essential.

This study aims to develop an intelligent model for the productive planning of electronic meters, integrating Industry 4.0 resources to improve decision-making and optimize operational flow. The model seeks to minimize bottlenecks, forecast material requirements, improve machine utilization, and increase planning reliability. The methodology was structured in four stages: mapping the production process and identifying critical variables; real-time data integration via IoT and MES systems; development of AI models based on machine learning; and the construction of a system capable of simulating scenarios and generating production plans. Tests using historical and real data were conducted. The results indicated higher accuracy in forecasts, reduced idle times, and better balance between capacity and demand. The model proved adaptable to different scenarios, demonstrating its potential to support companies in adopting more dynamic and efficient processes aligned with Industry 4.0.

I. INTRODUCTION

Industry 4.0 has established itself as one of the pillars of digital transformation in the industrial environment, driving integration between advanced technologies, real-time data, and intelligent production processes [1-3]. Characterized by the use of cyber-physical systems, connectivity via the Internet of Things (IoT), Big Data, advanced automation, and Artificial Intelligence (AI), this new industrial era provides significant gains in efficiency, flexibility, and analytical capacity [4-7]. In this scenario, the competitiveness of companies is directly related to the adoption of tools capable of improving decision-making and promoting Operational Optimization at all levels of production.

One of the sectors that most demands such advances is the manufacture of electronic meters, whose production process involves a wide variety of components, high precision requirements, and a constant need for traceability [8-10]. Production planning in this type of environment presents complex challenges, marked by demand variation, diversity of meter models, and the need to integrate information from different stages of the production chain. Traditional planning strategies, based on fixed rules or manual analysis, are limited in the face of growing operational complexity [11],[12]. Thus, there is a need for intelligent and adaptive solutions capable of dealing with dynamic and variable environments. The application of AI in this context offers significant opportunities for analyzing large volumes of data, forecasting scenarios, identifying bottlenecks, and supporting real-time decision-making, thereby increasing productivity and quality levels [13-15]. The proposal to develop an intelligent model for the production planning of electronic meters represents a significant contribution to the field, as it integrates essential Industry 4.0 technologies with advanced AI methods geared toward optimization. The innovation of this model lies in its ability to combine data collected by IoT sensors, Manufacturing Execution Systems (MES), and analytics platforms to create a more autonomous, responsive, and efficient production environment.

In addition, the use of machine learning algorithms enables more accurate predictions about production times, future demand, resource availability, and operational performance, resulting in more reliable production plans that are aligned with market needs [16-18]. The relevance of this topic is reinforced by the competitive pressures faced by the industrial sector, which demands rapid customer response, cost reduction, and increased overall efficiency. By incorporating elements of Industry 4.0 into the planning process, companies now have tools capable of transforming raw data into strategic information, promoting more assertive decisions and reducing uncertainty. The proposed model also contributes to improving traceability, increasing process reliability, and reducing waste, which are fundamental aspects for lean and sustainable production [19], [20]. Thus, this work presents an innovative approach that integrates intelligent planning, digital technologies, and Operational Optimization, demonstrating how Industry 4.0 can enhance productive performance and strengthen competitiveness in the electronic meter sector.

II. THEORETICAL REFERENCE

II.1 APPROACH TO INDUSTRY 4.0 AND ITS DEGREES OF MATURITY

Industry 4.0 represents a milestone in the evolution of production systems, characterized by the integration of advanced digital technologies, intelligent automation, and massive data analysis [21-23]. For manufacturers of electronic meters, whose production requires a high degree of precision, traceability, and reliability, the adoption of these concepts becomes not only strategic but fundamental to ensuring competitiveness and quality in an increasingly regulated and demanding market [24]. The application of Industry 4.0 in this sector generally occurs gradually, following different degrees of maturity. The first stage, known as initial digitization, involves replacing manual processes with computerized systems. For electronic meter manufacturers, this may include the digitization of production orders, electrical test records, calibration, and quality inspections. Although there is still no significant integration between systems, this stage lays the foundation for further advances, reducing errors and improving the traceability of components and batches [25]. In the second stage of maturity, data connectivity and integration emerge.

Here, welding machines, SMT (Surface Mount Technology) devices, test benches, and optical inspection systems are integrated into an MES (Manufacturing Execution System) [26]. This connection allows production data—such as cycle times, failures, welding parameters, and electrical test results—to be collected automatically and analyzed in real time. At an electronic meter manufacturer, this stage enables rapid detection of deviations, reducing rework rates and ensuring greater consistency in the performance of the equipment produced. The third stage corresponds to intelligent automation and the use of advanced technologies such as artificial intelligence, machine learning, and cyber-physical systems. At this level, electronic meter assembly lines become capable of automatically adjusting machine parameters according to observed conditions. For example, algorithms can predict failures in welding equipment, anticipating maintenance needs. In addition, computer vision systems can enhance the inspection of electronic boards, identifying micro-defects that would go unnoticed by the human eye. The analysis of historical data also makes it possible to predict variations in energy consumption in the meters, optimizing the final calibration.

At the highest level of maturity, the factory reaches an autonomous and fully integrated stage, in which production flows, internal logistics, inventory management, and quality control operate in a synchronized manner. Digital twins — digital replicas of production processes — allow scenario simulations, testing of new meter models, and validation of production parameters even before physical manufacturing. Continuous communication between ERP, MES, and IoT devices ensures a highly efficient and adaptable operation [16],[17]. For the electronic meter manufacturer, this results in shorter response times, significant cost reductions, and greater reliability in measurements and calibrations. Thus, the evolution through the maturity levels of Industry 4.0 is not merely a technological modernization, but a profound transformation of production processes. In companies that manufacture electronic meters, this journey represents the key to elevating quality standards, increasing competitiveness, and meeting the demands of a sector driven by precision, safety, and continuous innovation.

II.2 PRODUCTION PLANNING AND CONTROL FOR ELECTRONIC METERS

Production Planning and Control (PCP) plays a strategic role in the electronic meter industry, a segment that demands high precision, regulatory compliance, and complete product traceability. The complexity involved in manufacturing these devices—which include electronic boards, sensors, power supplies, communication modules, and calibration systems—makes PCP essential to ensuring operational efficiency, final quality, and on-time delivery [27-30]. The PCP process begins with long-term planning, which involves demand forecasting, production capacity analysis, and the definition of supply strategies. For electronic meter manufacturers, this stage is particularly sensitive, as demand fluctuations can occur due to public tenders, large utility projects, or technology replacement cycles.

Good planning must consider these variables, adjusting production capacity, the allocation of skilled labor, and the availability of critical inputs, such as microcontrollers and communication components, which are subject to variations in the global market. As part of medium-term planning, PCP transforms forecasts into master production plans, defining which meter models will be produced in each period. This includes balancing assembly lines, defining economic batches, and sequencing operations. Since many electronic meters have variations in communication modules (such as Wi-Fi, PLC, or RF) and advanced features, PCP must optimize production to minimize setup changes and maintain process fluidity. The operational stage, or production control, involves daily monitoring of the shop floor. At this point, the PCP monitors indices such as SMT line efficiency, soldering machine availability, functional test results, and rework rates. Integrated systems, such as MES and ERP, are widely used to record production data in real time, enabling quick decisions when deviations arise. For example, if a batch of boards shows recurring failures in electrical tests, the PCP can intervene by adjusting process parameters, reallocating resources, or engaging product engineering [16-18].

Another essential aspect is materials control, since the production of electronic meters depends on specific components that are often difficult to replace on the international market. PCP must ensure adequate stock levels, avoiding interruptions in production and preventing excess obsolete items. Techniques such as MRP (Material Requirements Planning) and ABC analysis assist in this management, ensuring that critical components receive priority [31]. Quality control is also part of PCP, as meters must comply with national and international metrological standards and regulations. Planning must allow adequate time for calibration, inspections, functional tests, and certifications, avoiding bottlenecks that compromise delivery times [32],[33]. Finally, PCP plays a crucial role in aligning production, engineering, purchasing, and logistics. In the electronic meter industry, where product reliability is essential for energy security and accurate consumption measurement, a well-structured PCP ensures not only efficiency but also business sustainability and full compliance with market requirements.

II.3 REAL-TIME DATA INTEGRATION VIA IOT

The research aims to improve this current system to encompass the development of an intelligent system for production planning, which is based on monitoring production events, which indicated actions to be taken to follow the planning carried out, integrating resource management and B.O.M, which is currently done by Jundsoft Software, optimizing business rules with new Design Patterns. As can be seen in Figure 2, the service layer has APIs developed for communication with the equipment and, therefore, continuously collects data from this equipment directly into the database.

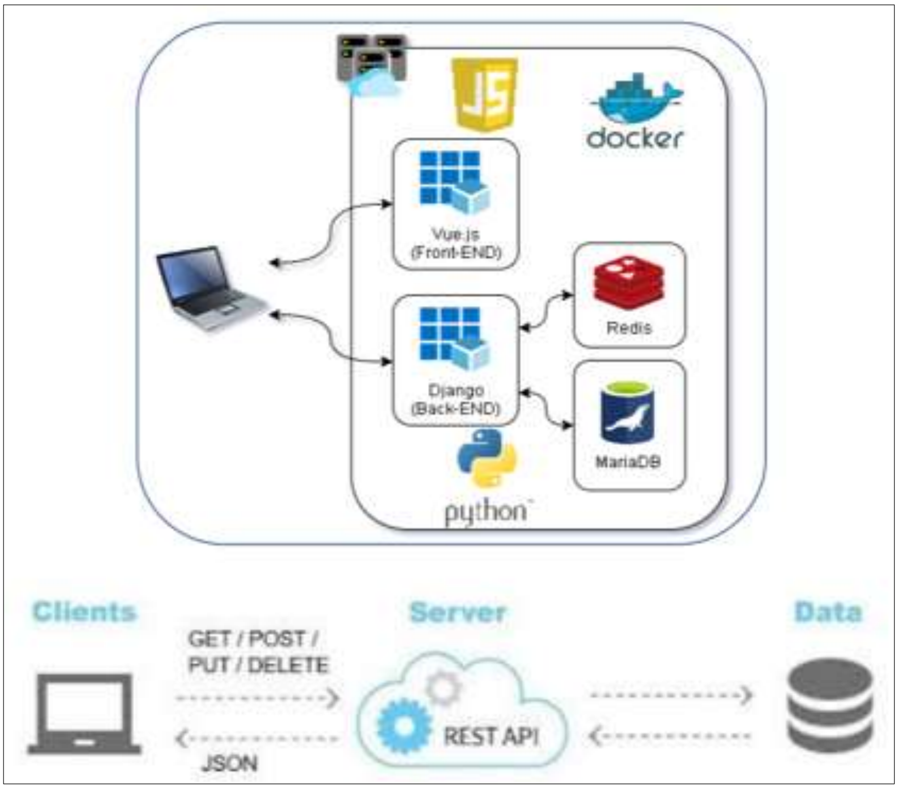

Figure 1: Draft of the Software Architecture for Intelligent MES System.
Source: Authors, (2026).

II.3.1 Traceability Device

This research aims to integrate software stacks (service layer API) with hardware stacks (Traceability Device), which in turn is connected to equipment that generally has RS232 serial communication. Therefore, the device will be the interface for communicating with the equipment and connecting them to the internal network, moving the equipment from stage 1 maturity to stage 2, where there is connectivity, for collecting data from each piece of equipment on a pilot line, which will be used to validate the collection. Some devices in this pilot production line do not have connectivity and will receive a traceability device for data collection, as shown below:

- **Parameterization device:**

This prototype device will be responsible for configuring the product's memory, recording the serial number, and checking other quality parameters to ensure that the product complies with the customer's purchase order requirements (verification according to the production order). This system should operate automatically, without the need for operator selection. Based on the production order number, the system will consult via API which configurations and checks should be performed on the product. As these configurations are made based on customer parameters, the name of the device is Parameterization.

- **PIMA Asynchronous Serial Output Device:**

This device will be a functional test prototype of the product's communication protocol. It will be responsible for ensuring that the product will function and communicate correctly, and for ensuring that the serial code is recorded in the memory (performed on the parameterization device). This step will be performed after the product is permanently closed, ensuring that there will be no cover exchange error, or that the mechanical closing process did not damage the product. To know what should be tested, the system will consult via API from the production order number what should be the correct serial number of the production sequence, which communication protocol, and other optional items to be verified.

II.4 MANUFACTURING EXECUTION SYSTEMS (MES)

Manufacturing Execution Systems (MES) play a central role in modern industrial operations management, acting as the bridge between strategic planning carried out by corporate systems, such as ERP, and operational activities on the factory floor. The main objective of an MES is to ensure that production is carried out efficiently, traceably, and in line with quality, time, and cost specifications. An MES collects real-time data from machines, operators, and processes, allowing managers to monitor production performance minute by minute. This data includes indicators such as productivity, downtime, material consumption, batch quality, and cycle time for each stage of the process. Based on this information, the company can quickly identify bottlenecks, anomalies, or deviations, making corrective decisions that increase efficiency and reduce waste. This continuous monitoring capability makes MES essential in highly technological environments, such as automated lines, electronic device assembly, and processes that require precision and repeatability.

In addition to monitoring, MES also controls production, managing manufacturing orders, guiding operators with digital instructions, and recording each step of the process, ensuring full traceability. Another relevant point is quality control, as MES integrates inspection tools, automatic collection of test results, and application of sampling plans. This ensures that non-compliant products are quickly isolated and that quality standards are strictly met [26]. In addition, MES contributes to the management of resources, including operators, machines, tools, and materials, optimizing their use. When fully integrated with ERP and automation systems, it becomes a pillar of Industry 4.0, enabling decisions based on real and reliable data. Thus, Manufacturing Execution Systems represent an indispensable tool for organizations seeking productivity, quality, and competitiveness in a constantly changing market.

III. MATERIALS AND METHODS

III.1 METHODOLOGY AND ACTION STRATEGY:

The study will be developed through research, by surveying existing data, collecting information at the factory with managers, administrators, and technicians in order to ensure the development of the project in accordance with the real needs of the company. This project will be developed by a team of developers, engineers, and technicians who will be assigned well-defined responsibilities in each phase of the project. To plan, execute, and manage this project, PMBOK principles will be adopted as shown in Figure 2. In this project, five groups of processes stand out.

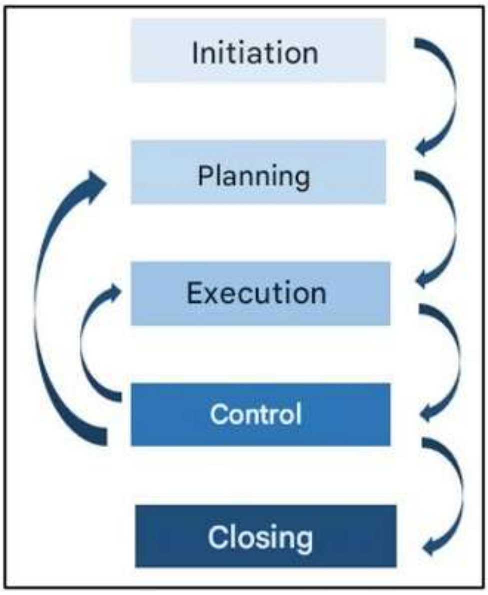

Figure 2: PMBOK management model.
Source: Authors, (2026).

- **Initiation:** In this phase, the project's needs will be listed to begin the development stages. Relevant data for the project's development will also be collected here, such as scope, risks, costs, participants, and schedule.
- **Planning:** The planning will be organized into a timeline according to the activities to be carried out. Frequent meetings are expected so the team can align ongoing work and determine ways to improve the process with agility. For this purpose, daily discussions are intended, enabling faster decision-making, value delivery to the customer, and participation from the project sponsor.
- **Execution:** The project will be executed by professionals with expertise in software, electrical, electronic, automation, and mechanical areas. This phase will also include the coordination of resources according to the project's progress and stage.
- **Control:** Project control will be performed to ensure that the objectives are achieved. This will be done through schedule analysis and meetings with team members and the project sponsor.
- **Closure:** In this stage, the client is expected to receive: reports, acceptance terms, maintenance and operation manuals (and other documents required by the Institute and the Company), as well as the new products developed. In addition, as the software development method, the incremental methodology will be used, in which each activity cycle will develop an integral part of the software, making it possible to measure the following phases of the process according to Figure 3.

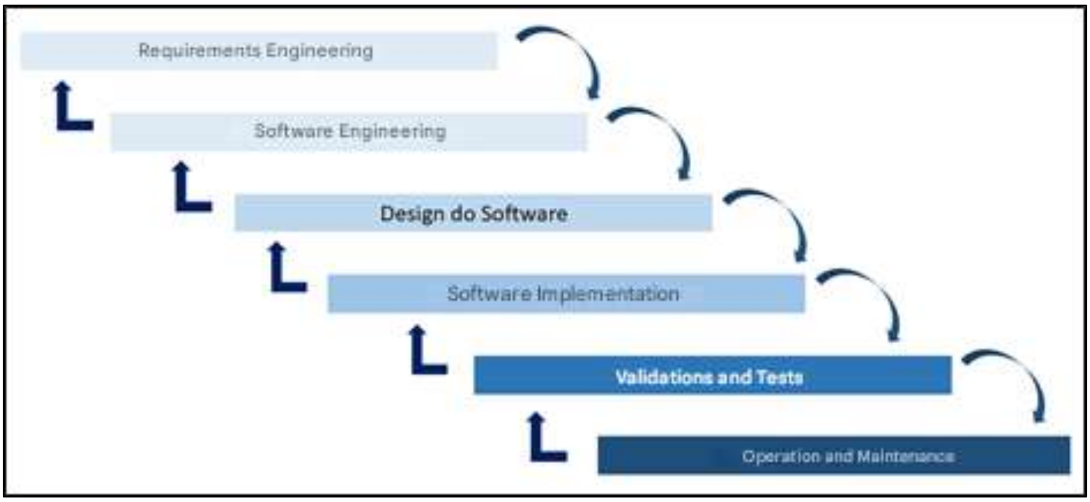

Figura 3: Ciclo incremental do Software.
Source: Authors, (2026).

- **Requirements Engineering:** In this stage, the needs related to the software—specifically the module to be developed—will be defined so that the solution meets the company's scenario, considering visual, behavioral, action-related, criteria-based, and operational limitations.
- **Software Engineering:** In this stage, diagrams and documentation regarding the module and the implemented functionalities will be developed. This document should address the software design, describing limitations, use cases, functionalities, technologies, and the technical definitions of the functional and non-functional requirements.
- **Software Design:** In this stage, the software design will be developed based on the user interaction interfaces, visual identity definitions, element layout, actions, behaviors, and company standards, taking operational limitations into account.
- **Software Implementation:** In this stage, the process of creating, defining, and executing the coding of the functionalities specified in the requirements document will be carried out, along with strategies to achieve the module to be delivered.
- **Validation and Testing:** This stage is characterized by activities that perform validations and tests to approve the application and the developed module. Functionality, integrity, security, unit, and installation tests will be executed as methods to assess product quality, support bug fixes, and carry out code refactoring processes.
- **Operation and Maintenance:** This stage will involve code refactoring and adjustments that may be necessary due to new requirements or technological updates. This includes carrying out coding activities during this phase.

III.2 TOOLS FOR PROJECT DEVELOPMENT

To develop this project, support tools will be needed to carry out scenario projections, technical drawings, simulation models, and coding of the items listed in Table 1.

Table 1: Types of tools involved in the research.

Tool	Concept	Application in the project
Proteus VSM	Software that allows the creation of circuits, simulation, and layout design for analog and digital applications, including microcontrollers.	It will be used for the development of electronic boards and connections.
Solid Works	Software designed for the creation of three-dimensional virtual mechanical prototypes. It also allows for the simulation of the functioning of parts, assemblies, movements, among others.	In the project, the software will be used to model mechanical parts and devices. From three-dimensional prototypes, 2D drawings will be generated and forwarded to the machining process.

PMBOK Guide	It is a set of project management practices organized by the PMI institute and is considered the basis of project management knowledge by professionals in the field.	It will be used to manage the project, from the initial stage to completion.
Visual Studio Code	Source code editor developed by Microsoft for Windows, Linux, and macOS. It includes support for debugging, built-in Git version control, syntax highlighting, and intelligent code completion.	Development environment.
MySQL Workbench	Client for executing SQL queries, system administration, and database modeling, creation, and maintenance through an integrated environment.	Development environment for queries, data structures, and logical models.
Astah Community	Class, Use Case, Sequence, Communication, State Machine, Activity, Component, Deployment, and Composite Structure Diagram Designer. Used in Software Engineering.	Class project diagrammer and requirements diagrams.
Draw io	Online graphic editor that allows you to develop drawings, graphics, and other designs without the need for expensive and heavy software. It provides resources for creating any type of design and has a section dedicated to information architecture.	Architecture project diagrammer and flowcharts.
Trello	Collaboration tool that organizes projects into boards. At a glance, Trello shows what is being worked on, who is working on what, and where something is in a process.	Activity manager.
Github Desktop	Application that allows you to interact with GitHub using a GUI instead of the command line or a web browser, with which you can upload, extract, and clone remote repositories.	Code versioning.
UX Prototyper - Justinmind	Justinmind is a prototyping tool for websites, software applications, and mobile applications that can work with Windows and Mac, or with iOS and Android. There is a free version that you can work with very well.	Design interface prototyper.
Barcode reader for meter tracking	Industrial scanner for reading 1D and 2D barcodes from 15 cm to 15 m	It will be necessary to track the item by station and identify through data where the product is located, whether it has been rejected or not, in addition to adding the completed stage information to the block body according to the line layout.

Source: Authors, (2026).

III.3 TECHNOLOGIES FOR PROJECT DEVELOPMENT

The technologies that will be used and applied in the project meet the needs of supplying the technology presented as the scope of the project, Internet of Things (IoT), Intelligent Systems, and Artificial Intelligence.

Table 2: Technologies applied in the research process.

Technology	Concept	Application in the project
Vue.js	Vue.js is an open-source JavaScript framework focused on developing user interfaces and single-page applications.	JavaScript framework for building user interfaces.
Vue Router	Vue Router is the official router for Vue.js. It integrates deeply with the core of Vue.js to make it easy to build Single Page Applications with Vue.	Library for page routing.
Vue-118n	Vue I18n is a plugin for internationalization in Vue.js. It easily integrates localization features into your Vue.js application.	Library for internationalizing Vue.js applications.
VueUse	It is a collection of hundreds of essential Vue composition utilities for interacting with various browsers, sensors, animations, and state APIs.	Hooks library for Vue.js.
Quasar or Naive UI	It is an open-source framework based on Vue.js for building applications with a single code base. It can be deployed on the web as SPA, PWA, SSR, in a mobile application using Cordova for iOS and Android, and in a desktop application using Electron for Mac, Windows, and Linux.	Vue.js component framework.
Echart	It is an open-source JavaScript visualization tool that can run fluently on desktops, web apps, and mobile devices.	Data visualization library for creating graphs.
Moment.js	It is a very popular JavaScript library that facilitates working with dates and times in projects developed in this language. With it, you can perform tasks such as manipulating, formatting, and validating dates more simply and efficiently.	Library for manipulating dates and times.
Axios	Axios is a library for making HTTP requests and handling data communication between the frontend and backend in web applications. It provides a simple and flexible API for making asynchronous API calls, such as getting data from a RESTful API, sending data to a server, or updating data in real time.	HTTP client for communicating with the back end.
FastAPI	It is a web framework first released in 2018 for building HTTP-based service APIs in Python. It is used to build APIs with Python 3.8+ based on standard Python type hints. FastAPI is based on Pydantic and uses type hints to validate, serialize, and deserialize data.	Web framework.
SQLAIchemy	It is a cross-platform framework that has quickly become one of the most widely used object-relational mapping tools in the Python community, the language for which it was developed. It provides full SQL flexibility,	ORM library for interacting with databases in Python.

	obtaining a complete set of well-known enterprise-level persistence patterns that are designed for efficient, high-performance database access.	
Redis	It is used by companies that need high-performance tools due to the processing of huge volumes of data, such as Twitter, or applications with real-time updates, such as betting sites.	In-memory database for caching.
Celery	It is a robust, simple, and flexible distributed system that allows you to execute large numbers of messages asynchronously. It is a task queue focused on real-time processing, in addition to supporting task scheduling.	Library for executing asynchronous tasks.
Websockets	WebSocket is a technology that enables bidirectional communication over full-duplex channels on a single Transmission Control Protocol socket. It is designed to run on browsers and web servers that support HTML5, but can be used by any application client or server.	Bidirectional communication protocol over HTTP.
Pydantic	Pydantic Python is a powerful library for Python developers, offering features such as data validation, automatic type conversion, data serialization and deserialization, and automatic documentation.	Library for data validation in Python.
Pytest	Pytest is a Python testing framework that originated from the PyPy project. It can be used to write various types of software tests, including unit tests, integration tests, end-to-end tests, and functional tests. Its features include parameterized tests, fixtures, and assertive rewriting.	Testing framework for Python.

Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

The execution of planning, coordination, and technical structuring activities throughout the period resulted in significant advancements in both administrative organization and the consolidation of the technical foundation required for system development. The main outcomes achieved include: validation of the technical scope with the company; alignment of execution and delivery schedules; structuring of the development team after a rigorous selection process; establishment of versioning and collaboration guidelines via GitHub; strategic prioritization of the Technical Sheets module; and practical immersion in the partner company’s manufacturing environment, enabling full understanding of production flows and critical process points. From these results, several relevant conclusions were drawn. First, the complexity of the company’s industrial processes requires a highly integrated and flexible approach capable of adapting to the demands of traceability, compliance, and automation. Second, replacing manual processes with integrated digital modules represents not only an operational necessity but also a concrete opportunity for gains in efficiency, standardization, and reliability. It was also found that the integration among the research’s technical teams was essential for advancing technical definitions, demonstrating that multidisciplinary collaboration is a key factor for the project’s success.

Among the deliverables produced in this activity, the following stand out:

- Technical diagram and mind map of the functional structure of the Technical Sheets module;
- Functional mockups of the SIPE system interfaces;
- Restructured schedule based on the new team composition;
- Individual and consolidated technical reports with documentary and visual evidence from technical visits;
- Versioned repositories with code documentation on GitHub;
- Initial architectural definitions involving the use of technologies such as FastAPI, Kafka, MariaDB, and ClickHouse;
- Technical visit reports mapping industrial processes and integration points with the integrated system.

In terms of investigation and experimentation, the activity validated the technical feasibility of digitizing and automating the Technical Sheets generation process, based on a critical review of the documents currently used by the company. The analysis of production flows—especially in the meter assembly, plastic injection, and metrological laboratory sectors—provided practical input for refining system requirements. Industrial communication technologies such as MQTT, HTTP, RS-232, RS-485, and IEC 62056-21 optical interfaces were also examined, confirming the feasibility of integration between physical devices and management systems. The activity significantly contributed to increasing the knowledge of the professionals involved regarding Industry 4.0 enabling technologies, particularly in industrial process automation, digital traceability, system integration, real-time data management, and information security. Coordinators and developers participated in practical training and immersion activities within the factory processes, gaining applied knowledge about digitizing technical documents, API modeling, structuring hybrid databases (OLTP and OLAP), scalable backend architecture, and interoperability standards with industrial ERPs. This continuous learning strengthened the team’s technical capabilities and raised the project’s overall technological maturity, aligning it with the principles of Industry 4.0.

The results obtained in the seventh month can be analyzed across three dimensions: qualitative, quantitative, and organizational. Each provides important insights into understanding the impact of the activities carried out and the added value brought to the project. In the qualitative dimension, progress was significant. User experience improved substantially with the redesign of the sidebar and the implementation of the sheet preview feature. The system became more intuitive, reducing learning curves and increasing operational efficiency. Additionally, standardization through templates brought greater reliability to the recorded information, reducing human error and strengthening traceability within production processes From a quantitative perspective, the numbers also demonstrate progress. More than twenty parameterized templates were created during the month, forming a solid foundation for different application scenarios. The average time required to complete the sheets was reduced by approximately thirty percent, showing the direct impact of automation and standardization on the team’s daily routine. Furthermore, fifteen critical inconsistencies identified in previous cycles were corrected, reinforcing the maturity of the validation process and improving system reliability, as shown in Figure 4.

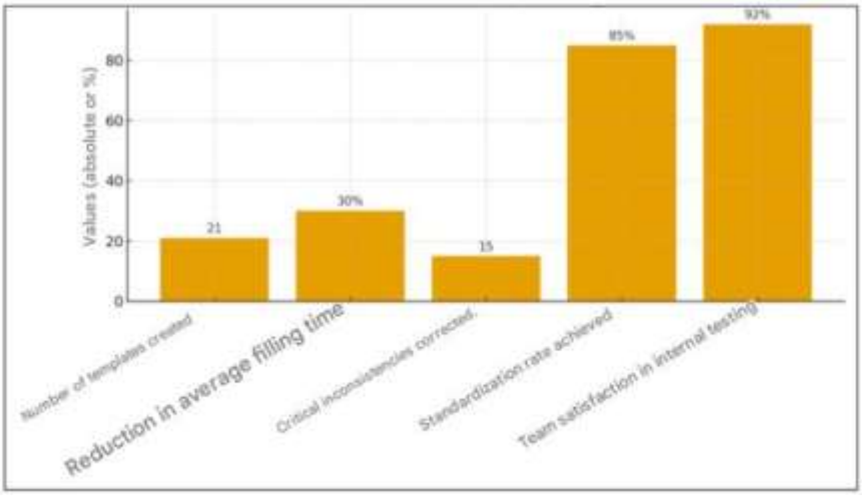

Figure 4: Quantitative performance indicators for the Technical Data Sheet module in the 7th month.
Source: Authors, (2026).

Following the implementation of product traceability, which was the focus of phase 1 of development, this new phase aims to elevate the system to a more comprehensive MES level, with greater control over production flow and production order management. This includes real-time monitoring of the production plan, allowing the system to actively interact with the equipment, determining what should be produced, reducing dependence on production operators, improving process quality, and applying stricter control over the production plan and quantities produced. To interact with production systems and equipment, various documents will be transferred to the SIPE system to avoid ambiguity and errors in data entry, such as labels, laser markings, and proper product configuration according to customer specifications. Figure 5 shows the hierarchical levels of industrial systems, organized in a pyramid ranging from machines (physical level) to ERP (corporate level). It shows the expected reaction times at each layer and the types of events managed, such as failures and rejections. This structure facilitates integration between the shop floor and management systems.

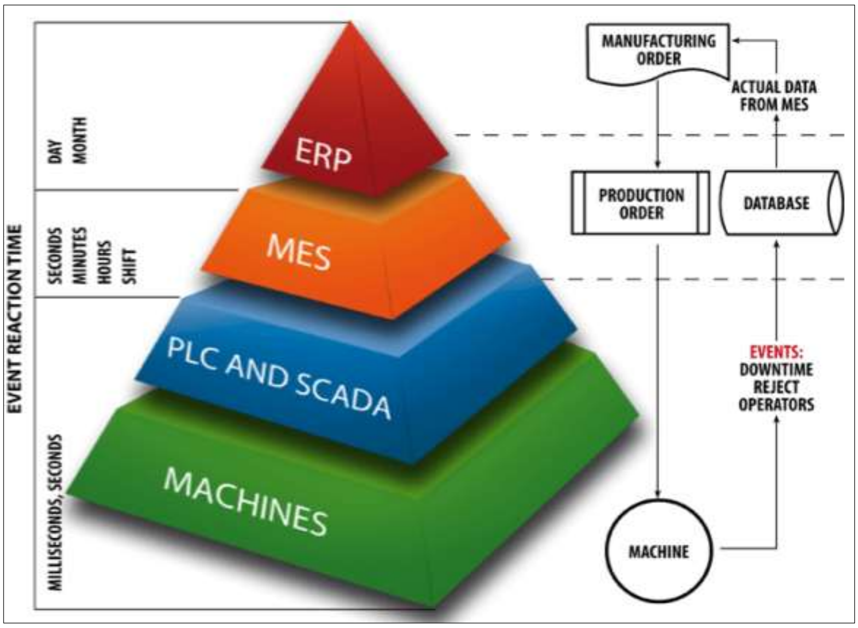

Figure 5: Layered Architecture of Industrial Automation.
Source: Authors, (2026).

IV.1 TECHNOLOGICAL INNOVATIONS

The SIPE System features process innovation, being a new solution for the company, for the Western Amazon region, and for Brazil. The main innovations include:

a. IoT-based traceability devices;
b. Intelligent production planning system with real-time data interpretation;
c. Artificial intelligence algorithms for dynamic production replanning;
d. Dashboards integrated with Business Intelligence (BI);
e. Integration via microservices and APIs for modularity and scalability;
f. Predictive production control based on industrial data analysis.

The system uses a simple yet powerful design approach, utilizing modern development SDKs for easy maintenance and improvement. All system functions and transactions are performed on the server side, using a REST API to interact with equipment for data collection and control. The following figure shows the SIPE system architecture diagram using Vue.js on the front end, Django (Python) on the back end, MariaDB database, Redis cache, and containerization with Docker. Communication between client and server occurs via REST API using data in JSON format, ensuring scalability, modularity, and performance in industrial applications. In Figure 6, the diagram is presented that connects template versions to an active workflow with sequential levels, where each level defines the minimum number of approvers and who is allowed to approve by role or by individual. Decisions are recorded per level, with a full audit trail. The setup sheet inherits the dynamic structure and directly references the original technical sheet, preserving traceability between the approved specification and the configuration executed on the production line. In this stage, a set of unit and integration tests was also conducted to validate the robustness of the Technical Sheet approval module and the derivation of the Setup Sheet. The focus was on ensuring logical consistency, data integrity, and performance under load, covering the following main scenarios:

- **Workflow:** Execution of scenarios with multiple approval levels, including approvers defined by role or by specific user. Chain rejections and alternative flows were simulated to validate system behavior in cases of partial quorum or lack of consensus.
- **Validations:** Tests for duplicate approvals by the same agent, status transitions (pending → approved/rejected), and automatic blocks when the minimum number of approvers was not reached. Business rules were validated with audit records for each event.
- **Setup Sheet:** Verification of correct data inheritance from the approved Technical Sheet, tests for submission of configuration parameters, and checklist registration. Traceability between the original Technical Sheet and the executed Setup was audited.
- **Integration and Performance:** REST endpoints related to the workflow and the Setup Sheet were subjected to moderate-load scenarios, evaluating response consistency, average latency, and stability under multiple concurrent requests.

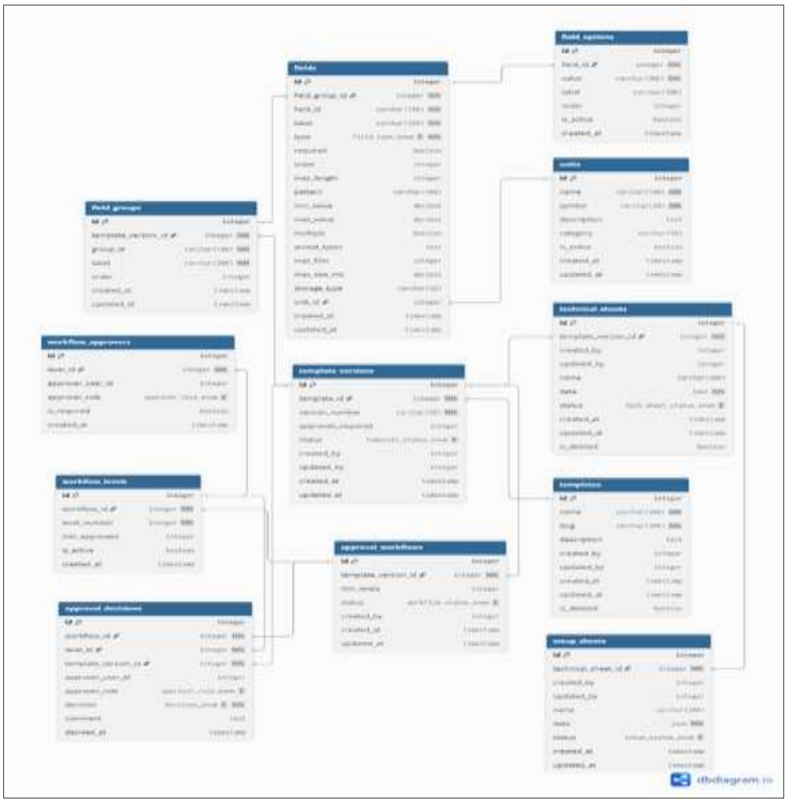

Figure 6: Multi-level approval workflow and derived setup form.
Source: Authors, (2026).

Table 3 below summarizes the main deliverables and improvements achieved in this development cycle.

Table 3: Improvement and delivery of the main activities of this sub-activity.

Delivery	Description	Benefit
Approval workflow	Multi-level flow with dynamic approvers	Document governance and traceability
Validation rules	Minimum number of approvers, specific positions/users	Reliability and security in the decision-making process
Auditing	Record of identity, position, decision, and date/time	Transparency and complete history
Setup sheet	Derived directly from the approved Technical Data Sheet	Traceable integration with machine configuration
Setup fields	Parameters, calibration, and operational checklists	Compliance and standardization in line preparation
REST integration	Endpoints for workflow and Setup Sheet	Standardized operability and secure consumption by external systems
Load testing	Tests with multiple approvers and stress scenarios	Stable and predictable performance
Duplicate prevention	Blocking of repeated approvals by the same agent	Integrity and fairness in the approval process

Source: Authors, (2026).

During the development cycle, critical points were identified and addressed, as they directly affected the system's consistency. Among the detected errors, the most notable was approval concurrency within the same level, which caused status inconsistencies when multiple approvers submitted decisions simultaneously. This issue was resolved through the adoption of transactional control with locks, ensuring the atomicity of operations. Another recurring error was the failure in linking the Setup Sheet to the Technical Sheet in cases of partial submission, which was corrected by enforcing mandatory referential integrity constraints, preventing setups from being created without a valid reference to the originating technical document. Duplicate approvals by the same user at different levels were also observed; this issue was corrected by implementing uniqueness validation per level, complemented by more robust audit trails. On the other hand, the successful aspects reinforced the solidity of the architecture. The workflow demonstrated high flexibility by allowing parameterization by roles and specific users, while maintaining adherence to business rules. The requirement for mandatory derivation of the Setup Sheet from an approved Technical Sheet ensured traceability between specification and factory execution. The APIs were standardized and submitted to integration tests, ensuring interoperability and consistency in external consumption. Furthermore, the complete audit trails—recording identity, role, decision, and timestamp—strengthened document governance. Finally, the endpoints maintained stable performance even under load scenarios, validating the system's scalability.

IV.2 HARDWARE AND BACKEND INTEGRATION

With the arrival and validation of the Raspberry Pi 5 and ESP32 hardware, the transition began from the code previously tested in simulation to the factory environment. This stage was carried out using an incremental integration approach, including bench tests and fine adjustments to communication protocols to ensure stability and adherence to real operating conditions. The first focus was on the ESP32 communication module, which was configured with firmware capable of supporting multiple communication channels, performing UART tests for interaction with sensors and actuators, as well as direct synchronization with the Raspberry Pi 5. The priority was to achieve low latency and deterministic response. To this end, a bottom-up methodology was adopted, in which lower-level routines were validated individually before assembling the main flow. Next, the Raspberry Pi 5 was integrated with the factory backend, receiving routines for collecting processed data from the ESP32 and sending it via REST API, with packet compression and exception handling. Dynamic authentication tokens were implemented in accordance with security guidelines, and load scenarios with multiple simultaneous connections were evaluated, simulating high-demand factory conditions. The integration followed Continuous Integration (CI) practices, with incremental builds and automated tests for each modification to drivers or communication routines.

Subsequently, synchronization tests were performed between the hardware and the factory system, validating consistency between the Raspberry Pi's local records and the data stored in the Horus database. Watchdogs were also implemented on the ESP32 to enable automatic reboot in case of communication failures, and peak-production tests were conducted with multiple meters connected. This phase followed principles of fault tolerance and minimal redundancy, supported by detailed logs for auditing and performance analysis. The results confirmed the robustness of the architecture, real-time traceability in Horus, and resilience against communication failures, preparing the solution for the next stage: the Production Control Module, focused on continuous data collection and metrics calculation such as productivity, downtime, losses, and rework. In parallel with the hardware integration, refinement of the template management module was carried out, focusing on code modularization, removal of redundancies, and performance optimization, ensuring greater structural clarity and maintainability. In terms of UX/UI, adjustments were applied to improve visual consistency and simplify navigation flows, reinforcing adherence to the standards established for the system.

Figure 7: Folders with refactored modules.
Source: Authors, (2026).

Critical bugs identified in template creation were corrected, including field validation failures, integration issues, and inconsistencies found in regression tests. The system's visual standardization was revised, reinforcing responsiveness for different devices. In this context, the Sidebar was redesigned with a scalable layout, optimized hierarchy, and more intuitive navigation, strengthening the visual identity and coherence of the frontend.

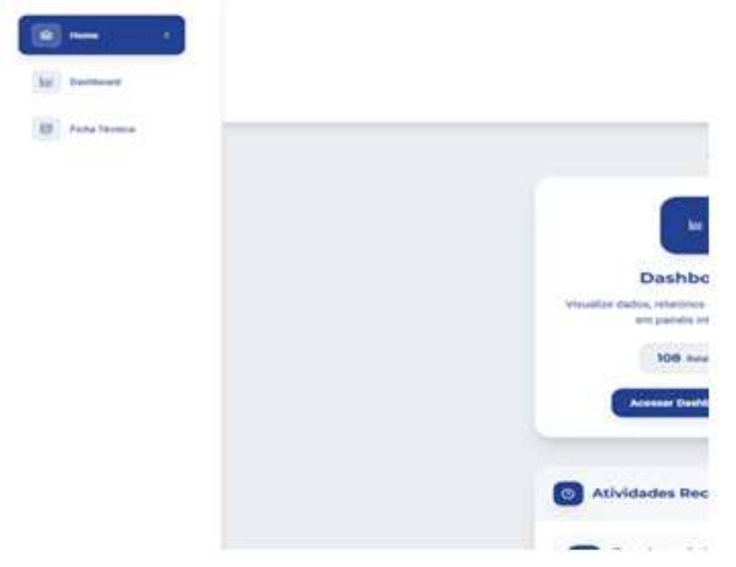

Figure 8: Sidebar.
Source: Authors, (2026).

The integration of the new functionalities into the backend was validated with revised API contracts and end-to-end tests. The DBeaver tool was extensively used to inspect data persistence, verify referential integrity, and confirm alignment between the user interface and the records actually stored in the database.

V. CONCLUSIONS

The execution of the project demonstrated significant progress in consolidating the Technical Data Sheets module, evidenced by the creation of a detailed technical diagram and a mind map that clearly represent the system's functional structure. These tools enabled the visualization of relationships between components and the flow of information, facilitating both the understanding of the module and the identification of potential improvements. In parallel, the functional mockups of the developed system's interfaces provided a solid foundation for validating the user experience, ensuring that the planned functionalities are aligned with operational needs and the manufacturing processes observed during technical visits. The research schedule was restructured according to the new team composition, ensuring optimized resource allocation and the achievement of established deadlines. Technical reports, both individual and consolidated, systematically documented the technical visits, presenting visual and descriptive evidence of the practices and mapped processes, which allowed the identification of critical integration points for the integrated system.

Furthermore, the maintenance of versioned repositories on GitHub ensured efficient control of the source code and associated documentation, promoting transparency and ease of tracking the development process. The initial architectural definitions, involving technologies such as FastAPI, Kafka, MariaDB, and ClickHouse, provided a robust foundation for scalable and efficient system development, ensuring interoperability and reliability in data processing. The detailed mapping of manufacturing processes and the identification of integration points with SIPE reinforce the importance of a structured, process-oriented approach, allowing the Technical Data Sheets module to effectively align with existing operations and support decision-making based on accurate and up-to-date information. In summary, the results obtained so far demonstrate consistent progress, technological integration, and adherence to best development practices, establishing a solid foundation for the next phases from the survey.

VI. AUTHOR'S CONTRIBUTION

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