applied sciences

MDPI

Article

# Using Petri Nets and 4M1E Identification Resolution for Manufacturing Process Control and Information Tracking: Case Study of Transformer Coil Production

**Xuedong Zhang, Wenlei Sun *, Shijie Song and Chen Lu**

School of Intelligent Manufacturing Modern Industry, Xinjiang University, Urumqi 830046, China; 107552204267@stu.xju.edu.cn (X.Z.); songshicn@foxmail.com (S.S.); lixinwang0127@163.com (C.L.)
* Correspondence: xjusunwenlei@163.com

**Abstract:** To solve the problems of chaotic information management and difficult traceability in the manufacturing process of transformer coils, a traceability and management method oriented towards the manufacturing process of transformer coils has been proposed. This method integrates industrial internet identification resolution and extension of Petri net modeling theory. A comprehensive identification and resolution framework for coil manufacturing processes has been constructed. In this manuscript, the authors proposed an industrial data-sharing space based on the producer-consumer model with unified coding identification. This enables information sharing for all resources, including personnel, machinery, materials, methods, environment, and measurements. A method for modeling extensible identification primitives of coil manufacturing process information was proposed, which formalizes the correlation and data structure of process information. A Petri net model for the comprehensive acquisition and integration of elemental information in coil manufacturing processes, as well as a mathematical model for quality traceability, were constructed, thereby forming a complete path for quality traceability information. Finally, based on the method proposed above, a software and hardware environment for identification and traceability for coil manufacturing was established. Taking a certain type of coil as an example, validation was carried out; the results indicate a significant enhancement in the production management and information traceability capabilities of the coil production workshop. This study provides reference and guidance for the process traceability management of power equipment manufacturing.

**Keywords:** transformer coil; production process; information traceability; identification and resolution; extenics; petri net



**Citation:** Zhang, X.; Sun, W.; Song, S.; Lu, C. Using Petri Nets and 4M1E Identification Resolution for Manufacturing Process Control and Information Tracking: Case Study of Transformer Coil Production. *Appl. Sci.* **2024**, *14*, 9321. https://doi.org/10.3390/app14209321

Academic Editor: Alexandre Carvalho

Received: 4 September 2024
Revised: 8 October 2024
Accepted: 9 October 2024
Published: 12 October 2024



## 1. Introduction

Transformers play a crucial role in the process of power transmission and transformation, serving as a core component in clean energy systems and transmission facilities. It provides stable energy transmission and conversion services essential for industrial production and people's livelihood. Coil, as the key component of transformer equipment, requires effective traceability and management during the manufacturing process to ensure quality and efficiency. In recent years, with the maturation and development of new-generation information technologies, research and applications in product information traceability and data integration have been increasing. This provides new methods and means for the traceability and management of transformer coil manufacturing processes.

Some scholars have explored and practiced the traceability and management of product information, achieving certain progress. Kuhn [1] proposed a traceability modeling approach based on the Neo4j graph database, suitable for customized and complex manufacturing systems, overcoming the reliance of existing models on the identification of physical objects. Bougdira [2] introduced a traceability model comprising intelligent traceability description, ontology modeling, and cloud-based applications, supporting remote sharing and querying of traceable information. Schuitemaker [3] explored the commonalities and differences in the framework design, implementation techniques, and data analysis of traceability systems, identifying three key components: product identification, transformation/routing files, and product attribute tracking. Chien [4] developed an integrated approach combining adaptive machine learning and nonlinear regression to accurately predict the final product quality of power transformers through digital transformation. SHI [5] constructed a traceability system for the circulation quality of traditional Chinese medicinal materials based on blockchain and NB-IoT technology, enabling real-time monitoring and information collection of the medicinal materials circulation process. Li [6] discussed the construction of a traceability system for special equipment, aiming to enhance the quality and safety management level of special equipment through traceability systems and standardization measures. CHEN [7] investigated the current application status of blockchain technology in the anti-counterfeiting traceability of products, especially in food packaging, electronic evidence preservation, and prescription drug traceability, arguing that blockchain technology provides a reliable and efficient solution to address trust issues in food safety. Li [8] proposed a QR code-based traceability system for key components to address the problems of chaotic management in automated production workshops and difficulties in tracing key components. For the manufacturing process of transformers, Zaoli Y [9] proposed a cloud-based q-rung orthogonal fuzzy multi-criteria framework to evaluate the manufacturing process of green distribution transformers. They identified key factors for improving manufacturing quality and expert recognition. Lettner [10] explored the application of machine learning in optimizing the manufacturing process of transformer cores in smart factories and proposed a method to support knowledge transfer between software systems. Noamna S [11] improved the efficiency of small transformer production through lean production methods and value stream mapping (VSM) analysis. Atamanchuk G [12] proposed a phased adjustment method for existing transformer manufacturing machines applicable to peripheral component production lines such as cores or tanks. However, the above-mentioned methods have not formed a unified resource identification and data-sharing system. There is a lack of structured integration of process data and formalized modeling of traceability paths, which makes it difficult to trace and manage information related to transformer coil manufacturing processes. This results in low accuracy and poor timeliness in traceability efforts.

In summary, previous research has proposed theoretical models and implementation strategies for information traceability and management, which have provided valuable insights into the traceability and management of information in the process of coil manufacturing to some extent. However, these methods still have some shortcomings. They have not formed a unified traceability information identification and sharing system, and they lack comprehensive data integration of traceability process elements and modeling of traceability paths. These deficiencies challenge the efficiency and accuracy of information traceability in the transformer coil manufacturing process. Integrating industrial Internet identification resolution and extension Petri nets can effectively address these issues, thereby achieving unified identification, modeling, and traceability of process information. Therefore, this study proposes a method for traceability and management of transformer coil production processes by integrating identification resolution and extension Petri nets. Unique identifiers are assigned to various resources and stages within the manufacturing of transformer coil products. Based on the Extenics information primitive model of coil production, a process traceability model based on manufacturing information flow is constructed, which realizes real-time monitoring and data integration of the entire manufacturing process, focuses on key influencing factors and bottleneck links in the manufacturing process, and achieves efficient traceability and management of production process and quality. The main contributions of this paper include the following:

Proposed a modeling method for a 4M1E identification resolution system and a shared space model of the entire process data for coil manufacturing.

Proposed a method for modeling extensible identification fundamentals for information related to the coil manufacturing process.

Developed a Petri net model for the collection and integration of comprehensive data elements in the coil manufacturing process, as well as for information traceability, enabling the formal modeling of information traceability paths.

## 2. Background

### 2.1. Industrial Internet Identification and Resolution

The industrial internet identification and resolution system is a technical framework specifically designed to meet the demands of industrial production aimed at providing efficient, secure, and stable identification services. Its core theory is based on the precise management of object identities, enabling lifecycle management of equipment, personnel, and materials through functions such as identification distribution, registration, resolution, and routing. The essence of this system lies in achieving seamless information interchange and sharing, allowing different systems, devices, and data to collaborate effectively, thereby enhancing overall production efficiency and resource utilization. On a technical level, the current identification and resolution system primarily relies on the Handle system, a globally distributed identification service. The Handle system employs a layered service model that consists of multiple parallel Global Handle Registries (GHR) and Local Handle Services (LHS), facilitating dynamic and flexible resolution requests. Its open protocol and namespace design enable efficient identification and management of various digital objects, services, and network resources. By providing effective identity identification and resolution capabilities, the system significantly mitigates data silos, laying a foundation for real-time data analysis and decision-making.

### 2.2. Petri Net Theory

In the field of system theory and applications, Petri nets are widely adopted as a formal tool for simulating and analyzing complex systems involving concurrent operations and resource allocation. As an effective system modeling and analysis tool, Petri nets enhance the descriptive capability of system operations, facilitating a deeper understanding of their complexity and interactions. The core of Petri nets lies in their graphical representation, utilizing places (representing states) and transitions (representing changes) to depict the dynamic behavior of the system. Each place can store a certain number of tokens, and the distribution of these tokens reflects the system's state. Through transitions, tokens move between places, thereby simulating system behavior and resource flow. Petri nets possess powerful analytical capabilities, enabling the identification of potential issues within the system and assisting in the design of more efficient and reliable systems. Through visualization and formalization, Petri nets provide system designers with intuitive understanding tools that aid in identifying bottlenecks, reducing costs, and improving efficiency. In modern systems engineering, Petri nets play an indispensable role, offering robust theoretical support and practical guidance for the design and optimization of complex systems.

### 2.3. Extenics Theory

Extenics is an original interdisciplinary field proposed by Chinese scholars, aimed at exploring the possibilities of expanding affairs and the rules and methods of innovation through formalized models. Its core theoretical framework includes the fundamental theory, extensional set theory, and extensional logic, with the fundamental theory serving as the foundation for all extensional theories. In the areas of system modeling and data modeling, extenics holds significant application value. The fundamental theory utilizes elementary units—object elements, event elements, and relationship elements (collectively referred to as "fundamentals")—to unify the characteristics of quality and quantity, action and relation within a triplet, thereby formally describing objects, events, and relationships. This structured approach allows for the clear modeling of dynamic behaviors and data in complex systems, facilitating analysis and optimization. Additionally, based on extensional set theory, composite elements can be established to describe more complex affairs and relationships, such as information, knowledge, and strategies. This capability enables extenics to demonstrate powerful potential in big data analysis, dynamic system modeling, and decision support systems, effectively handling multidimensional and dynamically changing data, and providing new theoretical support and practical guidance for modern systems engineering.

## 3. Related Work

In recent years, the construction and application of the Industrial Internet identification resolution system have opened up new ideas and pathways for information traceability and management. The identification resolution system assigns unique identity tags to each physical or virtual entity, enabling the tagging, management, and localization of resources. It facilitates the interconnection and interoperability of resources, as well as the acquisition, processing, transmission, and exchange of related information, thereby achieving interconnectedness and efficient management of information. Ren [13] studied the IRSII progress and classified existing identity resolution systems into two categories based on the evolution mode: DNS improvement path and DNS-independent innovation path. Wan [14] analyzed the construction scheme of key technology systems such as the network, logo analysis, platform, and security of the industrial internet. He also explored the application mode of the industrial internet in combination with the application practice of traditional industries, such as manufacturing, packaging, and printing. Song [15] combined the OPC-UA system architecture with the identification parsing service to better integrate the latter with the equipment and perform efficient collection of key data in all the production aspects. Zou [16] conducted unified hierarchical registration and real-time analysis of different enterprises, orders, equipment, materials, production processes, and products through the identification analysis system. Wu [17] developed the industrial Internet identification and resolution node system for the instrument and meter industry. This allowed the achievement of unified coding and connected the national top nodes and enterprise nodes, which ensures data coherence across the entire value chain of the instrumentation and metering industry. Fei [18] pioneered the new chemical materials industry, achieving cross-regional, cross-industry, and cross-enterprise data sharing through the use of industrial internet identification and resolution technology. He demonstrated innovative applications such as product life cycle tracking, product quality traceability, and industrial chain collaboration. Diao [19] designed the platform architecture, application architecture, and functional architecture of the secondary nodes of the petrochemical industry. He also studied the innovation scenario of the identification and resolution system according to the characteristics of the petrochemical industry, including production, equipment, and energy management. This design lays the foundation for the construction of an industrial internet + smart factory in the petrochemical industry. Li [20] studied the construction approach of industry secondary nodes based on the Handle system. He also proposed a Handle identification analysis system and a technical realization method that can be applied to the electric power equipment manufacturing industry.

In addition, the extension Petri net, as a powerful tool for system modeling and analysis, offers significant advantages in describing dynamic behaviors of complex systems, analyzing system performance, optimizing resource allocation, and modeling information traceability. Giua [21] provided an overview of the historical development of Petri nets in the fields of system theory and automatic control, with a focus on their representative applications in discrete system modeling. Jangid [22] investigated the reachability and topological properties of Petri nets in concurrent systems, discussing methods for homomorphically simplifying reachability trees and identifying multidimensional topological networks, offering new perspectives for analyzing the business flow, information flow, and data flow of concurrent systems. Grobelna [23] presented the application of Petri nets in modeling manufacturing systems and analyzed current technological challenges and opportunities. Kaid [24] addressed the issue of unreliable resources in Petri net-based automated manufacturing systems by employing neural networks and colored Petri nets to tackle deadlock and fault detection problems. Jiliang Luo [25] proposed an optimization modeling method based on Petri nets and deep reinforcement learning for task assignment and real-time scheduling in automated manufacturing systems.

## 4. Materials and Methods

### *4.1. Structure and Process of Coil Production*

Transformers are precision electrical devices based on the principle of electromagnetic induction, involving multiple manufacturing processes and strict design standards. Among them, coils are the core components of transformers, possessing certain electrical, thermal, and mechanical strengths. Coils are composed of enameled wire and insulation materials, requiring uniform winding of copper wire on molds, with strict adherence to the accuracy of turns and positions. Taking the manufacturing of coils for a specific model of 110 kV transformer as an example, it involves complex process steps such as inner mold assembly, coil winding, terminal welding, outer mold assembly, resin pouring, drying and curing, mold disassembly, airway board disassembly, coil grinding, and dimensional inspection. The structure and process of coil products is shown in Figure 1.

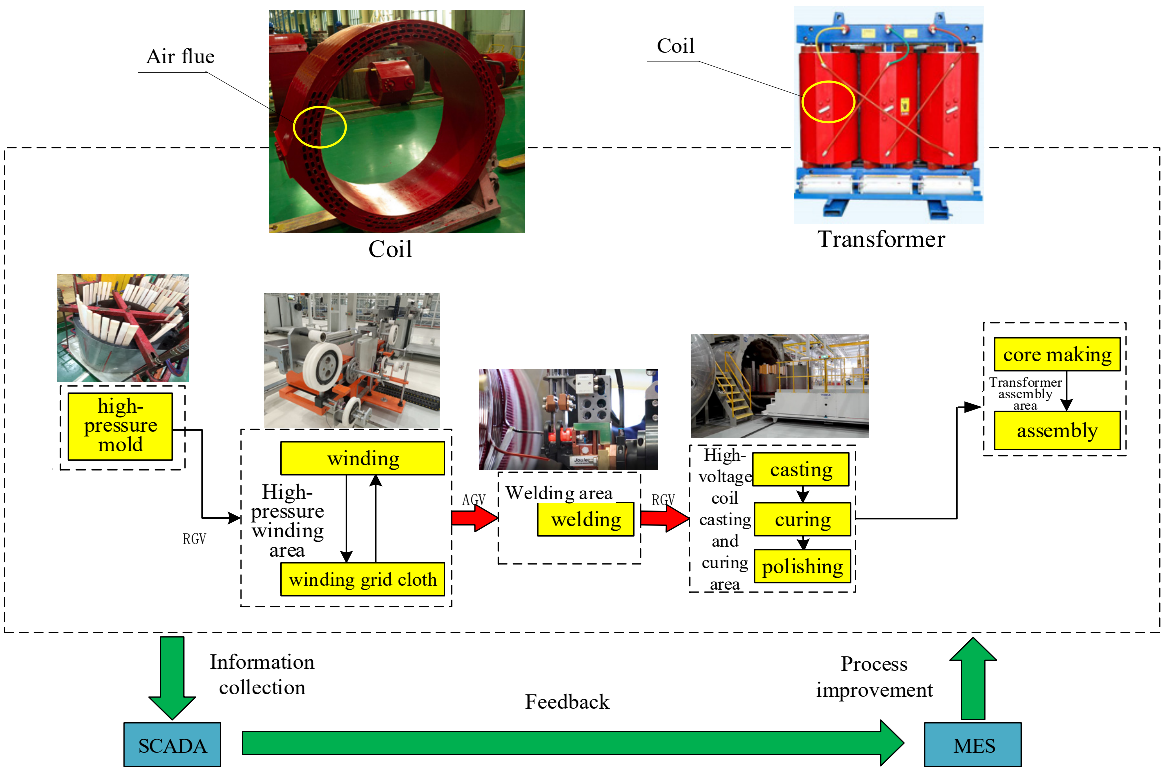



**Figure 1.** Structure and process of coil production.

### *4.2. Construction of Identification and Resolution System for Coil Manufacturing*

#### 4.2.1. Identification and Encoding Methods for All Element Information

Based on the industrial Internet identification resolution system, unique codes are assigned to the "4M1E" (Man, Machine, Material, Method, Environment) in the coil production workshop, marking, managing, and locating all element resources in the workshop. This facilitates the interconnection, information acquisition, processing, transmission, and exchange of all element resources, thereby providing high-value data resources and operational means for deep, intelligent scenario applications in the coil workshop. To achieve unified coding and identification of all elemental resources in the coil workshop, the Handle coding rule is adopted. The code structure consists of an identification prefix and an identification suffix, separated by the UTF-8 character "/". The identification prefix is composed of the country's top-level node code, the secondary node code, and the enterprise node code, separated by the UTF-8 character ".". The identification suffix consists of element types, element object codes, etc., separated by the UTF-8 character ".". Element types are divided according to the categories of Man, Machine, Material, Method, Environment, and Measurement. The schematic of the identification coding specification is shown in Figure 2.

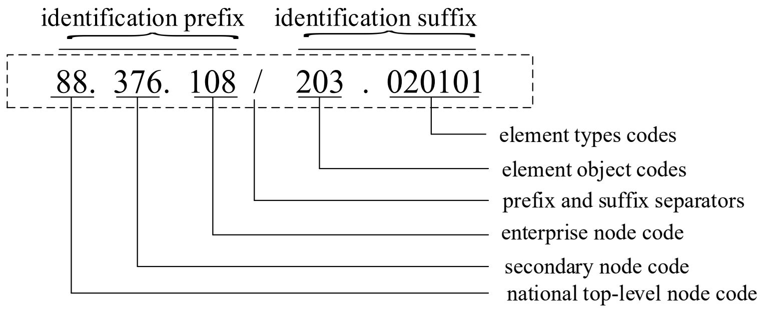



**Figure 2.** Illustration of identification code specification.

Based on the aforementioned identification coding rules, the coding of all elemental objects involved in the coil product manufacturing process exhibits a hierarchical structure. The enterprise code serves as the top-level code within the enterprise; for example, "88.376.108" represents a certain transformer coil production enterprise. Subsequently, based on the categories of Man, Machine, Material, Method, Environment, and Measurement, the code is divided into six major classes. Using the enterprise code as a foundation, six secondary codes are constructed by concatenating fields. For instance, "88.376.108/1" to "88.376.108/6" represent the codes for the major categories of Man, Machine, Material, Method, Environment, and Measurement, respectively. Following this pattern, the next level of type codes is progressively concatenated. The encoding of all elemental information is illustrated in Tables 1–6.

**Table 1.** Personnel element types and codes based on identification resolution.

| Serial Number | Major Element Category | Category Code | Element Type | Element Type Code | Element and Identifier Code (Illustration) |
|---|---|---|---|---|---|
| 1 | Man | 88.376.108/1 | R&D engineer | 88.376.108/101 | 88.376.108/101.001010 (Engineer A) |
| 2 | | | Process design engineer | 88.376.108/102 | 88.376.108/102.227758 (Engineer B) |
| 3 | | | Procurement engineer | 88.376.108/103 | 88.376.108/103.032711 (Engineer C) |
| 4 | | | Production engineer | 88.376.108/104 | 88.376.108/104.062001 (Engineer D) |
| 5 | | | Quality engineer | 88.376.108/105 | 88.376.108/105.094221 (Engineer E) |
| 6 | | | Inspection engineer | 88.376.108/106 | 88.376.108/106.403581 (Engineer F) |
| 7 | | | Testing engineer | 88.376.108/107 | 88.376.108/107.350021 (Engineer G) |

**Table 2.** Equipment element types and codes based on identification resolution.

| Serial Number | Major Element Category | Category Code | Element Type | Element Type Code | Element and Identifier Code (Illustration) |
|---|---|---|---|---|---|
| 1 | Machine | 88.376.108/2 | Work center | 88.376.108/201 | 88.376.108/201.21 (Winding station) |
| 2 | | | Tooling | 88.376.108/202 | 88.376.108/202.010101 (Coil fixing jig) |
| 3 | | | Equipment | 88.376.108/203 | 88.376.108/203.020101 (High-frequency induction welding machine) |
| 4 | | | AGV | 88.376.108/204 | 88.376.108/204.101 (Coil transfer AGV) |
| 5 | | | Mold | 88.376.108/205 | 88.376.108/205.0401 (Coil inner mold) |
| 6 | | | Production line | 88.376.108/206 | 88.376.108/206.014 (Body assembly line) |
| 7 | | | Instrument | 88.376.108/207 | 88.376.108/207.020234 (Insulation resistance measurement equipment) |
| 8 | | | Stereo warehouse | 88.376.108/208 | 88.376.108/208.011 (Raw material warehouse) |
| 9 | | | Transportation line | 88.376.108/209 | 88.376.108/209.014 (Voltage coil guide roller) |

**Table 3.** Material element types and codes based on identification resolution.

| Serial Number | Major Element Category | Category Code | Element Type | Element Type Code | Element and Identifier Code (Illustration) |
|---|---|---|---|---|---|
| 1 | Material | 88.376.108/3 | Raw materials | 88.376.108/301 | 88.376.108/301.02010045 (Enamel wire) |
| 2 | | | Components | 88.376.108/302 | 88.376.108/302.20010120 (Clamp) |
| 3 | | | Semi-finished products | 88.376.108/303 | 88.376.108/303.23010101 (Support pillar) |
| 4 | | | Parts | 88.376.108/304 | 88.376.108/30425030108 (Coil) |
| 5 | | | Finished product | 88.376.108/305 | 88.376.108/305.10013523 (Transformer) |
| 6 | | | Standard part | 88.376.108/306 | 88.376.108/306.03010203 (M12 Nut) |
| 7 | | | Spare part | 88.376.108/307 | 88.376.108/307.30040798 (M20 Grounding bolt) |

**Table 4.** Process element types and codes based on identification resolution.

| Serial Number | Major Element Category | Category Code | Element Type | Element Type Code | Element and Identifier Code (Illustration) |
|---|---|---|---|---|---|
| 1 | Method | 88.376.108/4 | Process route | 88.376.108/401 | 88.376.108/401.PP10013523 (10013523 Coil process route) |
| 2 | | | Certain manufacturing process | 88.376.108/402 | 88.376.108/402.1001352307 (Winding process) |
| 3 | | | Certain inspection process | 88.376.108/403 | 88.376.108/403.11001352334 (Partial discharge testing) |
| 4 | | | Certain transportation process | 88.376.108/404 | 88.376.108/404.RK10013523 (Finished product storage) |
| 5 | | | Process document | 88.376.108/405 | 88.376.108/405.SOP10013523 (10013523 Assembly process SOP) |
| 6 | | | Testing process | 88.376.108/406 | 88.376.108/406.SY10013523 (10013523 Finished product testing) |

**Table 5.** Environment element types and codes based on identification resolution.

| Serial Number | Major Element Category | Category Code | Element Type | Element Type Code | Element and Identifier Code (Illustration) |
|---|---|---|---|---|---|
| 1 | Environment | 88.376.108/5 | Temperature | 88.376.108/501 | 88.376.108/501.100101 (Drying tank 01 temperature) |
| 2 | | | Humidity | 88.376.108/502 | 88.376.108/502.100201 (Drying tank 01 humidity) |
| 3 | | | Lighting | 88.376.108/503 | 88.376.108/503.102 (Lighting at winding station measurement point) |
| 4 | | | Air pressure | 88.376.108/504 | 88.376.108/504.100401 (Drying tank 01 air pressure) |
| 5 | | | Dust | 88.376.108/505 | 88.376.108/505.113 (Dust at winding station measurement point) |
| 6 | | | Noise | 88.376.108/506 | 88.376.108/507.104 (Noise at winding station measurement point) |

**Table 6.** Detection element types and codes based on identification resolution.

| Serial Number | Major Element Category | Category Code | Element Type | Element Type Code | Element and Identifier Code (Illustration) |
|---|---|---|---|---|---|
| 1 | Measurement | 88.376.108/6 | Inspection item | 88.376.108/601 | 88.376.108/601.3004512 (Coil inner diameter) |
| 2 | | | Inspection requirement | 88.376.108/602 | 88.376.108/602.100023 (Tolerance upper and lower limits of 0.1 mm) |
| 3 | | | Inspection tool | 88.376.108/603 | 88.376.108/603.3001011 (Digital caliper) |
| 4 | | | Inspection fixture | 88.376.108/604 | 88.376.108/604.020201 (Internal diameter gauge) |

#### 4.2.2. A Shared Space Model for Full Process Data

To achieve rapid positioning, addressing, and information sharing of all-element resources and full-process data in coil production processes, a parsing and sharing system for coil production data are constructed based on the Industrial Internet identification resolution platform. Taking the entire process path of coil production as the main focus, a producer-consumer industrial data-sharing space model for coil production is constructed, as illustrated in Figure 3. This enables the realization of identity-based, all-element, and all-process resource operation and integration. The client serves as the operational gateway and is responsible for initiating identification resolution requests. The GHR (Global Handle Registry) acts as the central registration and management node, maintaining unified records of global identifiers. Meanwhile, the LHS (Local Handle Server) functions as the provider of local identification services, managing partial namespaces and responding to local resolution demands. Together, they form the identification resolution framework of the Handle system, facilitating the allocation, management, and resolution services of globally unique identifiers. By establishing data mutual recognition, data mapping, and interaction protocols among various resources and data segments, comprehensive resolution services are achieved, mapping identifiers to identifiers, identifiers to addresses, and identifiers to data. According to relevant standards, a unified management and heterogeneous-compatible identification resolution node service network is formed, promoting the interconnection and interoperability of multiple identification systems. This addresses the lack of rule interchangeability and compatibility caused by differences in data definitions and structures during coil production processes.

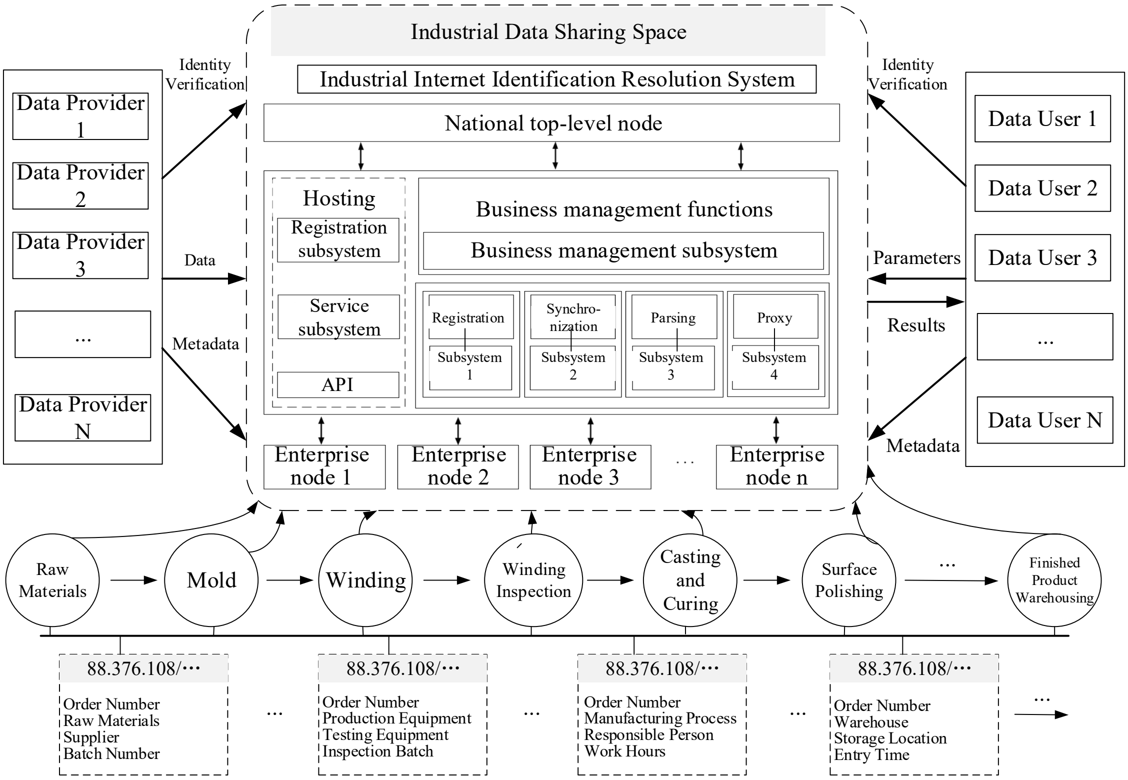



**Figure 3.** Overall process and architecture for data parsing and sharing in coil production.

### 4.3. *Extenics-Based Identification Primitive Modeling of Coil Manufacturing Process Information*

In Extenics set theory, matter elements (denoted by $M$), events (denoted by $A$), and relationship elements (denoted by R) are collectively referred to as basic elements (denoted by $Q$). Based on this formalized modeling theory, identification information elements for the manufacturing process of coil products can be established. These elements are used to describe the physical objects, such as equipment, personnel, materials, etc., that exist in the workshop reality, as well as processes, algorithms, and other virtual resources. Identification information elements for the manufacturing process of coil products are established to describe the events occurring during the coil manufacturing process and the interactions between resource objects. Relationship elements for the manufacturing process of coil products are established to formalize the relationships between objects and events. Let symbol $O$ represent a certain identification object, where c denotes the characteristic attribute of object $O$, and $v$ represents the corresponding value of characteristic c. This elemental representation can be depicted as $Q = (O, c, v)$ using an ordered triple, where the key-value pair $(c, v)$ forms the characteristic element of object $O$. Assuming a given elemental entity (physical, event, or relational) possesses $n$ characteristics, the entity can be formally represented using a matrix composed of characteristics $c_i$ ($i = 1, 2, \ldots, n$) and their corresponding values $v_i$ ($_i = 1, 2, \ldots, n$), as shown in Equations (1)–(3). Here, $Q_m$ represents a physical element, $Q_a$ represents an event element, and $Q_r$ represents a relational element.

$$Q_m = (O_{mj}, C_{mi}, V_{mi}) = \begin{bmatrix} O_{mj}, & c_{m1}, & v_{m1} \\ & c_{m2}, & v_{m2} \\ & \vdots & \vdots \\ & c_{mn}, & v_{mn} \end{bmatrix} \tag{1}$$

$$Q_a = (O_{aj}, C_{ai}, V_{ai}) = \begin{bmatrix} O_{\mathrm{aj}}, & c_{a1}, & v_{a1} \\ & c_{a2}, & v_{a2} \\ & \vdots & \vdots \\ & c_{an}, & v_{an} \end{bmatrix} \tag{2}$$

$$Q_r = (O_{rj}, C_{ri}, V_{ri}) = \begin{bmatrix} O_{\mathrm{rj}}, & c_{r1}, & v_{r1} \\ & c_{r2}, & v_{r2} \\ & \vdots & \vdots \\ & c_{rn}, & v_{rn} \end{bmatrix} \tag{3}$$

In the manufacturing process of coil products, there exists diverse and complex product forms, process events, and the interrelations between events and resources. For instance, a coiled product can be perceived as an entity composed of various raw materials and components, where its production activities entail the process of merging different resources and information units through specific rules. This complexity of processes, logic, and relationships can be described and expressed using the theory of compound elements in extension set theory. Based on the compound element model, the 4M1E elements of coil production and the pairwise correlations and interactions between objects and objects, events and events, and objects and events in the production process can be realized. The nested parent-child structure of resource entities is formalized using compound physical elements as $Q_{\mathrm{m1}}(Q_{\mathrm{m2}}(Q_{\mathrm{m3}})) = [Q_{\mathrm{m1}}, C_{\mathrm{m1}},(Q_{\mathrm{m2}}, C_{\mathrm{m2}}, C_{\mathrm{m3}}(Q_{\mathrm{m3}}))]$. Similarly, the causal relationships between events and changes in product states in the coil manufacturing process can be described in the form of compound event elements $Q_{\mathrm{a1}}(Q_{\mathrm{a2}}(Q_{\mathrm{a3}}))[Q_{\mathrm{a1}}, C_{\mathrm{a1}},(Q_{\mathrm{a2}}, C_{\mathrm{a2}}, C_{\mathrm{a3}}(Q_{\mathrm{a3}}))]$. Furthermore, the relationships between products and events, materials and events, equipment and events, and events and events can be depicted in the form of compound relational elements $Q_{\mathrm{r1}}(Q_{\mathrm{r2}}(Q_{\mathrm{r3}})) = [Q_{\mathrm{r1}}, C_{\mathrm{r1}},(Q_{\mathrm{r2}}, C_{\mathrm{r2}}, C_{\mathrm{r3}}(Q_{\mathrm{r3}}))]$. In the Extension Strategy Generating System(ESGS), the most fundamental data structures are the elemental and compound element structures described above. In the coil production process, there are multiple operational steps and stages, where each production activity selectively operates on certain resources as per specific rules, logic, and procedures under certain conditions. Modeling these production activities using a compound element model is illustrated in Equation (4); for a specific production activity, let it be represented by the composite element $A$. Then, for any $A$, it can be constructed using at least one physical element $Q_m$, one event element $Q_a$, and one relational element $Q_r$.

$$A = Q_m \otimes Q_a \otimes Q_r \tag{4}$$

In the transformer coil production workshop, there is a large quantity of all-factor resources, including personnel, machinery, materials, methods, and environment, resulting in a vast number of traceability information elemental models. This can lead to confusion and ambiguity in the relationships and identities of data and resources. To address this issue, the Industrial Internet Identification and Resolution code can serve as a bridge connecting production resources and traceability information. Each instance of machinery, materials, processes, semi-finished products, and information elements involved in the coil manufacturing process is assigned a unique code identifier. Through the integration of identification resolution methods with the extensible element theory, a core-based identification element information model for the "4M1E" elements of coil production is constructed. This facilitates the establishment of a traceability information association network with clear hierarchies and defined structures. Each elemental unit corresponds to production traceability information in the database table. Drawing from the object modeling principles in software engineering, meta-model elements are defined to imbue objects with internal structure and variability. Through this approach, real-world entities, events, and relationships are systematically mapped and associated with virtual models within the information system. This process is illustrated in Figure 4.

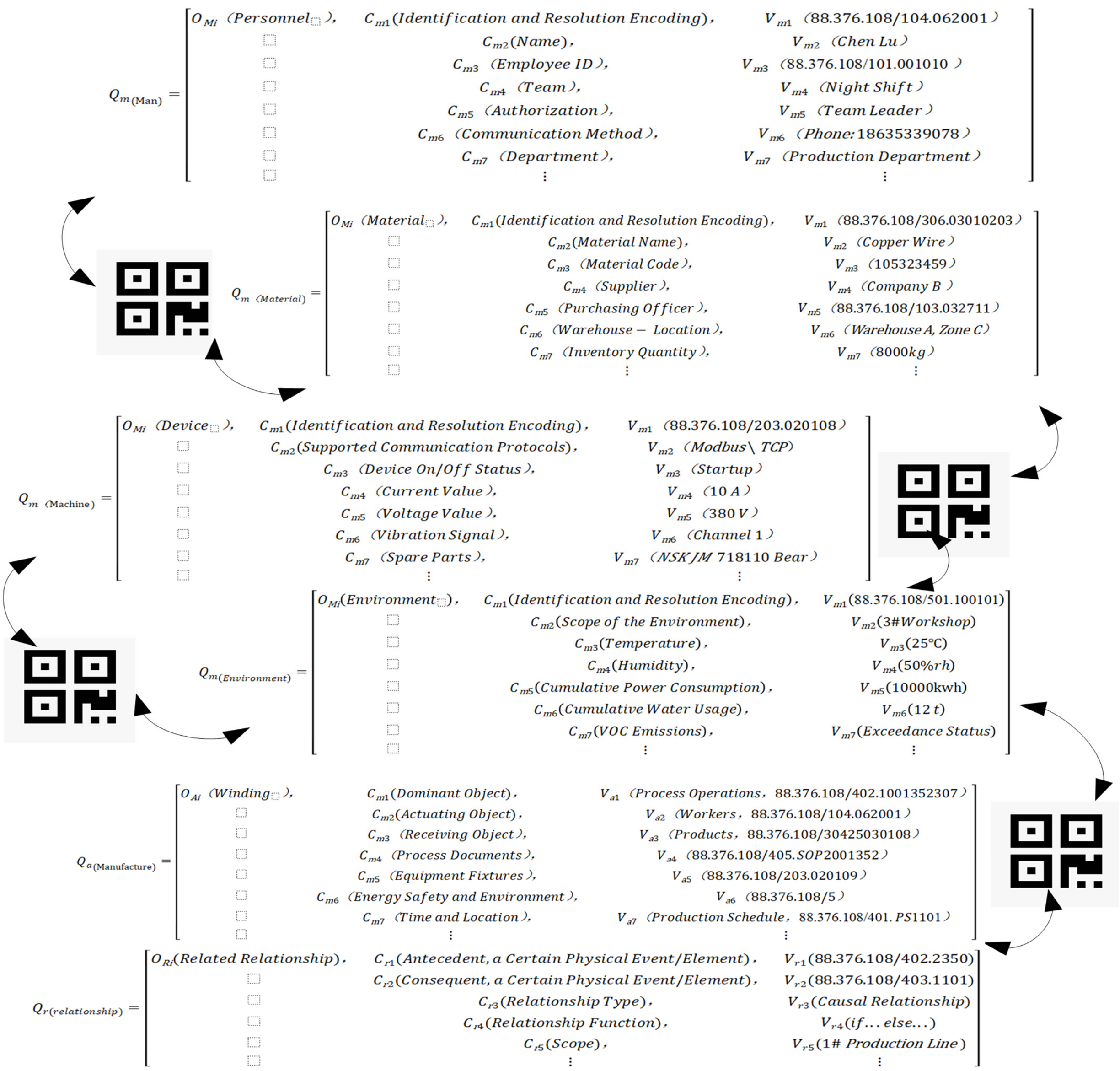



**Figure 4.** Integration and fusion of production information elements based on identification resolution code.

### *4.4. Information Fusion and Traceability of Coil Manufacturing Process Based on Extensible Petri Net Models*

#### 4.4.1. All Elements Information Fusion Based on Extensible Petri Net Model

By deeply integrating identification resolution code, expandable information element modeling, and Petri nets, the coil manufacturing process is modeled and simulated to achieve high-fidelity modeling of process information propagation paths and process traceability. The identification resolution expandable Petri net for coil production process traceability can be considered as a septuple composed of the finite sets of places $P$ and transitions $T$, the directed arcs set $F$, the expandable element sets ($Q_m$, $Q_a$, $Q_r$), and the mapping set f as follows:

$$\sum\nolimits_{\mathrm{petri}} = \{P, T, F, Q_m, Q_a, Q_r, f\} \tag{5}$$

where $P = \{P_1, P_2, \ldots, P_\mathrm{i}\}$ represents all the variations of information surrounding the coil product manufacturing process. $T = \{t_1, t_2, \ldots, t_i\}$ represents the processes where changes occur in the position, quality, and form of the coil product. $F \subseteq (P \times T) \cup (T \times P)$ represents the directed arcs connecting $P$ and $T$. $Q_m$, $Q_a$, and $Q_{r,}$ respectively, denote the information resource entity elements, process event elements, and process relationship elements revolving around coil product manufacturing. $f = \{f_P, f_T, f_F\}, f_P, f_T, f_F$ are mappings of place $P$ to element $Q_m$, transition $T$ to element $Q_a$, and directed arc $F$ to element $Q_{r,}$ respectively.

The identification-resolving expandable Petri net for traceability of coil production processes simulates and analyzes system behavior through the interaction of four basic elements: places $P$, transitions $T$, directed arcs $F$, and token. $P$ represents the system's states, depicted by circles; transitions represent events in the system, depicted by short rectangles; directed arcs define the causal relationships between states and events, depicted by arrows; while tokens indicate whether states satisfy the transition conditions. The specific symbols are illustrated in Figure 5.

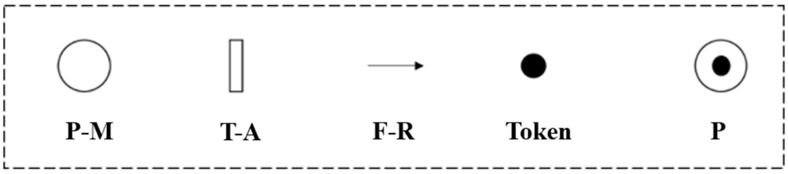
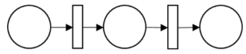
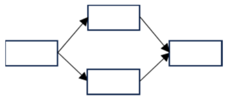
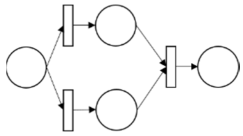
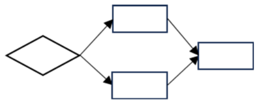
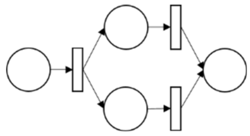
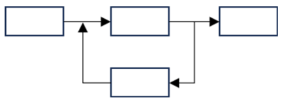
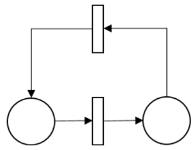



**Figure 5.** Related Symbols of Petri Net.

The transformation process of coil production involves four possible forms: sequence, selection, parallel, and loop. In the modeling process of identification-resolving expandable Petri nets, these forms can be achieved by adjusting the connections between transitions and places. Sequential structure uses a concatenation between places and transitions to represent the sequential execution of tasks. The selection structure employs multiple output places to represent different branching paths, thus implementing decision-making functionality. The parallel structure reflects the simultaneous execution of multiple tasks through branching transitions. The loop structure simulates repetitive activities by using closed-loop directed arcs returning to input places. The representations of these four relationships and their corresponding expandable transformations in Petri nets are illustrated in Table 7:

**Table 7.** Relationship table between business processes and Petri net.

| Logical Relationship | Business Process | Petri Net Representation |
|---|---|---|
| Sequential relationship |  |  |
| Parallel relationship |  |  |
| Selection relationship |  |  |
| Loop relationship |  |  |

Based on the modeling method described above, a dynamic system model of the coil product manufacturing process is constructed by closely integrating the business flow, data flow, and information flow of coil production. This formalizes descriptions of the physical-temporal processes, event response mechanisms, unit behavior rules, operational transformation logic, etc., in coil manufacturing. This, in turn, provides a theoretical foundation for information traceability in coil production. The identification resolution and expandable Petri net construction process for transformer coil production involve the following three steps:

(1) Define the sets of places and transitions of the system model based on the technological processes and business operational flows of coil production.
(2) Describe the extension of each transition through interactions between places and transitions, thereby forming a network structure with causal relationships and sequential orders, further constructing a set of directed arcs.
(3) Establish mapping relationships of system model elements, including places to object elements (such as equipment, materials, and related information entities), transitions to event elements (such as manufacturing, inspection, etc.), and directed arcs to relation elements (such as relationships of quality data and information or resource flows), enabling the Petri net to accurately simulate and analyze the entities and information flows in the actual business processes of coil production. The mapping of places and transitions sets to resources and conditions in the production process is shown in Table 8.

**Table 8.** Collection of places and transitions in extendable Petri net model of identification resolution in the coil production process.

| Place | Description | Transition | Description |
|---|---|---|---|
| $P_1$ | Coil production order (Including material code, order number, process path, planned start time, planned completion time and other information) | $t_1$ | Scan identification to decode and start work |

**Table 8.** *Cont.*

| Place | Description | Transition | Description |
|---|---|---|---|
| $P_2$ | Internal mold assembly (Including mold number, mold model, size parameters and other information) | $t_2$ | Personnel-order-mold identification association; Process information identification association |
| $P_3$ | Material flow (Including AGV number, starting point, ending point, path, and other information) | $t_3$ | AGV-mold identification association |
| $P_4$ | Winding station operation (Including personnel code, skills, winding equipment code, equipment operation parameters, workstation coordinates, start time, completion time, and other information) | $t_4$ | Personnel-order-equipment-process-semi-finished coil identification association; Process information identification association |
| $P_5$ | Real-time monitoring of coil winding (Including equipment code, inspection items, inspection standards, and other information) | $t_5$ | Coil size detection and result association |
| $P_6$ | Terminal welding station operation (Including welding equipment code, process parameters, and other information) | $t_6$ | Process information identification association |
| $P_7$ | External mold assembly station operation (Including mold number, mold model, size parameters, and other information) | $t_7$ | Personnel-order-mold identification association; Process information identification association |
| $P_8$ | Resin Casting Operation (Including casting equipment number, temperature, pressure, formulation, and other process information) | $t_8$ | Equipment-formula-semi-finished product identification association; Process information identification association |
| $P_9$ | High-pressure curing furnace operation information (Including equipment number and temperature of the furnace, and other process information) | $t_9$ | Equipment-semi-finished product identification association; Process information identification association |
| $P_{10}$ | Mold disassembly station operation (Including equipment number, disassembly sequence, working hours, and other information) | $t_{10}$ | Robot-semi-finished product identification association; Process information identification association |
| $P_{11}$ | Grinding station operation (Including personnel number, equipment number, working hours, and other information) | $t_{11}$ | Personnel-semi-finished product identification association; Process information identification association |
| $P_{12}$ | Finished Product Appearance Inspection Station Operation (Including equipment code, inspection items, inspection standards, and other information) | $t_{12}$ | Association between finished product appearance inspection and results |
| $P_{13}$ | Material Flow (Including AGV number, starting point, ending point, path, and other information) | $t_{13}$ | Association between AGV-coil finished product-warehouse identification |
| $P_{14}$ | 3D Warehouse (Including warehouse number, storage location, entry time, and other information) | $t_{14}$ | Identification association of warehouse storage location, quantity, entry time, and other information |
| $P_{15}$ | Coil Production Completion | | |

The complete manufacturing process of a transformer coil starts with the online placement of production orders and enters the production state by scanning the identification resolution code of the orders. Following the production process path and workflow of the coil, it goes through operations such as inner module assembly, coil winding, resin casting, high-voltage curing, etc., at respective workstations to perform related process operations. Additionally, activities such as quality inspection of materials and semi-finished products, transportation circulation, and equipment parameter collection are involved. Throughout the manufacturing process, real-time collection of comprehensive production information and status regarding personnel, machinery, materials, methods, environment, and measurements related to coil production is conducted. This is achieved through identification resolution coding for the entire process identification, and correlation and pathways for process evolution and information flow are established based on Petri nets. Finally, the finished coils that have passed inspection are stored in a three-dimensional warehouse. This study establishes a comprehensive information collection and integration model for coil production processes using identification resolution and expandable Petri nets, as shown in Figure 6.

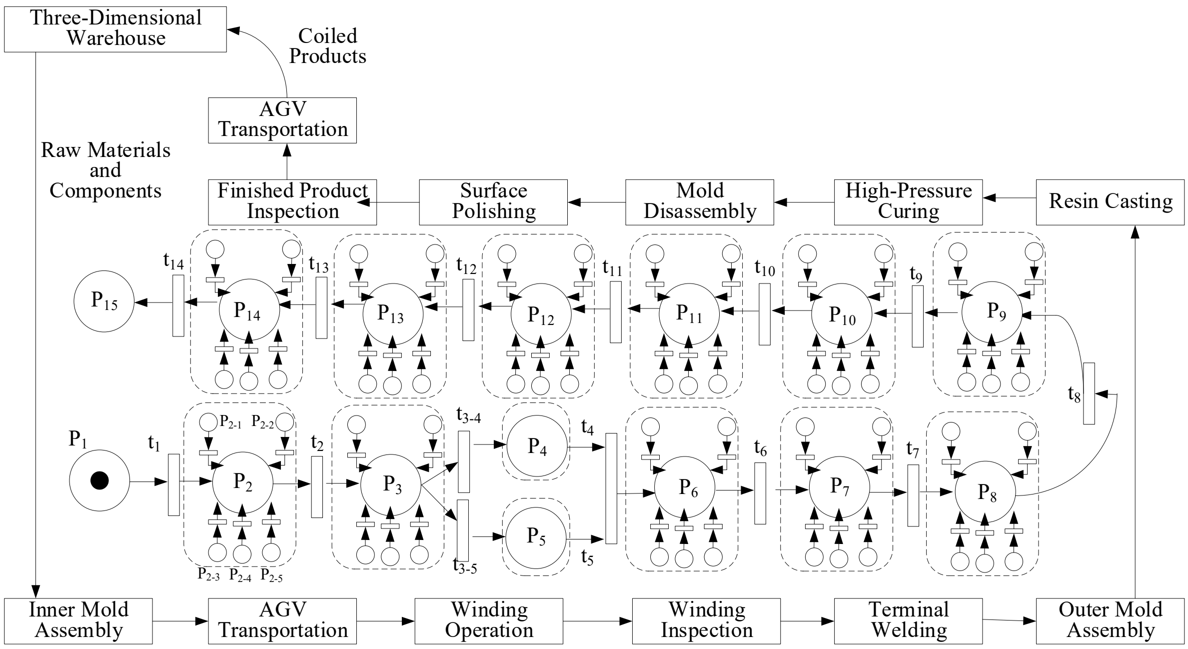



**Figure 6.** Identification resolution extendable Petri net for comprehensive element information collection and fusion.

In Figure 6, the entire coil production process encompasses 15 positions and states, denoted as $P_1$–$P_{15}$. Prior to transitioning to each state, an accumulation period is required, during which information gathering and confirmation of the five core elements—man, machinery, materials, methods, and environment—need to be completed. Taking the example of inner module assembly ($P_2$) in coil production, initially, the statuses and information of personnel ($P_{2\text{-}1}$), machinery ($P_{2\text{-}2}$), materials ($P_{2\text{-}3}$), methods ($P_{2\text{-}4}$), and environment ($P_{2\text{-}5}$) involved in this production task need to be separately collected and confirmed. Subsequently, the process information of the five elements is associated and integrated based on the identification resolution code, thereby constituting the identification resolution expandable information meta-model $P_2$ for the inner module assembly phase. Similarly, for each production phase, the process information of the five core elements (4M1E) needs to be collected, associated, and integrated. Furthermore, based on the time sequence and process order, the process information of multiple production phases is associated and integrated. Ultimately, this forms a complete identification resolution expandable Petri net model for the entire coil production process. Thus, it structurally describes and expresses the role processes and key events of all essential resources, including people, machines, materials, methods, and environment, throughout each product's production process.

#### 4.4.2. The Construction of the Mathematical Model for Process Information Traceability Based on Expandable Identification Primitives

Based on the continuity and structural composition of traceability information in coil product production, it can be divided into two forms: identifiable traceability units and identifiable traceability scenarios.

(1) Identifiable Traceability Units (Unit, abbreviated as "*u*" below)

During the coil production process, multiple traceability entities integrated into an adaptation container (physically present or virtually existent) within the identification resolution system are consolidated, forming a fundamental unit that remains stable within a specific environment. If this fundamental unit requires traceability management at the overall level, it is considered an identifiable traceability unit. This unit possesses a unique code identifier, along with traceability capabilities. The extensible element model mentioned above serves as an example of an identifiable traceability unit.

(2) Identifiable Traceability Scenarios (Site, abbreviated as "*s*" below)

The manufacturing process of coil products often involves complex variations in location, time, and element information. Information traceability may involve multiple traceability items and traceability indicators. In an identification resolution traceability environment consisting of multiple traceability indicator items (such as within a specific space, within a specific time frame, and within a specific production process), several basic units may serve as input traceability units ($u$) and interact to generate several new traceability units, forming more complex traceability scenarios.

Traceability in the manufacturing process of coil products must be based on the identification resolution code of each physical entity and traceability unit. This code must be unique, capable of accompanying the entire lifecycle of traceability entities, and able to distinguish any different traceability entities at any time, in any place, and in any scenario. Furthermore, even after the disappearance of traceability entities, their uniqueness representation must remain valid for a considerable period. By analyzing the transformation principles of traceability information, theoretically, traceability activities can be classified into three types of transformations: traceability scenario acquisition transformation, leading traceability unit acquisition transformation, and subsequent traceability unit acquisition transformation.

(1) Traceability Scenario Acquisition Transformation $\Gamma$

The transformation of obtaining traceability scenarios based on traceability units as conditions are achieved, where '$h$' has two options (0 or 1), indicating whether the transformation needs to obtain the pioneer traceability scenario or the follower traceability scenario of traceability unit 'u'. When $h = 0$, it indicates obtaining the pioneer traceability scenario of the trace unit. When $h = 1$, it refers to obtaining the follower traceability scenario of the trace unit. The mathematical expression is as follows:

$$\Gamma(h,u) = \begin{cases} S^{prioneer}, h = 0 \\ S^{follower}, h = 1 \end{cases} \tag{6}$$

(2) Pioneer Traceability Unit Acquisition Transformation $P$

Assume $u_k$ is a trace unit. If it is a source trace unit (indicated as true), then it has no pioneer trace unit. If $u_k$ is a non-source trace unit (indicated as false), then a pioneer trace unit exists. The mathematical expression is as follows:

$$P(u_k) = \begin{cases} \varnothing, true \\ S^{prioneer}(u_k), false \end{cases} \tag{7}$$

From the definition of transformation $P$, the following relationship holds for non-source traceability unit $u_k$, (where $\Gamma^{-1}$ is the inverse transformation of $\Gamma$).

$$P(u_k) = S^{\text{prioneer}}(u_k) = \Gamma^{-1}(0,\, u_k)(u_k) \tag{8}$$

(3) Follower Traceability Unit Acquisition Transformation $F$

Similarly, if $u_k$ is a source trace unit (indicated as true), then it has no follower trace unit. If $u_k$ is a non-source trace unit (indicated as false), then a follower trace unit exists. The mathematical expression is as follows:

$$F(u_k) = \begin{cases} \varnothing, true \\ S^{follower}(u_k), false \end{cases} \tag{9}$$

From the definition of transformation $F$, the following relationship holds for the non-terminal traceability unit $u_k$:

$$F(u_k) = S^{\text{follower}}(u_k) = \Gamma(1,\, u_k)(u_k) \tag{10}$$

According to the basic configuration, the traceability scenario types of coil production process information can be categorized into three types: linear, disassembly, and merging.

(1) Linear Type

The fundamental type is represented by a traceability scenario "$s$" with a fan-in of 1 and a fan-out of 1, referred to as a linear traceability scenario, as shown in Figure 7.

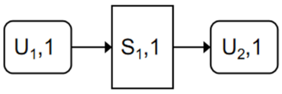



**Figure 7.** Linear Traceability Scenario.

As illustrated in Figure 5, $(u_1, 1)$ and $(u_2, 1)$ are two traceability units. $(u_1, 1)$ transitions to $(u_2,\ 1)$ through a traceability scenario $(s_1,\ 1)$. During this transition, the following traceability information transformation relationship exists:

$$u_2, 1.\text{Info} \ = u_1, 1.\text{Info} \oplus s_1, 1.\text{Info} \tag{11}$$

$$P\ (u_2, 1) = (\Gamma(0,\ u_{2,1}))^{-1}(\bigcup_{j=1}^{n} u_{2,\mathrm{j}}) = \bigcup_{i=1}^{m} u_{1,i} = \{u_1, 1\ \} \tag{12}$$

$$F(u_1, 1) = \Gamma(1,\ u_1, 1)\left(\bigcup_{j=1}^{m} u_{1,j}\right) = \bigcup_{i=1}^{n} u_{2,i} = \{u_2, 1\ \} \tag{13}$$

(2) Disassembly Type

The fundamental type represented by a traceability scenario "$s$" with a fan-in of 1 and a fan-out greater than 1 is referred to as a disassembly traceability scenario.

As depicted in Figure 8, $(u_1, 1)$, $(u_2, 1)$, $(u_2, 2)$, …, $(u_2, n)$ are n + 1 traceability units. $(u_1, 1)$ transitions to $(u_2, 1)$, $(u_2, 2)$, …, $(u_2, n)$ through a traceability scenario $(s_1, 1)$. During this transition, the following traceability information transformation relationship exists:

$$u_2, i.Info = u_1, 1.Info \oplus s_1, 1.Info(\ i\ ) \wedge \forall i \in \{1, 2, \ldots, n\} \tag{14}$$

$$P\ (u_2, i) \overset{\forall i \in \{1,2,\ldots,n\}}{=} s_{1,1}^{-1}(\bigcup_{j=1}^{n} \mathrm{u}_{2,j}) = \bigcup_{i=1}^{m} u_{1,i} \tag{15}$$

$$F(u_1, 1) = s_1, 1\left(\bigcup_{j=1}^{m} u_{1,j}\right) = \bigcup_{i=1}^{n} u_{2,i} \tag{16}$$

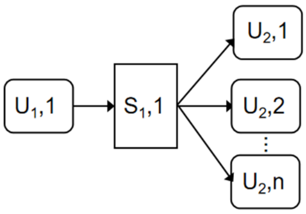



**Figure 8.** Disassembly Traceability Scenario.

(3) Merging Type

Merging Type: The fundamental type represented by a traceability scenario "*s*" with a fan-in greater than 1 and a fan-out of 1, referred to as a merging traceability scenario.

As shown in Figure 9, $(u_1, 1)$, $(u_1, 2)$, . . ., $(u_1, n)$, and $(u_2, 1)$ are $n + 1$ traceability units. $(u_1, 1)$, $(u_1, 2)$, . . ., $(u_1, n)$ transition to $(u_2, 1)$ through a traceability scenario $(s_1, 1)$ to form a single traceability unit. During this transition, the following traceability information transformation relationship exists as the following:

$$u_2, 1.Info = u_1, 1.Info \oplus u_1, 2.Info \oplus \ldots \oplus s_1, n.Info \tag{17}$$

$$u_1, i.tid \neq u_1, j.tid \wedge \forall i, j \in \{1, 2, \ldots, n\} \wedge i \neq j \wedge n > 1 \tag{18}$$

$$P(u_2, 1) = s_{1,1}^{-1}\left(\bigcup_{j=1}^{n} \mathrm{u}_{2,j}\right) = \bigcup_{j=1}^{\mathrm{m}} u_{1,j} \tag{19}$$

$$F\ (u_1, i) \overset{\forall i \in \{1,2,\ldots,m\}}{=} s_{1,1}^{-1}\left(\bigcup_{j=1}^{m} \mathrm{u}_{1,j}\right) = \bigcup_{i=1}^{n} u_{2,i} = \{u_2, 1\} \tag{20}$$

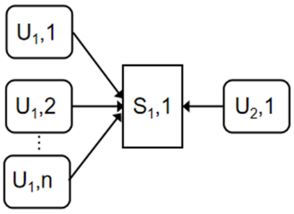



**Figure 9.** Merge Traceability Scenario.

Taking the traceability of quality information in the coil manufacturing process as an example, coils flow continuously along the process path, with states and information constantly changing and migrating. The paths of information association are extremely complex, making it exceptionally difficult to trace quality issues; the main characteristic elements of quality traceability information are shown in Tables 9 and 10. To address this challenge, integrate the above mathematical model with Petri nets; a traceability path is constructed based on the physical element model corresponding to each place P and the event element model corresponding to each transition t in the transformer coil manufacturing process. Taking the influencing factors of coil manufacturing quality as nodes, a traceability and control path for quality anomalies has been established. As shown in the Figure 10, $P_{\mathrm{q}1}$–$P_{\mathrm{q}10}$ represent ten key control stations for the quality of coils (traceability scenario); during the coil production process, the tasks mainly include mold inspection, raw material inspection such as insulation paper, full-process inspection of the winding process, casting and curing inspection, coil polishing, finished product appearance inspection. Each $P_{qi\text{-}j}$ associated with $P_{qi}$ represents all the traceability units included in that traceability scenario. For example, from $P_{\mathrm{q}10\text{-}\mathrm{i}}$ to $P_{\mathrm{q}10}$, it includes traceability units such as mold outer diameter measurement, circumference measurement, perpendicularity measurement, and overall appearance cleanliness inspection in the "Mold Quality Inspection" scenario. The directed arc between $P_{qi\text{-}j}$ and $P_{qi}$ represents a merging traceability scenario; if the direction of the arrow is reversed, it indicates a disassembly traceability scenario. The rectangle *t* represents the transformation for acquiring traceability scenarios and traceability units. The directed arc from $P_{qi}$ to $P_{qj}$ represents the linear transfer of traceability information based on the traceability scenario. $P_{q10}$ to $P_{q9}$ indicates that after the mold parameters have passed inspection and been fully recorded, transition $t_9$ is triggered, changing the inspection task from the mold inspection state to the insulation cylinder appearance inspection. By analogy, each $P_{qi}$ is an equality report state built upon the integration and accumulation of $P_{qi\text{-}j}$ on the basis of $P_{qi\text{-}1}$. $P_{q1}$ represents the final complete quality report after coil production, containing all quality information from $P_{q1}$ to $P_{q9}$. The formation of the quality report involves the integration and accumulation of quality information from each stage. The transmission and traceability path of quality information in the coil manufacturing process has been constructed based on the above rules. At any point (any $P_{qi}$ and $P_{qi\text{-}j}$), by scanning the identification codes carried by the in-process coils (such as QR codes, barcodes, or RFID tags), one can quickly obtain forward traceability information (records of historical information that has occurred) and backward traceability information (upcoming stations and relevant information) based on the Petri network structure. This enables precise quality traceability and efficient management of processes.

**Table 9.** Main quality feature elements of the production preparation process.

| Process Object | Characteristics | Corresponding to the Place of Petri Net |
| --- | --- | --- |
| Mold inspection | Mold outer diameter, mold circumference, mold perpendicularity | $P_{q10\text{-}1}$, $P_{q10\text{-}2}$, $P_{q10\text{-}3}$, $P_{q10\text{-}4}$, … |
| Raw material inspection | Insulation paper without damage; insulation paper trademark, thickness, number of layers; cushion block without sharp edges or burrs; insulation tube surface smooth and flat; insulation tube outer diameter; wire insulation paper without damage | $P_{q9\text{-}1}$, $P_{q8\text{-}1}$, $P_{q8\text{-}2}$, … |

**Table 10.** Main quality feature elements of the manufacturing process.

| Process Object | Characteristics | Corresponding to the Place of Petri Net |
| --- | --- | --- |
| Winding process (divided into pre-winding, mid-winding, and post-winding) | Material code; rated capacity (KVA); drawing number (with transformer identification); this drawing number; mold drawing number; winding method (wire/foil); interlayer insulation thickness (mm); total number of segments; tapping range; length of elongated oval; wire material (mm); weight of single-phase wire (kg); number of parallel wires; number of interleaved wires; wire thickness (mm); wire width (mm); wire cross-sectional area (mm$^2$); foil winding coil table height (mm); foil winding coil table width (mm); lead pitch (mm); lead thickness (mm); thickness of first air gap layer (mm); thickness of second air gap layer (mm); total thickness of coil in width direction (mm); inner diameter of air gap 1 in short axis direction of coil (mm); insulation thickness inside coil (mm); thickness of layer 1 in width direction of coil (mm); inner diameter of short axis of coil (mm); inner diameter on coil short axis line (mm); inner diameter of air gap 1 in short axis direction of coil (mm); outer diameter of long axis of coil (mm); axial height of coil (mm); height of coil in terms of reactance (mm); total number of turns in coil; number of turns per layer (1 segment; 1 layer); total number of layers in coil; number of layers (1 segment); stopping number of winding 1; stopping number of upper cutting; stopping number of lower cutting; recommended tension setting for foil material; recommended tension setting for foil material 1; recommended tension setting for interlayer 1; recommended tension setting for interlayer; recommended tension setting for unwinding; recommended tension setting for unwinding 1… | $P_{q7\text{-}1}$, $P_{q7\text{-}2}$, $P_{q7\text{-}3}$, $P_{q7\text{-}4}$, $P_{q6\text{-}1}$, $P_{q6\text{-}2}$, $P_{q5\text{-}1}$, $P_{q5\text{-}2}$, $P_{q5\text{-}3}$, … |

**Table 10.** *Cont.*

| Process Object | Characteristics | Corresponding to the Place of Petri Net |
|---|---|---|
| Casting and curing process | Vacuum degree (mbar); temperature (°C); duration (min); bottom temperature 1 of the tank (°C); bottom temperature 2 of the tank (°C); front temperature of the tank (°C); middle temperature of the tank (°C); rear temperature of the tank (°C); mold temperature (°C); vacuum degree (°C); duration (min); epoxy resin ratio in resin tank A; toughening agent ratio in resin tank A; silica fume ratio in resin tank A; curing agent ratio in resin tank B; silica fume ratio in resin tank B; pressure; vacuum degree; failure; casting shrinkage; local softening | $P_{q4\text{-}1}$, $P_{q4\text{-}2}$, $P_{q4\text{-}3}$, $P_{q4\text{-}4}$, $P_{q4\text{-}5}$, $P_{q4\text{-}6}$, ... |
| Coil grinding, appearance inspection, etc. | Finished product coil surface finish, roundness, perpendicularity, height, etc. | $P_{q3\text{-}1}$, $P_{q2\text{-}1}$, $P_{q2\text{-}2}$, $P_{q2\text{-}3}$, ... |

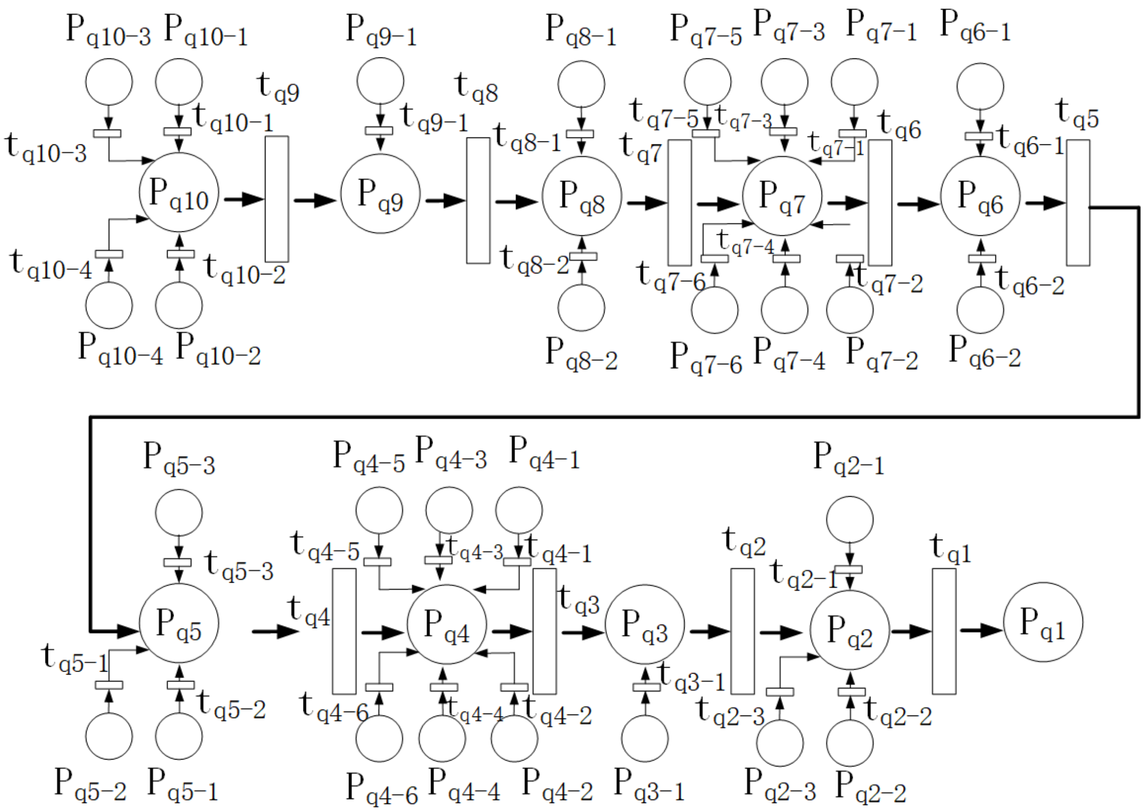


**Figure 10.** Example of extendable Petri net for identification resolution in coil quality traceability.

## 5. Results

### *5.1. Experimental Setup*

To verify the effectiveness and applicability of the methodology proposed in this study, the research team conducted field validation in the production workshop of a 110 kV dry-type transformer coil at Company A (The company is located in Changji, China). The aim was to assess the capability of this methodology in managing the coil manufacturing process and information traceability. The workshop is equipped with five smart warehouses, two intelligent pouring devices, nineteen smart curing ovens, five AGVs, two RGVs, eight sets of automatic KBK, one raw material testing center, fourteen CNC winding machines, and two sets of beam robots for spool loading. In previous digital transformation efforts, comprehensive digital business systems were established, utilizing remote calling interfaces such as Webservice and Restful for data exchange and integrating platforms, including SCADA, MES, WMS, QMS, AGV control systems, and the Industrial Internet. Each device, workstation, material, personnel, and work-in-progress was assigned a unique identification code. Smart sensors and gateways were employed to automate the collection and association of essential data, including operational data from key equipment, environmental monitoring data, material information, and quality inspection data. Based on this, the implementation and validation of the research method took place primarily from February to June 2024, with detailed content and processes introduced in the following sections.

### *5.2. Construction of Industrial Internet Identification Resolution Platform*

The industrial Internet identification resolution system is divided into five levels: international root nodes, national top-level nodes, secondary nodes, enterprise nodes, and recursive nodes. The secondary nodes provide functions such as identification registration, identification resolution, and data services, connecting upwards to national top-level nodes and downwards to enterprise nodes. To establish an identification resolution environment for the comprehensive resource and process information of coil production, a secondary node platform for industrial Internet identification resolution was constructed. This platform interfaces with the national top-level nodes, thus forming a unified identification resolution network. Building upon the foundation of the secondary node platform, an enterprise node system tailored for transformer coil production was developed. This system encompasses functional modules such as identification registration, code parsing, data synchronization, data management, identification proxy, and business management. It facilitates the planning, application, and allocation of identification codes, feedback on usage, lifecycle management, validity management, collection of information on identification allocation and usage, as well as collection of associated identification information. Furthermore, it offers services including registration modification of enterprise identification prefixes, product and equipment identification, data querying, and statistical analysis. Users can initiate identification resolution requests through a browser to the proxy server and display the results returned by the resolution system to the user through the browser. This system achieves interconnectedness and interoperability of data related to personnel, materials, processes, and quality throughout the coil production process, providing comprehensive data support services across the entire process. The platform's functional architecture is shown in Figure 11.

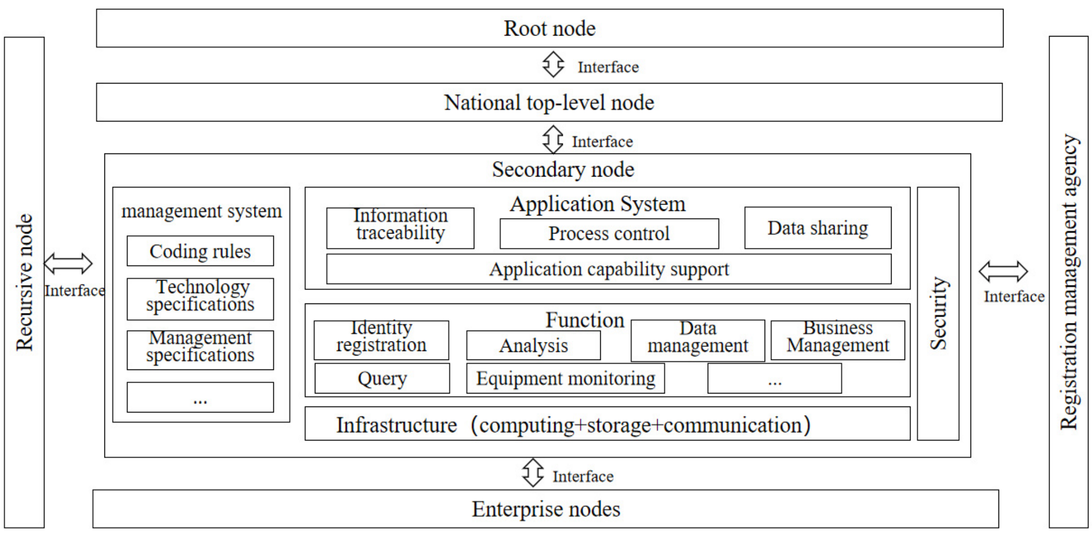



**Figure 11.** Architecture and function of industrial internet identification resolution platform.

### *5.3. Coding and Identification of Resources in Coil Production Process*

Based on the Industrial Internet Identification Resolution Service System, unique identification resolution codes are applied and registered for electromagnetic coil raw materials, AGV carts, molds, winding equipment, casting equipment, drying equipment, work-in-process coils, finished coils, production lines, and other elements involved in the coil production process. All comprehensive information regarding orders, processes, and quality related to coil product manufacturing is associated with identification resolution codes. As shown in Figures 12 and 13, the workshop has set up coding stations to achieve one-to-one mapping and binding correlation between physical entities and identification codes, barcodes, QR codes, IC cards, RFID chips, and other carriers employed as coding mediums. RFID readers/writers, industrial cameras, laser scanning devices, etc., are deployed in three-dimensional warehouses, workstations, and other locations for real-time identification of the identity information of materials, work-in-process items, personnel, etc. This information is then associated with collected data such as order information, work hours, equipment parameters, quality information, etc. The data are synchronized to the server through Ethernet-connected data acquisition systems. The commonly used coding carrier technologies and their performance in the coil workshop are summarized in Table 11.


**Figure 12.** Production of the carrier for identification code. (**a**) Laser marking station; (**b**) Paper label printing; (**c**) Radio frequency identification (RFID).

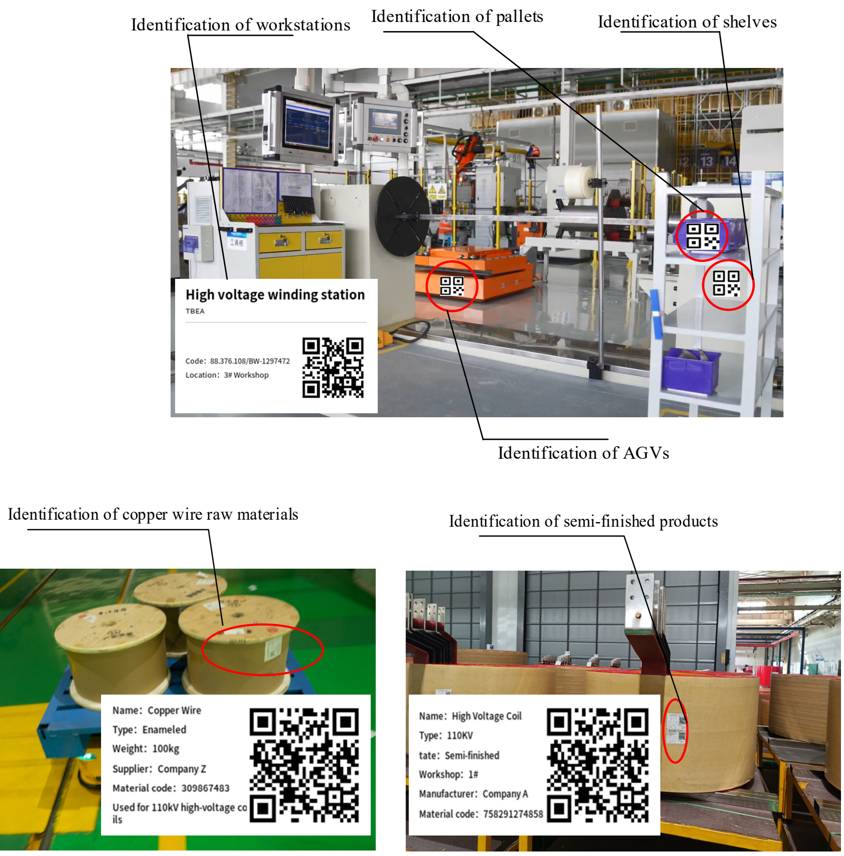



**Figure 13.** Unified identification of all-factor resources in the workshop.

**Table 11.** Comparison of code recognition technology characteristics in the workshop.

| Performance Parameters | Barcode | QR Code | IC Card | RFID |
|---|---|---|---|---|
| Information storage capacity | 1–100 B | 1–110 B | 16–64 KB | 16–64 KB |
| Data carrier | Paper, plastic or metal | Paper, plastic or metal | EEPROM | EEPROM |
| Cost | Very low | Very low | Low | Medium |
| Reading method | CCD or laser scanning | CCD or laser scanning | Additional translation | Point erase Wireless radio frequency |
| Reading speed | Slow | Slow | Relatively slow | Fast |
| Covering effect | Complete failure | Complete failure | / | No impact |
| Read-write distance | 0–50 cm | 0–50 cm | Direct contact | 0–5 m |

### 5.4. Mapping and Integration of Coil Production Process Data

Based on the extensible information primitive modeling method proposed in this paper and the logical flow of production traceability, Petri nets, a resource information repository for the coil production process, is established by utilizing the association relationships between information primitives. The identification resolution codes of primitives are utilized as primary keys in data tables, while the identification resolution codes of associated primitives serve as foreign keys, enabling the realization of data-level fusion and feature-level fusion. On the basis of unified identification coding, data governance systems such as metadata management and master data management are constructed, achieving the modelization and standardization of all elements of the coil manufacturing process identification data. Through the integration technology of OPC-UA system architecture and identification resolution services, compatibility with various IT/OT-side network protocol hardware and application systems is ensured, facilitating the integration and access of heterogeneous communication protocol data sources, data quality evaluation and cleansing, fusion, real-time transmission, data security, etc. This process constructs a comprehensive identification data model library and resource pool for the coil manufacturing workshop, forming a closed-loop data optimization system. As shown in Figure 14.

### 5.5. Implementation of Coil Production Process Information Traceability

A lightweight software application (The version of the software used in this study is version 1.2.1) for information traceability in the coil manufacturing process was developed based on the industrial Internet identification and resolution system, combined with the extended Petri net analysis proposed in this study. As shown in Figures 15–17, information traceability cards with identification codes are attached to coils, equipment, personnel, and materials, facilitating the collection and correlation of all process information based on these identification codes. For example, in the coil production process, operators must complete a permission verification based on identification codes before starting the equipment. Once the equipment is successfully started, it automatically associates the device code with the operator's code. Additionally, operators do not need to interact with the system; they can simply scan the device code and order code to automatically retrieve drawings and work instructions. Once prepared, by scanning the identification code of the work-in-progress, they can automatically obtain and distribute process parameters, initiating the winding operation. Each of these scanning actions triggers automatic data collection and recording, laying the foundation for information traceability. At any stage of coil production, by identifying the unique code, information flow paths and detailed information within the Petri net can be obtained based on this code. For example, historical information can include the source of raw materials, process parameters, production personnel, production equipment, and quality inspection data. Moreover, based on the "modeling theory for the acquisition transformation of traceability scenarios and traceability units” proposed in this paper, predicting the position and process status of the coil at future moments is considered an acquisition transformation of subsequent traceability units. Utilizing the coil’s current position, standard working time, accumulated quality errors, and process path, the production progress can be determined in real time, enabling the prediction of potential production waiting for waste and bottleneck risks. In logistics, warehousing, distribution, and other processes, the movement of key materials undergoes multiple traceable stages, which can be conceptualized as a linear traceability scenario. By leveraging identification resolution codes, the movement time, location, usage records, and operators of materials can be sequentially associated and recorded. Furthermore, upon completion of coil production, the identification resolution code serves as input to associate and retrieve multiple traceability units through a disassembled traceability scene transformation. This process allows for the retrieval of detailed information, including product batches, production entities (factories, workshops, production lines), raw material suppliers, process station records, and comprehensive quality reports. Furthermore, by integrating and analyzing the collected product traceability information, a data platform and management system are constructed to establish a database and traceability records for coil production information within the system. Utilizing data analysis methods, process data are mined and analyzed to identify potential issues and trends, providing a basis and support for quality management and safety control.

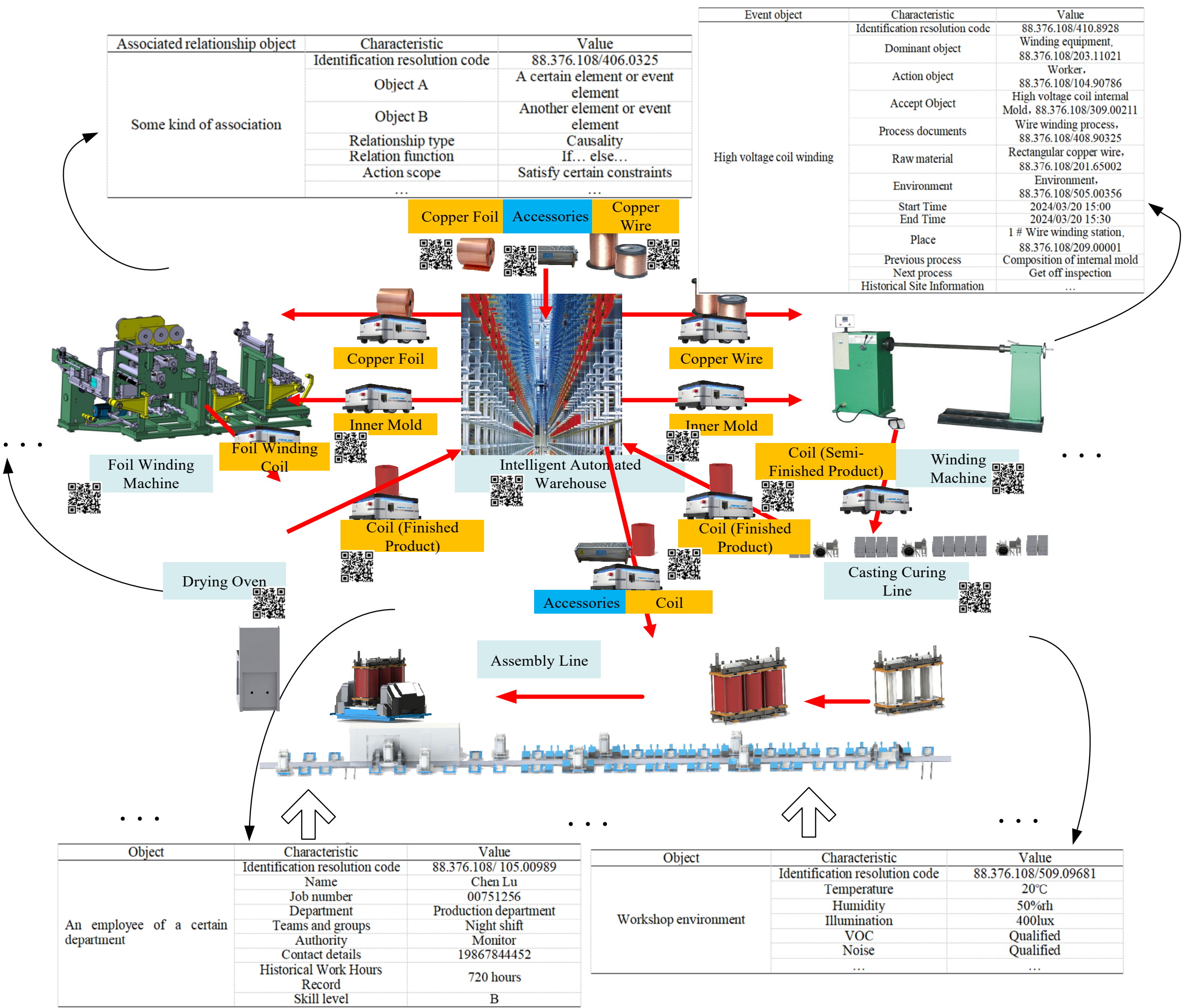



**Figure 14.** Mapping and integration of coil production process data.

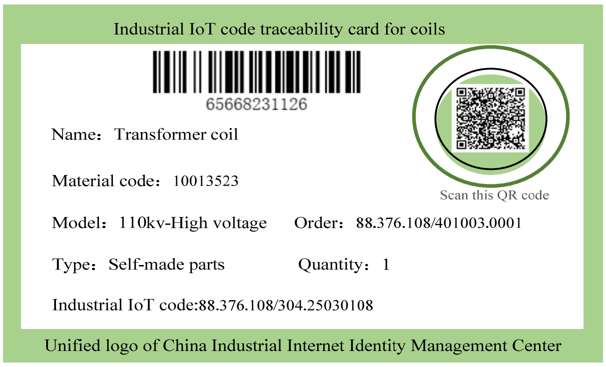
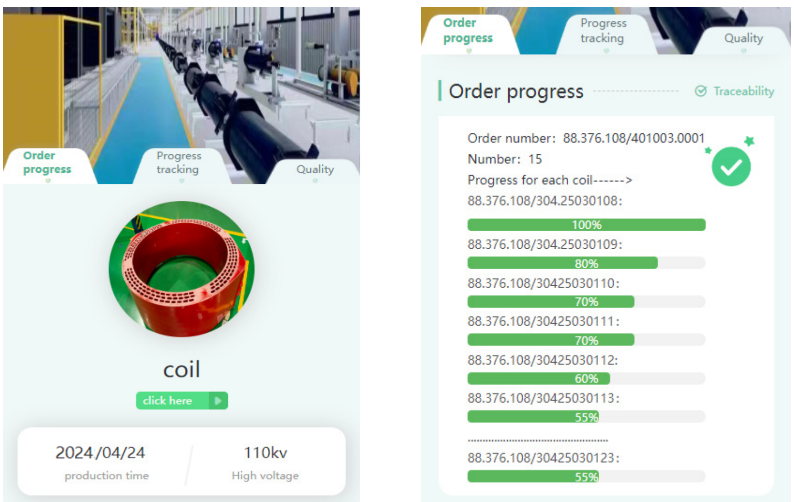


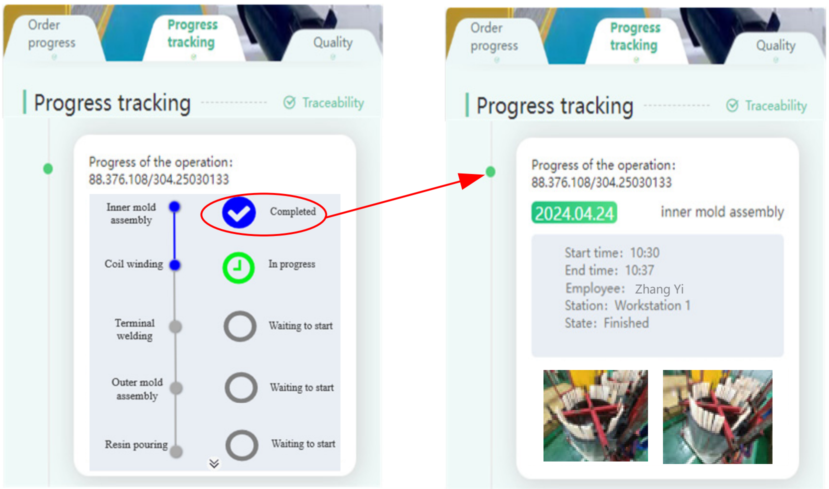

**Figure 15.** Process Identification Traceability Card.


**Figure 16.** Process control and information collection based on unified identification of all-factor resources.

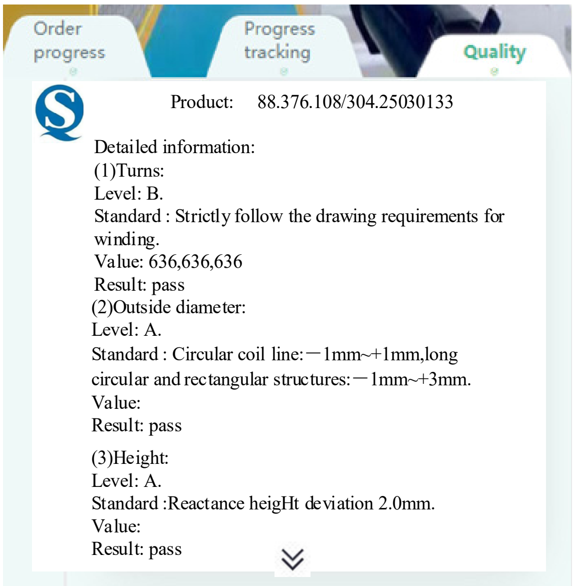



(**a**)

**Figure 17.** *Cont.*




(**b**)




(**c**)

**Figure 17.** Implementation of Traceability of Manufacturing Process Information. (**a**) Traceability of Order Progress, (**b**) Traceability of Work in Process, (**c**) Traceability of Quality Information.

### *5.6. Analysis of Improvement Effects before and after Implementation*

To comprehensively evaluate the improvement effects before and after implementation, an analysis was conducted on the enhancement of four capability domains: information traceability, production efficiency, cost control, and quality control. Multiple key indicators were selected under each capability domain to measure the operational status of the workshop. Additionally, a nine-point scale method was employed to scientifically assess the importance of each indicator, with a particular focus on performance in areas such as information traceability, quality control, and the reduction of non-value-added time. To determine the weight coefficients of the evaluation indicators, the Full Consistency Method (FUCOM) was utilized to ascertain the specific weight for each indicator. The advantage of this method lies in minimizing the deviation between the weight coefficients and the estimated comparative priorities, ensuring the accuracy and consistency of the weight coefficients. The indicator parameters and weight coefficients used for evaluation are shown in Table 12; the main evaluation indicators under the traceability capability domain include traceability coverage (denoted as $I_1$), traceability accuracy (denoted as $I_2$), and traceability response speed (denoted as $I_3$). The main evaluation indicators under the production efficiency capability domain include cycle time (denoted as $I_4$) and equipment maintenance response time (denoted as $I_5$). The main evaluation indicators under the cost control capability domain include material outbound operation time (denoted as $I_6$), finished products inbound time (denoted as $I_7$), raw material waste (denoted as $I_8$), and work-in-progress transfer time (denoted as $I_9$). The main evaluation indicators under the quality control capability domain include pass rate (denoted as $I_{10}$) and error-proofing status of materials (denoted as $I_{11}$).

**Table 12.** Evaluation indicator parameters and weight coefficients.

| Capability Domains | Indicators | Description | Values of Nine-Point Scale | Weight Coefficient |
|---|---|---|---|---|
| Traceability capability | Traceability coverage ($I_1$) | The proportion of traceable information to total information | 9 | 0.12 |
| | Traceability accuracy ($I_2$) | The degree of compliance between traceability information and actual data | 9 | 0.12 |
| | Traceability Response Speed ($I_3$) | The time required from initiating traceability to retrieving the necessary information through the system | 8 | 0.10 |
| Production efficiency | Cycle time ($I_4$) | The time consumed to produce a single product | 4 | 0.05 |
| | Equipment maintenance response time ($I_5$) | The average time required from equipment failure to the start of troubleshooting | 5 | 0.06 |
| Cost control | Material outbound operation time ($I_6$) | The time taken to retrieve materials from the warehouse and load them onto the transport vehicle | 7 | 0.09 |
| | Finished products inbound time ($I_7$) | The time taken for a completed product to move from the workstation to the warehouse | 6 | 0.08 |
| | Raw material waste ($I_8$) | The proportion of raw materials that are idle or wasted | 7 | 0.09 |
| | Work-in-progress transfer time ($I_9$) | The time consumed for work-in-progress to flow between processes | 6 | 0.08 |
| Quality control | Pass rate ($I_{10}$) | The percentage of compliant products to the total quantity of products | 8 | 0.10 |
| | Error-proofing status of materials ($I_{11}$) | The number of times materials were incorrectly delivered or used | 9 | 0.12 |

Based on the data requirements of the four capability domains and eleven parameters, the average daily operational data of the workshop was continuously collected and recorded for 15 days before and after implementation, as shown in Table 13.

**Table 13.** Workshop operational data for a certain period.

| Day | $I_1$/% | $I_2$/% | $I_3$/S | $I_4$/min | $I_5$/min | $I_6$/min | $I_7$/min | $I_8$/% | $I_9$/min | $I_{10}$/% | $I_{11}$/Times |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $D_1$ | 90 | 93 | 2 | 350 | 30 | 4 | 5 | 3% | 3.5 | 95 | 5 |
| $D_2$ | 93 | 95 | 1.5 | 355 | 35 | 3.5 | 5 | 2.8% | 3.8 | 96 | 3 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $D_{28}$ | 100 | 99 | 0.5 | 346 | 8 | 1 | 3 | 1.5% | 2 | 100 | 0 |
| $D_{29}$ | 100 | 98 | 0.5 | 346 | 5 | 1.5 | 2 | 1.5% | 2 | 100 | 0 |
| $D_{30}$ | 100 | 99 | 0.5 | 345 | 5 | 1 | 3 | 1% | 2 | 100 | 0 |

Since the values of the indicators contain data of different dimensions and scales, normalization was applied to these raw data for ease of subsequent analysis and comparison (as shown in Formula (21)). Then, the scores for the four capability domains and the total score for workshop operations were calculated.

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{21}$$

The score for each capability domain is the weighted sum of all indicator parameters under that domain, as shown in Formula (22). For indicators where smaller parameter values are better, the weight coefficient is negative; for indicators where larger parameter values are better, the weight coefficient is positive.

$$Score\ of\ the\ capability\ domain = \sum (Weight\ of\ the\ indicator \times Value\ of\ the\ indicator) \tag{22}$$

The overall score for workshop operation is the sum of the scores from all capability domains, as shown in Formula (23).

$$Total\ score = \sum Score\ of\ the\ capability\ domains \tag{23}$$

Based on the calculation principles outlined in Formulas (21)–(23), the average scores for the capability domains and the total daily scores were obtained for the 15 days before and after project implementation. As shown in Figure 18, the average levels of the four capability domains have improved post-implementation, particularly in traceability and quality control, which saw significant enhancements. Figure 19 illustrates that the workshop operation scores after the project implementation are notably higher than those before, and the fluctuations in the curve indicate a smoother operation process, which is more conducive to stable workshop performance. The results indicate that the project implementation significantly improved various capability indicators, demonstrating its effectiveness. This not only enhanced workflow and increased operational stability but also helped reduce production risks, laying a foundation for future continuous improvement. It holds considerable value and significance for workshop production management and information traceability.

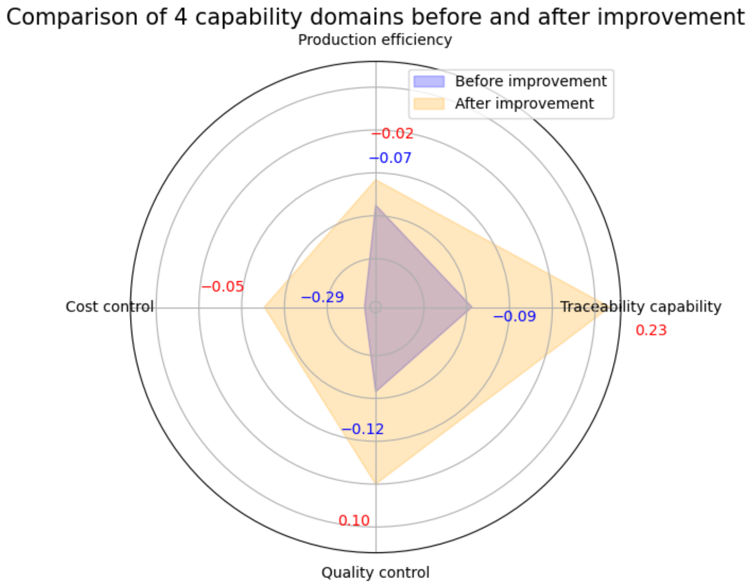



**Figure 18.** Comparison of the four capability domains before and after improvement.

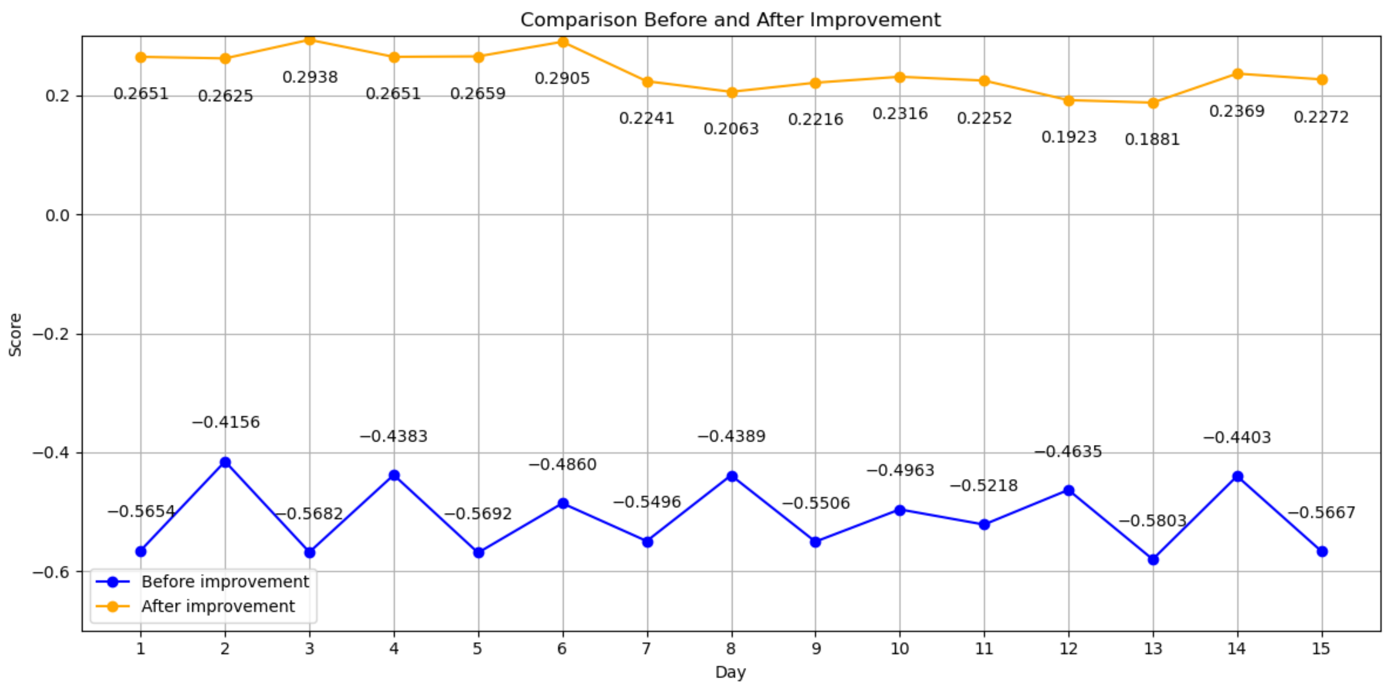



**Figure 19.** Comparison of the overall workshop operational status before and after improvement.

## 6. Discussion

The manufacturing process of transformer coils is complex, involving a wide variety of elemental resources and information types, which presents significant challenges for efficient collection, integration, and precise traceability of process information. To address the shortcomings of existing traceability methods, it is necessary to establish a unified resource identification and data-sharing system. This system enables structured integration of traceability information in the coil manufacturing process and formal modeling of traceability paths. This paper systematically explores a set of methods for information modeling and traceability in coil manufacturing processes based on industrial internet identification resolution, extenics theory, and Petri nets. Constructed an industrial internet identification resolution system for coil manufacturing, achieving unified encoding and identification of all elemental resources and information. We established a shared space model for all elemental data by utilizing the Handle resolution system, thereby enabling interconnectedness, interoperability, exchange, and sharing of process data. The elemental model for identification information in the coil manufacturing process was established based on the theory of extenics basic-element, achieving a unified data structure for traceability information and identification of relational connections. An extensible Petri net model was established for the collection and integration of information in the coil manufacturing process, achieving modeling and integration of information flow throughout the coil production process. Simultaneously, a mathematical model for quality traceability in coil manufacturing processes was developed, achieving a formal analysis of the coil quality traceability process. Finally, validation was conducted in the coil production workshop, where a traceability and management system tailored for coil manufacturing processes was established. This system uniformly identifies, associates, and structurally stores all elemental resources and process information within the coil workshop, achieving efficient control and information traceability of the production process. Results indicate a significant enhancement in the production management and information traceability capabilities of the coil production workshop.

Although this study provides a novel methodological approach and implementation pathway for traceability in coil product manufacturing processes, there are still some shortcomings that need to be addressed. Currently, traceability in coil manufacturing processes primarily involves recording and tracking objective facts that have already occurred. However, there has not been further exploration into leveraging machine learning, deep learning, and other artificial intelligence algorithm models to mine and analyze historical data. This would help uncover hidden relationships between manufacturing process information, product quality, and production scheduling, thereby improving manufacturing processes. Furthermore, there has been limited real-time prediction of process trends and quality issues in the next steps based on preceding process information, limiting the real-time adjustment and control capabilities of coil manufacturing processes. Future research will focus on these two aspects further.

**Author Contributions:** Conceptualization, X.Z. and W.S.; methodology, X.Z.; software, C.L.; validation, C.L. and S.S.; formal analysis, X.Z.; investigation, S.S.; data curation, S.S.; writing—original draft preparation, X.Z.; writing—review and editing, X.Z.; visualization, C.L.; supervision, W.S.; project administration, W.S.; funding acquisition, W.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** (1) Full Element Integration Platform Project Based on Identification and Resolution System of Industrial Internet, TC210A02E, supported by the Ministry of Industry and Information Technology of China. (2) Key technology research and development project of Industrial Internet Identification and Resolution System for Full Element Integration Platform, 2022B01049, supported by the Department of Science and Technology of Xinjiang Uygur Autonomous Region. (3) Excellent PhD Innovation Program-Research on Quality Inspection and Control Methods for Special Transformers for Interconnected Digital Factory, XJU2023BS053, supported by Xinjiang University.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Acknowledgments:** We would like to extend our deepest gratitude to Ke Chen for his invaluable assistance and unwavering support throughout the course of this research.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Kuhn, M.; Franke, J. Data continuity and traceability in complex manufacturing systems: A graph-based modeling approach. *Int. J. Comput. Integr. Manuf.* **2021**, *34*, 549–566. [CrossRef]

2. Bougdira, A.; Akharraz, I.; Ahaitouf, A. A traceability proposal for industry 4.0. *J. Ambient. Intell. Humaniz. Comput.* **2020**, *11*, 3355–3369. [CrossRef]
3. Schuitemaker, R.; Xu, X. Product traceability in manufacturing: A technical review. *Procedia Cirp* **2020**, *93*, 700–705. [CrossRef]
4. Chien, C.H.; Trappey AJ, C.; Wang, C.C. ARIMA-AdaBoost hybrid approach for product quality prediction in advanced transformer manufacturing. *Adv. Eng. Inform.* **2023**, *57*, 102055. [CrossRef]
5. Shi, M.-Y.; Liu, C.-Y.; Wen, C.-B.; Xu, X.; Liu, S.-N. Design and development of quality traceability system for circulation of Chinese herbal medicine based on blockchain and NB-IOT. *China J. Chin. Mater. Medica* **2020**, *45*, 4267–4272.
6. Li, J.; Liu, L.-M.; Li, L.; Li, G.-S.; Xue, Q. Research on Traceability System and Standardization of Special Equipment Quality and Safety. *Stand. Sci.* **2019**, *9*, 150–154+176. [CrossRef]
7. Chen, S.-Y.; Cui, Z.-J.; Liu, D.-F.; Liu, L.; Pu, Y.-M.; Zhong, Y.F. Application Progress of Blockchain in Product Traceability and Packaging Anti-counterfeiting. *Packag. Eng.* **2023**, *44*, 91–100.
8. Li, C.-X.; Peng, X.-Y.; Li, Y. Tracking System for Parts of Automated Workshop Based on QR Code. *Pop. Sci. Technol.* **2019**, *21*, 7–9.
9. Yang, Z.; Shang, W.L.; Zhang, H.; Garg, H.; Han, C. Assessing the green distribution transformer ma-nufacturing process using a cloud-based q-rung orthopair fuzzy multi-criteria framework. *Appl. Energy* **2022**, *311*, 118687. [CrossRef]
10. Lettner, C.; Moser, M.; Pichler, J. An integrated approach for power transformer modeling and manufacturing. *Procedia Manuf.* **2020**, *42*, 351–355. [CrossRef]
11. Noamna, S.; Thongphun, T.; Kongjit, C. Transformer Production Improvement by Lean and MTM-2 Technique. *ASEAN Eng. J.* **2022**, *12*, 29–35. [CrossRef]
12. Atamanchuk, G.; Giraldo, O. Staged Investment for Intelligent Automatic Transformers Winding Manufacturing Lines. In Proceedings of the IEEE/PES Transmission and Distribution Conference and Exposition (T&D), Chicago, IL, USA, 12–15 October 2020; IEEE: New York, NY, USA, 2020; pp. 1–5.
13. Ren, Y.; Xie, R.C.; Zeng, S.Q.; Zhao, H.R.; Yu, J.Y.; Huo, R. Survey of identity resolution system in industrial Internet of things. *J. Commun.* **2019**, *40*, 138–155. [CrossRef]
14. Wan, X.; Jiao, Z.; Liu, M.; Liu, D. An Overview of Industrial Internet Applications. *Print. Digit. Media Technol. Study* **2021**, *2*, 1–26.
15. Song, T.; Li, K. Data Communication Technology and Applications for Intelligent Manufacturing Workshops Based on OPC UA. *China Mech. Eng.* **2020**, *31*, 1693–1699.
16. Zou, B.; Hou, X.; Huang, Z.; Liu, B. Research on Collaborative Manufacturing Based on Identification and Resolution System of Industrial Internet. *Inf. Commun. Technol. Policy* **2021**, *47*, 14–19.
17. Wu, L. Design and Application of Identification Analysis System for Instrument Industry. *Process Autom. Instrum.* **2022**, *43*, 82–85.
18. Fei, H.; Tang, B.; Yang, M. Application of Logo-based Analysis in New Chemical Materials Industry. *Digit. Commun. World* **2020**, *8*, 194–197. [CrossRef]
19. Diao, J.; Wang, G.; Qiu, B. Research on the Application of Industrial Internet Identification Resolution System in the Petrochemical Industry. *Internet Things Technol.* **2022**, *12*, 89–92.
20. Li, J.; Gao, Z.; Wu, W.; Chen, B.; Shi, Z. Research on application and development of an identity resolution system of the industrial internet in the power equipment manufacturing industry. *Power Syst. Prot. Control* **2020**, *48*, 179–187.
21. Giua, A.; Silva, M. Petri nets and automatic control: A historical perspective. *Annu. Rev. Control* **2018**, *45*, 223–239. [CrossRef]
22. Jangid, R.; Singh, G.P. Construction of m-cube mesh networks using Petri nets. *Int. J. Syst. Assur. Eng. Manag.* **2023**, *14* (Suppl. 1), 256–262. [CrossRef]
23. Grobelna, I.; Karatkevich, A. Challenges in application of Petri nets in manufacturing systems. *Electronics* **2021**, *10*, 2305. [CrossRef]
24. Kaid, H.; Al-Ahmari, A.; Nasr, E.A.; Al-Shayea, A.; Kamrani, A.K.; Noman, M.A.; Mahmoud, H.A. Petri net model based on neural network for deadlock control and fault detection and treatment in automated manufacturing systems. *IEEE Access* **2020**, *8*, 103219–103235. [CrossRef]
25. Luo, J.; Yi, S.; Lin, Z.; Zhang, H.; Zhou, J. Petri-net-based deep reinforcement learning for real-time scheduling of automated manufacturing systems. *J. Manuf. Syst.* **2024**, *74*, 995–1008. [CrossRef]