Digital twin simulation for quality and efficiency evaluation on industrial manufacturing: A Theoretical Analysis

XueXue Zhang [1] Xuan Ouyang [2]

[1] Beijing Zhongtian Xingye Cultural Development Co., Ltd., Haidian District 100083, Beijing, China;

[2] Institute of Forest Resource Information Techniques, Chinese Academy of Forestry, Haidian District 100091, Beijing, China

ABSTRACT This paper presents an integrated intelligent manufacturing quality and efficiency assessment system that leverages real-time data collection, knowledge graphs, and machine learning to optimize assessments and intelligently analyze production processes. A digital twin simulation platform is utilized for precise mapping of physical environments to virtual models, enhancing manufacturing quality and efficiency. The system's objectives include developing a data collection and analysis framework for interoperability of heterogeneous data sources, employing advanced machine learning models for event extraction and causal relationship identification, and constructing a comprehensive causal graph for in-depth quality analysis. A novel method integrating graph convolutional neural networks with knowledge graphs is proposed for precise quality and efficiency assessment, featuring a knowledge graph embedding-based GCN model and a regularized loss function for improved accuracy. The system also incorporates a digital twin approach for accurate simulation, with a focus on online data collection, network resource allocation, and the creation of virtual models through digital modeling techniques. A communication network and data management system are designed to enhance M2M communication, using MILP and cloud computing for network adaptability and data real-timeness. The project aims to automate the design process with STEP standards and build an IMT digital twin system for comprehensive machine tool monitoring, ultimately achieving the intelligent manufacturing goal of "controlling the real with the virtual."

Keywords Intelligent Manufacturing, Digital Twin, Knowledge Graph Integration.

I. INTRODUCTION

The scale of China's manufacturing industry has grown rapidly, positioning it as a global leader in manufacturing. However, there is still a gap in technological level compared to manufacturing powerhouses such as the United States, Germany, and Japan. The manufacturing industry is the core of the real economy, and its development quality directly affects the country's productivity level and the high-quality development of the economy. The report of the 20th National Congress of the Communist Party of China emphasizes that promoting high-quality development is the theme of current economic work, requiring the manufacturing industry to achieve effective improvement in quality and reasonable growth in quantity. Intelligent manufacturing, as a strategic direction for the transformation and upgrading of China's manufacturing industry, plays an important role in enhancing both the "quantity" and "quality" of manufacturing. Intelligent manufacturing promotes technological transformation and structural optimization and upgrading of the manufacturing industry by introducing new generation information technologies such as big data, artificial intelligence, and the Internet of Things, facilitating high-quality development of the manufacturing industry. It is key to realizing the transition from "Made in China" to "Smart Made in China" and building a modern socialist strong country. In this context, the assessment of quality and efficiency in the equipment production process is an important safeguard for safe production in the intelligent manufacturing industry.

We introduce a causal graph-based approach to quality and efficiency assessment, offering a novel perspective on quality issues in equipment manufacturing. This method transcends traditional analysis by dynamically deducing the mechanisms behind quality events, visualizing causal relationships, and unearthing the logic behind quality issues. By integrating graph convolutional neural networks with knowledge graphs, we model the complex interplay of multi-source, heterogeneous data across the product lifecycle, enhancing the traditional industry's analytical capabilities.

We also integrate knowledge graph-based data fusion with a digital twin simulation platform for intelligent manufacturing, providing an innovative solution for quality and efficiency assessment. Online twin data collection, multi-source data processing, and virtual environment modeling facilitate real-time state prediction and control, optimizing manufacturing processes. The designed communication network and terminal construction technology enable precise control and operation execution, enhancing production efficiency and quality. This digital twin-based assessment method bolsters sustainable industry development with practical technological support.

II. Literature review

With the widespread application of emerging technologies such as big data, the Internet of Things, cloud computing, artificial intelligence, and digital twins in the manufacturing industry, numerous intelligent manufacturing solutions have been implemented, leading to profound changes in manufacturing production methods. Promoting the intelligent transformation of the manufacturing industry has become a national development strategy in the industrial sector of major countries worldwide. Therefore, in the wave of intelligent manufacturing, China is currently facing fierce competition, but it is also a good opportunity to promote industrial upgrading and deepen supply-side reform. Against this backdrop, China has introduced the "Made in China 2025" strategy [1], proposing to promote the rapid development of the intelligent manufacturing industry, develop manufacturing equipment, and advance the digital control, simulation optimization, and real-time monitoring of the manufacturing process. Consequently, there is an urgent need to develop an integrated intelligent manufacturing quality and efficiency system that can fully utilize multi-source heterogeneous industrial manufacturing quality data for in-depth integrated analysis and enhance manufacturing quality and efficiency assessment and intelligent level through digital twin technology. Currently, domestic and international research has been conducted on industrial data collection and integrated analysis, quality and efficiency assessment, and industrial digital twin systems:

(1) Quality and efficiency assessment data collection and integration

To address the unclear and incomplete data requirements in equipment testing and evaluation, [2] proposed a model tree-based data requirement analysis method, starting with the root model set, decomposing and simplifying to form the leaf model set, then merging, simplifying, and categorizing these sets to ultimately determine the data requirements for quality and efficiency assessment. Xia Zhenghong et al. [5] analyzed a large amount of text containing efficiency evaluation and constructed a scientific knowledge map to effectively integrate and analyze these multi-source heterogeneous data. Zhu Lihong et al. [4] proposed a large-scale constellation efficiency evaluation method, which establishes an efficiency evaluation index system, collects data, and uses the Analytic Hierarchy Process to determine the weight of evaluation indicators, corrects the dynamic evaluation indicators with variable weights, and calculates the system efficiency of the constellation communication system. In terms of R&D efficiency measurement, [3] introduced the "Five Improvements of R&D Efficiency Measurement" practical framework, including the ability to automatically collect efficiency data, design an efficiency measurement index system, and establish an efficiency measurement analysis model, emphasizing the importance of data collection. [6] provided an intelligent algorithm efficiency evaluation method based on a multi-dimensional model, including establishing an efficiency evaluation model for SAR image ship target recognition models, collecting data, setting weight coefficients, and calculating the comprehensive efficiency evaluation score. [7] analyzed the basic principles and current status of efficiency evaluation methods based on neural networks, summarized the advantages and disadvantages of evaluation methods based on various artificial intelligence models, and pointed out that efficiency evaluation methods based on small sample deep learning will become a future development trend. Zhou Xingwang et al. [8] proposed an efficiency evaluation method based on the fusion of BN and BP neural networks, which used BP neural networks in the process of dimensionality reduction for the index system, facilitating the establishment of the network structure for the Bayesian network, and ultimately establishing a scientific and reasonable efficiency evaluation model. In the field of efficiency evaluation, it is necessary to find a method that can perform dimensionality reduction and de-correlation processing. Qiao Rong et al. [9] proposed an efficiency evaluation method based on PCA-BP neural networks in 2020, which used principal component analysis (PCA) to process the original data. This method can effectively solve the above problems and obtain better prediction values. Due to the large and complex relationship between the index system and various indicators in the field of efficiency evaluation, the sample data obtained through various channels has the characteristics of large data dimensions, large data volume, and complex correlation between variables. There is an urgent need for a knowledge map-based data fusion technology to effectively depict the complex correlation relationships of these data.

(2) Industrial manufacturing quality and efficiency

Common methods used in quality and efficiency evaluation include analytical methods, statistical methods, simulation methods, and comprehensive evaluation methods. The analytical method reveals the relationship between efficiency indicators and constraints through functional expressions and calculates the value of efficiency indicators [12][13], such as the ADC method (composed of availability, credibility, and capability) commonly used in weapon equipment efficiency evaluation [14], while the System Effectiveness Analysis (SEA) method [15][16] evaluates the dynamic efficiency of weapon systems by comparing system capabilities and mission requirements. Although the analytical method is simple to calculate, it is difficult to consider all influencing factors, and the understanding of the relationship between efficiency indicators and constraints is high, which limits the persuasiveness of the evaluation results. The simulation method or simulation method [17] establishes a mathematical model of the quality infrastructure and its elements, uses computer simulation technology to build a virtual operating environment, and conducts a series of simulation experiments, such as policy efficiency simulation experiments, to obtain efficiency evaluations under different constraints. This method is easy to implement, but the key is to build a running environment that is close to the actual application of the quality infrastructure. The statistical method [18] relies on a large amount of statistical data and materials obtained from practical activities. The efficiency evaluation value obtained by this method is more accurate and can analyze the impact of system performance indicators and operating modes on efficiency indicators. However, it requires necessary verification, such as tracking the formulation and implementation process of standards to obtain empirical data on standardized efficiency, which makes the cost higher and the cycle longer. The comprehensive evaluation method [17] is suitable for quality infrastructure systems with complex hierarchical structures, such as standards, measurement, conformity assessment, accreditation, and market supervision [11][10]. Since it is difficult to establish a clear functional relationship between comprehensive efficiency and element evaluation indicators, this method requires a comprehensive analysis of multiple evaluation indicators. It has strong applicability and wide application, but human factors have a greater impact, such as the need to construct an evaluation index system and the corresponding weight system, and the efficiency evaluation result depends on the choice and determination of [14] efficiency evaluation indicators and their importance. At present, quality evaluation is still based on more traditional methods. If quality and efficiency can be comprehensively and fully evaluated from the perspective of diversified information fusion, the results will be more accurate and credible.

(3) Industrial digital twins

In the field of digital twin data application, Zhu et al. [23] developed a cyber-physical system-based automotive rear axle assembly line simulation system, achieving the integration of the physical and information worlds. Liu et al. [24] proposed a digital twin management method driven by applications in the industrial edge environment to enhance the management capability of twin data package content and solve the problems of application isolation and heterogeneity. Lai et al. [25] proposed a method of integrating manufacturing execution systems and simulation models, achieving modeling and integration with MES software through MATLAB and Simulink, and completing bidirectional data communication. Athan et al. [26] emphasized that digital twin technology is an extension of intelligent automation technology, building a digital twin system through real-time heterogeneous data collection, data integration, and simulation capabilities, and combining AI technology to achieve predictive maintenance. In the application of digital twin technology to factory planning, Erranda et al. [27] built a digital twin factory to achieve cost control and workshop layout optimization, updating the material list and layout through real-time 3D scanning. Liu et al. [28] proposed a five-step planning method to create data-driven digital twins to achieve twin interaction of the manufacturing system. Cheng et al. [29] developed a digital twin manufacturing cyber-physical system (MCPS) for smart workshops, achieving dynamic autonomy and proactive decision-making of manufacturing resources. Adel et al. [35] proposed a data and model fusion-driven process full-process workshop multi-dimensional digital twin system, solving the collaborative operation and iterative operation of complex process manufacturing workshops. Van et al. [36] proposed a real-time data-driven twin factory workshop construction method, building a virtual simulation digital workshop with high fidelity corresponding to the real physical factory workshop, and building a modular and universal twin virtual factory workshop system using event-driven data management methods.

(4) China's efforts

In domestic research, Tao Fei et al. [30][31][32] first explored and proposed the concept of digital twin workshops, elaborating in detail the components, operation methods, and key technologies of twin workshops, fundamentally explaining the system components, operation methods, operation mechanisms, and characteristics of digital twin workshops, and also providing the basic theory, methods, and tools for the realization of digital twins, laying a theoretical foundation for the realization of virtual and real mapping, data services, and model fusion in manufacturing workshops; Wang Jinfeng et al. [33] proposed the concept of digital twin technology on the basis of the background of digital twin production, elaborating in detail the connotation of product twins, providing the system architecture, implementation approaches, and development trends. The above scholars have clarified the methods for the future application and implementation of digital twins and laid a theoretical foundation. On the basis of the theoretical background, Xu Pengyue et al. [34] proposed a digital twin visualization control method for production units, achieving the construction of a visualization control model and synchronization technology based on edge computing gateways.

At present, there are rich industrial applications of digital twins both domestically and internationally, but these industrial digital twin systems still lack effective data fusion analysis technology, network comprehensive design, and equipment twin modeling to achieve accurate simulation of quality and efficiency evaluation.

III. Our proposal of the method

(1) Quality Performance Evaluation Data Fusion and Analysis Based on Knowledge Graph

This paper first investigates multi-source heterogeneous quality data in digital workshops and smart factories, achieving real-time collection and interoperability through standardized schemes, and uses structured text to record daily quality issues. After data cleaning and feature selection, it provides data support for the quality performance evaluation in intelligent manufacturing. Furthermore, this paper innovatively proposes a deep integration method for quality performance evaluation data based on knowledge graphs, aiming to strengthen the evaluation and management of quality performance in the production process through causal event extraction and the construction of causal diagrams. It first identifies causal cue words in structured text, then uses pattern matching technology to extract cause and result clauses, and finally conducts event extraction through dependency syntax analysis, ultimately extracting event pairs that show causal relationships, providing complete information for the quality performance evaluation of the production process. Specifically:

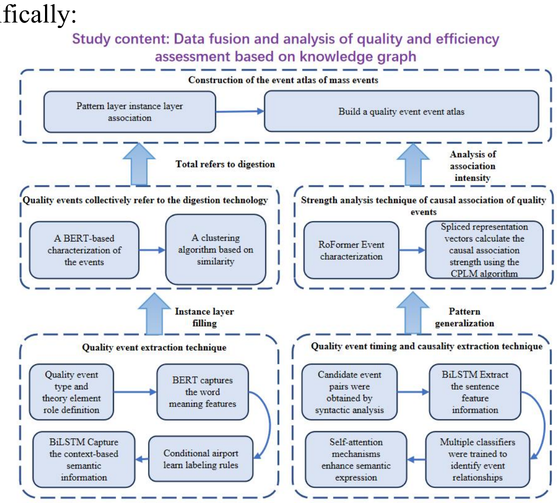

Figure 1. Data fusion and analysis of quality and efficiency assessment based on knowledge graph

In the construction of production process quality data acquisition systems for intelligent manufacturing, this paper comprehensively collects the quality data flow and data interfaces in the production process under the environment of digital workshops and smart factories, ensuring the automatic online collection of key data and addressing the real-time collection and interoperability issues of multi-source heterogeneous quality data. By deeply analyzing the interface and protocol requirements of different types of quality data such as process, product, and production process, a standardized scheme for the entire process quality data types and their access methods is designed to achieve real-time dynamic collection and interoperable analysis of multi-type quality data during the production process. In terms of data format, the data in this paper comes from the daily quality issue records of an electronics manufacturing company in the past two years, which are reflected in structured text form, focusing on key information such as design quality, production quality, full-cycle quality, quality issues, and causes of quality issues. After completing the data collection, this paper studies field-oriented data cleaning, transformation, modularization, integration, and standardization operations, and uses a Filter-Wrapper hybrid algorithm for feature selection to create a dataset suitable for downstream tasks, providing strong data support for the quality performance evaluation of intelligent manufacturing.

In terms of the integration and analysis of multi-source heterogeneous manufacturing process quality data based on knowledge graphs, this paper studies the integration and analysis methods of multi-source heterogeneous manufacturing process quality data based on knowledge graphs, aiming to deeply analyze and understand quality issues through causal event extraction and the construction of domain-specific dictionaries. First, this paper studies highly specialized domain dictionaries and applies dependency syntactic analysis technology to accurately extract quality issue events. The construction of the domain dictionary will focus on including proprietary vocabulary and industry colloquial expressions unique to the field, ensuring the completeness and professionalism of the vocabulary. Considering the complexity of industry terminology, the domain dictionary will include indivisible information units and specific vocabulary combinations to ensure accuracy and completeness in text processing and quality issue analysis. Further research employs a dependency syntax-based atomic event extraction method, defining quality issue events as a series of actions and behaviors that lead to problems and the resulting state changes. By analyzing the clauses in the cause and result, this paper reveals the causal logic of quality issue formation, and atomic events are considered the smallest units of the event, whose extraction follows strict semantic integrity standards to ensure that the subject, object, and related core syntactic relationships are preserved.

Next, this paper studies precise causal relationship extraction rules, aiming to extract cause and result event tuples from manufacturing domain text data and store this information in a structured form. The research will use explicit causal relationship extraction methods, focusing on summarizing and matching syntactic patterns. It first studies the causal relationship structure of quality events, analyzes the progressive structure from cause to result in the text, identifies expressions containing two or more layers of causal relationships, considers analyzing multiple causal cue words in sentences, reveals the pattern of one cause and multiple effects, and constructs a causal chain to fully display the development rules of quality issues. The research summarizes and induces syntactic patterns, summarizes causal cue words, and combines them with industry data characteristics to form a fixed causal relationship expression pattern. Further, this paper studies the design of regular matching rules, establishes boundary matching rules for causal relationship extraction based on syntactic patterns, and uses regular expressions along with greedy and non-greedy matching to design precise matching rules. Finally, the paper studies the implementation of causal relationship extraction, applies the designed regular matching rules, and performs causal relationship extraction on processed text data to identify and extract cause and result clauses.

Furthermore, this paper deeply studies the causal relationship extraction technology of quality issue events, aiming to automatically identify the temporal and causal relationships between events and present them in the form of triples (<Event1, Relationship, Event2>). First, this paper studies a feature-based supervised learning method to extract the temporal relationships of events. It identifies all events from consecutive sentences and forms a candidate event pair set. For this, a series of features such as frequency, proportion, context, and association are constructed. The paper studies a classic classifier to model the temporal relationship of candidate event pairs as a binary classification task, achieving accurate extraction of temporal relationships.

Next, the paper studies a sequence labeling-based supervised method to extract the causal relationships of events and enhance them. It extracts causal event pairs from individual sentences, assuming that each sentence contains at most one pair of causal events. The research uses the BIO (Begin, Inside, Outside) tagging strategy to label the text. Through the labeled event pair tags, the research treats the event relationship extraction problem as a multi-classification problem and uses a Bi-LSTM model combined with Self-Attention to obtain event pair features, achieving relationship classification, and thus obtaining the event clauses and their corresponding relationship combinations. In addition, to cope with the uncertainty of complex event causal relationships, this paper studies the use of the pre-trained language model RoFormer, combined with the advantages of absolute and relative position encoding, to further construct the Sentence-BERT model, achieving enhancement of causal relationships.

Finally, this paper uses an event representation clustering algorithm for coreference resolution, reducing the redundancy of event descriptions, and supplements the relationships between the event pattern layer and the instance layer, improving the hierarchical system of events. Ultimately, it uses a graph database and the Cypher language to visualize and query the causal diagram, providing a new method of data fusion and analysis for quality performance evaluation.

(2) Research on Quality Performance Evaluation Technology Based on Graph Convolutional Neural Networks

To effectively conduct quality performance evaluation and achieve performance optimization, this paper proposes a quality performance evaluation method based on graph convolutional neural networks to analyze the quality performance represented by knowledge graphs.

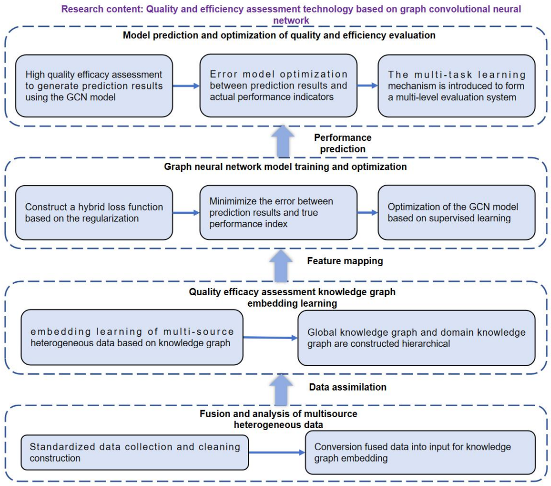

Figure 2 Quality and efficiency assessment technology based on graph convolutional neural network

This method not only integrates and analyzes complex multi-source heterogeneous data but also synthesizes information on key indicators of quality performance through graph neural networks to achieve accurate evaluation and optimization. The core innovation of this paper lies in embedding the knowledge graph as input to the GCN, aiming to enhance the accuracy of performance evaluation through the rich data structure and semantic relationships of the knowledge graph. In terms of multi-source heterogeneous data fusion processing, this paper employs a representation learning method based on knowledge graphs, using GCN for embedding learning of multi-source heterogeneous data, which involves dividing the knowledge graph into hierarchical levels to construct both a global knowledge graph and domain-specific knowledge graphs. The global knowledge graph represents key entities and relationships in the entire manufacturing process, such as product design, production steps, quality inspection, etc. The domain-specific knowledge graph provides a more refined description for specific functional modules and data differences.

The complete quality performance evaluation knowledge graph constructed in this paper, which includes causal relationships, represents the interconnections between entities in quality performance evaluation and potential paths for the propagation of quality issues. GCN is a neural network model capable of processing graph-structured data, learning node representations through the connectivity between nodes. Therefore, the paper utilizes the knowledge graph to generate feature-based embedded representations as input for the GCN model, achieving multi-source data-driven quality performance evaluation. Specifically, in the graph convolution process, this paper first constructs the connectivity between nodes through the graph's adjacency matrix and combines embedded representations for feature transmission. This process uses multiple layers of GCN to extract and learn features from each node in the graph (such as equipment, quality issues, quality indicators, etc.), aggregating information from adjacent nodes layer by layer. This allows each node's representation to include not only its own information but also information from nodes it is directly or indirectly connected to, thereby capturing global performance evaluation indicators.

In the training process of the performance evaluation model, this paper optimizes the GCN model using supervised learning. The actual performance from historical data is used as a supervisory signal, and the model is optimized by minimizing the error between predicted results and true performance indicators. Additionally, the paper employs a regularized loss function design, integrating knowledge graph embeddings and local performance data to create a hybrid loss function that constrains performance indicators at different levels with embedded representations. This allows the model to focus not only on the fitting effect of local data but also to fully utilize the information from the global knowledge graph, thereby enhancing the overall accuracy of performance evaluation. To further enhance the model's predictive capabilities, the paper also introduces a multi-task learning mechanism, which allows the model to learn the potential relationships with other related indicators while evaluating a certain type of performance indicator, forming a multi-level evaluation system. In this way, GCN can not only make accurate predictions for a single indicator but also identify the coupling relationships between different quality indicators, providing a more comprehensive performance evaluation.

To enhance the GCN model's generalization ability in different scenarios, this paper will also explore how to strengthen the model's performance through the expansion and optimization of the knowledge graph. This involves dynamically updating entities and relationships in the knowledge graph to ensure its timeliness and accuracy. Furthermore, the paper will introduce knowledge distillation techniques, using the pre-trained language model RoFormer to optimize embedded representations. By combining self-attention mechanisms with positional encoding, the paper can further enhance the GCN model's perceptual capabilities, enabling it to more accurately evaluate performance in complex quality performance evaluation scenarios.

(3) Constructing a Digital Twin-Based Quality Performance Evaluation Simulation Platform

This paper aims to develop a digital twin-based intelligent manufacturing simulation platform. By researching integrated status sensing, data fusion, communication network design, digital modeling, machine learning prediction and control, and terminal execution technology, it achieves real-time monitoring, analysis, and optimized control of the manufacturing process. This leads to increased production efficiency and quality, reduced costs, and enhanced market competitiveness.

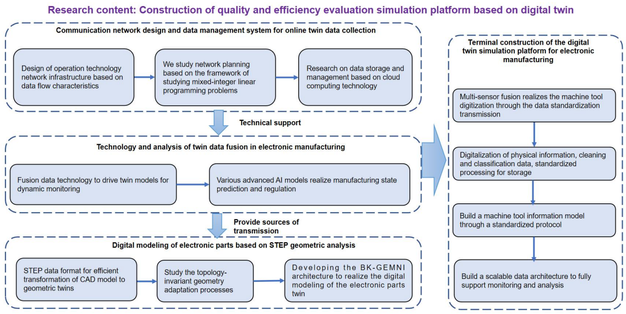

Figure 3 Construction of quality and efficiency evaluation simulation platform based on digital twin

This paper studies the design of communication networks and data management systems for online twin data acquisition, analyzes communication requirements, and then designs a detailed factory layout that can intuitively display the flow of information and task execution. This paper researches the design of operational technology (OT) network infrastructure based on the characteristics of data flows in different areas, taking into account specific quality of service (QoS) requirements, and combines the spatial distribution of tasks within the factory to ensure the rationality of network design. Furthermore, this paper studies network planning based on the mixed integer linear programming (MILP) problem framework, regarding the physical network infrastructure as the carrier of data flows, optimizing the manufacturing process through information exchange, and building a network synthesis problem modeling.

This paper also researches graphical front-end tools, which interact with back-end tools through RESTful web services to achieve network synthesis. Finally, regarding data collection, storage, and processing, this paper studies the collection of data through operational management infrastructure and sensors, integrates different data sources, and ensures the timeliness and effectiveness of the data. It researches data storage and management based on cloud computing technology, supporting highly scalable and shareable storage solutions. It also studies data preprocessing technology on the edge side to improve the scalability of the data architecture and meet real-time requirements.

This paper proposes a STEP-standard-based geometric analysis digital modeling technology aimed at achieving the digital construction of electronic component twins. By integrating 3D CAD models with actual measurement data, it aims to generate a geometric representation that matches actual manufacturing. Using the STEP data format under the ISO 10303 standard, it enables efficient transformation of CAD models into geometric twins in the later stages of product development. The project researches a topology-invariant geometric adaptation process, studies the geometric elements and their representation methods in the STEP format, forms an operation list and modification guide to ensure the precision and efficiency of geometric modifications. Additionally, this paper also studies the BREP shape representation in the STEP format, detailing its topology-geometry structure and improved features. Finally, this paper develops the corresponding BK-GEMNI architecture for the digital modeling of electronic component twins and generates a geometric model of a pneumatic cylinder base that matches actual measurement data through empirical research.

In terms of the terminal construction of the digital twin simulation platform, this paper focuses on the digital twin system of intelligent machine tools (IMT) in the field of electronic manufacturing. It utilizes the MTConnect protocol and develops human-machine interfaces and applications to achieve efficient terminal management of data. The specific research includes the collection, processing, fusion of multi-sensor data, and the construction of information models to ensure data standardization and system scalability. Using MTConnect and OPC UA protocols, it achieves data digitization, formatting, and construction of machine tool status information, providing comprehensive support for machine tool monitoring and analysis.

VI. Discussion

This paper proposes to construct a knowledge graph-based data analysis system, a graph convolutional neural network performance evaluation model, and a digital twin simulation platform, aiming to achieve real-time collection, integration, analysis, and quality performance evaluation of multi-source heterogeneous data in the manufacturing process to enhance production efficiency and product quality. Specific key issues to consider include:

This paper addresses the issue of real-time collection, integration, and analysis of multi-source heterogeneous data in the field of intelligent manufacturing. Therefore, how to achieve standardized collection and interoperability of multi-source heterogeneous data during the production process, and how to enhance quality performance evaluation through advanced data analysis technologies such as knowledge graphs and causal event extraction, are the first core issues of this paper. Technically, the challenges the project needs to overcome include designing a standardized access scheme for the entire process quality data types, achieving real-time dynamic collection and analysis of production process data, and constructing domain-specific dictionaries and employing dependency syntactic analysis to extract and understand causal relationships in quality issue data.

The aim of this paper is to build a graph convolutional neural network integrated analysis and performance evaluation system based on knowledge graphs. The first consideration is how to achieve efficient data integration and knowledge graph representation technology, and how to enhance the accuracy of performance evaluation through the optimization of the GCN model. Technical challenges include developing learning methods for knowledge graph feature embedding and aggregating information from the knowledge graph layer by layer through a hierarchical GCN model to optimize quality performance evaluation. Further, building a performance evaluation model with strong generalization capabilities, designing a regularized loss function, combining global knowledge graphs with local performance data, focusing on the fitting effect of local data and optimizing global information, and introducing multi-task learning mechanisms to enhance the model's ability to identify coupling relationships between different quality performance evaluation indicators, achieving more accurate performance evaluation.

The core objective of this paper is to construct a digital twin-based quality performance evaluation simulation platform, integrating the physical manufacturing environment with precise virtual models to achieve real-time monitoring and analysis of the manufacturing process. Therefore, how to effectively design communication network synthesis technology to collect multi-source heterogeneous data in the intelligent manufacturing process, and how to use this data to optimize production efficiency and product quality are key. Technical challenges include developing an efficient data management system and an integer programming-based network synthesis method to support the collection and processing of online twin data; developing STEP-based geometric analysis digital modeling technology to create accurate electronic component twins, and through data fusion technology, mapping processed data to the physical environment state to support the prediction and control of manufacturing status.

V. Conclusion

The advancement of smart manufacturing and the application of new-generation information technology are forming a new manufacturing model with smart manufacturing as the main direction of development. This not only improves production efficiency and product quality but also promotes the transformation and upgrading of the manufacturing industry, enhancing the international competitiveness of enterprises. This paper aims to achieve real-time monitoring and optimization in the manufacturing process, improving production continuity and traceability, thereby reducing production costs and enhancing product reliability.

Firstly, the data fusion and analysis technology for quality performance evaluation based on the knowledge graph can achieve real-time collection and interoperability of multi-source heterogeneous quality data through standardized schemes, providing data support for quality performance evaluation. The aim is to enhance production efficiency and product quality comprehensively, reduce costs, thereby enhancing the market competitiveness of enterprises, and promoting high-quality economic development.

Furthermore, by extracting causal events and constructing a causal diagram, the quality performance evaluation and management in the production process are strengthened, ensuring the continuity and traceability of the production process. This is of great significance for improving the quality of products and services, meeting consumers' pursuit of a high-quality life, and thus helping to improve the overall quality of life in society and promoting social harmony and stability.

In addition, the quality performance evaluation technology based on graph convolutional neural networks is expected to improve the accuracy of quality performance evaluation by fully combining the structured information of the knowledge graph and the efficient fusion capability of graph neural networks, reducing resource waste, and thus promoting sustainable development.

Finally, by applying digital twin technology to the entire process monitoring, enterprises can perform closed-loop optimization of product design, manufacturing, and intelligent services in a virtual environment, further improving production efficiency and product quality. This promotes the rapid development of smart manufacturing, fosters technological innovation, and improves the optimization and upgrading of the industrial structure towards high-end transformation

REFERENCES

[1] Siemens Industry Software Inc., Siemens Central Research Institute. Industrial 4.0 in Action [M], Beijing: Mechanical Industry Press, 2015.9

[2] Chi Kuo, Yang Lei, Li Huifen, et al. Research on Data Requirements Analysis Method for Equipment Performance Evaluation [C] // National University of Defense Technology, Systems Engineering College. Proceedings of the 6th Academic Conference on Systems Engineering—Systems Engineering and High-Quality Development. China Satellite Maritime Tracking and Control Department;, 2024:6.

[3] Zhang Le, Core Methods and Practices for R&D Performance Measurement: Design of Practical Framework and Indicator System.

[4] Zhu Lihong, Wang Xianyu, Zhou Quan, et al. A Large-Scale Constellation Performance Evaluation Method, CN202211526538.

[5] Xia Zhenghong, Wan Jian, Zhu Xinping. Visualization Analysis of Performance Evaluation Research Based on Scientific Knowledge Graph [J]. Fire Control & Command Control, 2020, 45(3):5.

[6] Sun Xian, Diao Wenhui, Fu Kun, et al. Multidimensional Model-Based Algorithm Performance Evaluation Method: CN202110020794.8[P]. CN112700158A[2024-10-18].

[7] Yu Xiaolan, Xiong Wei, Han Chi, A Review of Performance Evaluation Methods Based on Neural Networks, Ordnance Industry Automation, 2023-03 42(3).

[8] Zhou Xingwang, Cong Fuzhong, Pang Shichun. Ground-Air Joint Combat Effectiveness Evaluation Based on BN-and-BP Neural Network Fusion [J]. Fire Control & Command Control, 2018, 43(4): 3-8.

[9] Qiao Rong, Zhou Feng. PCA-BP Neural Network-Based Air-to-Ground Missile Weapon System Combat Effectiveness Evaluation [J]. Military Operations Research and Systems Engineering, 2020, 34(4): 38-43, 67.

[10] Blind K. The economics of standards [M], 2004.

[11] Daddi T, Frey M, Giacomo MRD, et al. Macroeconomic and development indexes and ISO14001 certificates: A cross-national analysis [J]. Journal of Cleaner Production, 2015 （108） : 1239-1248.

[12] Gonçalves J, Peuckert J. Measuring the impacts of quality infrastructure [R]. Impact Theory, Empirics and Study Design. Braunschweig, Germany: Physikalisch-Technische Bundesanstalt, 2011.

[13] Gonçalves J, Peuckert J. The contributions of quality infrastructure to national innovation systems: Implications for development policy [R]. Innovation Systems and Capabilities in Developing Regions: Concepts, Issues and Cases, 2012.

[14] Harmes-Liedtke U, Oteiza Di Matteo J. Measurement of Quality Infrastructure[R]. Discussion Paper 5/2011 Physikalisch Technische Bundesanstalt, International Technical Cooperation, 2011.

[15] PTB. The functioning of quality infrastructure [R], 2015.

[16] PTB. The Answer to the Global Quality Challenge: A National Quality Infrastructure[R], 2014.

[17] Ulrich Harmes-Liedtke. The Relevance of Quality Infrastructure to Promote Innovation Systems in Developing Countries [J]. Discussion Paper, 2010 （3） :3-27. UNIDO. Quality Infrastructure[R], 2006.

[18] Wang Ning, Li Panpan, Zhao Zheyun, Yang Jianfeng. Quality Anomaly Diagnosis in Intelligent Manufacturing Process Based on Convolutional Neural Network [J]. Operations Research and Management, 2022, Vol. 31(6): 220-225

[19] Z. Shan et al., "GPA-Net: No-Reference Point Cloud Quality Assessment With Multi-Task Graph Convolutional Network," in IEEE Transactions on Visualization and Computer Graphics, vol. 30, no. 8, pp. 4955-4967, Aug. 2024

[20] Huang Hongqing, Ni Daohong, Liu Xuesong. Power Quality Evaluation Based on Graph Convolutional Network. Electronic Science and Technology, 2024, 37(09):43-47.

[21] K. Zhou, Y. Ma, H. P. H. Shum and X. Liang, "Hierarchical Graph Convolutional Networks for Action Quality Assessment," in IEEE Transactions on Circuits and Systems for Video Technology, vol. 33, no. 12, pp. 7749-7763, Dec. 2023

[22] Zhu Z. X, et al. Digital Twin-driven machining process for thin-walled part manufacturing[J]. Journal of Manufacturing Systems, 2021, 59: 453–466.

[23] Liu S M, et al. Machining process-oriented monitoring method based on digital twin via augmented reality[J]. The International Journal of Advanced Manufacturing Technology, 2021, 113(11): 3491–3508.

[24] Lai X N, et al. Designing a shape－performance integrated digital twin based on multiple models and dynamic data: A boom crane example[J]. Journal of Mechanical Design, 2021, 143(7): 071703.

[25] Athan L. et. al, A molecular dynamics based digital twin for ultrafast laser material removal processes[J]. The International Journal of Advanced Manufacturing Technology, 2020, 108(1): 413–426.

[26] Erranda I, et al. Digital twin for maintenance: A literature review[J]. Computers in Industry, 2020, 123: 103316.

[27] LIU Q, ZHANG H, LENG J W, et al. Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system[J]. International Journal of Production Research, 2019, 57(12): 3903–3919.

[28] Cheng Qiang, Xu Wenxiang, Liu Zhifeng, et al. A Review of Machine Tool Equipment for Smart Green Manufacturing [J]. Journal of Huazhong University of Science and Technology (Natural Science Edition), 2022, 50(6): 31–38.

[29] Tao Fei, Liu Weiran, Liu Jianhua, et al. Exploration of Digital Twin and Its Applications [J]. Computer Integrated Manufacturing Systems, 2018, 24(1): 1–18.

[30] JONES D, SNIDER C, NASSEHI A, et al. Characterising the digital twin: A systematic literature review[J]. CIRP Journal of Manufacturing Science and Technology, 2020, 29: 36–52.

[31] Qi Hao, Li Xiaoyue, Tao Qiang, et al. Research Progress of Digital Twin-Driven Mechanical Process Systems [J/OL]. Acta Aeronautica et Astronautica Sinica, [2023–08–14].

[32] Wang Jinfeng, Wen Congchuan, Hua Guangru. A Review of Digital Twin: Concepts, Technologies, and Applications [J]. Journal of China Mechanical Engineering, 2023, 21(2): 112–116, 133.

[33] Xu Pengyue, Liu Pan, Zheng Xiaofei. A Review of the Application of Digital Twin in Manufacturing Industry [J]. Modern Manufacturing Engineering, 2023(2): 128–136.

[34] ADEL A. Future of industry 5.0 in society: Human-centric solutions, challenges and prospective research areas[J/OL]. Journal of Cloud Computing, 2022, 11(1): http:doi.org/10.1186181 3677 – 022 – .00314–5.

[35] VANDERHORN E, MAHADEVAN S. Digital Twin: Generalization, characterization and implementation[J]. Decision Support Systems, 2021, 145: 113524.