Application of Edge Computing in the Quality Control of Cable Production Process

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Abstract: Given the lack of quantifiable evaluation criteria for the quality supervision and control in the existing power cable industry, insufficient research on the correlation of production indexes in the production process, and low timeliness in the analysis and processing of massive multi-source production data, the video monitoring model and data-driven process quality evaluation strategy model under the edge computing framework were constructed. Next, all the production data and test data in the cable production procedures were captured using edge nodes, and the factory-side data was cleansed, processed, and analyzed. The cable manufacturing quality was evaluated through edge computing, and the business process was arranged based on the edge computing results, so as to improve the cable product quality and finally optimize the total value chain of production in the whole cable industry.

1. Introduction
On May 8, 2015, the State Council released Made in China 2025 [1], elaborating the development prospects of China's manufacturing industry. Power cables constitute the foundation for realizing the safe and stable supply of energy resources and the sustainable and healthy development of the national economy as one of the categories with the greatest demand, the highest product performance requirements, and the broadest application scenarios in the industry of electrical equipment. Extensive attention has been paid to supervising and managing the intelligent manufacturing quality of power cables.

When strengthening the production quality control, power cable enterprises are mainly faced with three difficulties and challenges: First, there lacks generally accepted evaluation criteria for the quality control of the power cable industry. A lot of manpower, materials, and time need to be input in order to integrate and converge related production parameters for quality control, along with enormous costs. Second, different from the universal production line, the data in various links of cable products bound to meet specific high requirements, such as process design, procurement, production, test, logistics, and order, will be adjusted more or less, and the fluctuation link is long. Third, both the equipment quantity and data generated by cable enterprises are surging [2], and given the complex feature—multi-source heterogeneity [3]—of access equipment, the access of miscellaneous data can easily lead to the system network congestion and substantially affect the cloud-end data acquisition and processing efficiency.

To ensure the healthy and sustainable development of the power cable industry and promote the effective quality evaluation of the production process, an edge computing-based data-driven decision analysis model was constructed in this study, and then a cable quality evaluation system was established to process and analyze the cable production data and detection data at the edge. It was expected to reduce nonconforming cable products in the power industry as much as possible through...
comprehensive product quality control, lower the quality control cost for cable enterprises, strengthen the technological innovation of production processes \cite{4}, and facilitate the transformation of China's cable manufacturers from the low-cost competitive advantage into the competitive advantages in quality and benefit.

2. Overview of Edge Computing

2.1 Meaning of edge computing
Edge computing refers to a new-type computing model that executes distributed computation at network edge under the background of internet development and evolution. It serves as the basic bridge connecting the Industry Internet and bottom-layer physical devices.

The objects of edge computing operation include the cloud-end downlink data and the uplink data of interconnected devices \cite{5}. Edge computing can integrate potential hundreds of millions of communication equipment like sensors, video collectors, video cassette recorders, testing equipment, and smartphones into the data center to perform the data acquisition and transmission from physical layer to platform layer, and the protocol analysis and conversion of heterogeneous equipment, meeting the key data processing needs in the era of IoT like agile connection \cite{6}, real-time business, remission of computing pressure and data optimization.

2.2 Advantages of edge computing
When applied to cable enterprises, edge computing mainly has the three following advantages: First, it has strong service performance, since it performs quality alarm and process analysis in the production process and processes data and makes decisions close to the data production site, not needing to request the response from the cloud data center, thus considerably reducing the system delay; second, the data security is strengthened. Edge computing saves sensitive data on edge devices, which avoids security and privacy problems brought by the data disclosure after data transmission to the shared data center; third, the operating cost is lowered. Edge computing can reduce the data transmission quantity and bandwidth of edge devices and data centers, so as to reduce the cost generated by the computing and storage in the network and cloud data center during industrial production.

2.3 Edge intelligence architecture
The edge computing-based industrial internet architecture will play an irreplaceable role in the intelligent transformation and upgrading of cable production and manufacturing. With the functions of managing network, computing, storage, and application, the industrial internet electrical equipment category management center \cite{7} not only supports traditional protocols and interfaces, ensuring that the interconnected devices gaining access at the beginning will not only be influenced by the intervention of edge layer, thus losing the connectivity, but also enable the devices that originally cannot be interconnected to realize information interconnection under the help of the edge computing technology and further solve the connection problem between devices.

The edge intelligence architecture of the electrical equipment category management center facing intelligent manufacturing big data processing is as shown in the following figure. This architecture is mainly divided into four layers: device layer, edge layer, cloud computing layer, and application layer, with heterogeneity and supporting multiple application services.
Field device layer: The device and business system involved in each production procedure of access cables at the field device layer, mainly including PLC (programmable logic sensor), production line video recorder, digital testing device, simulation testing device, network video recorder, all kinds of handheld smart devices, etc. The business system interfaces include ERP system, MES system, LIMS system, etc. All devices in the production procedures are connected in a wireless way, thus forming an internetwork with wide coverage, complete links, and large capacity, and providing data and transmitting tasks to the edge layer.

Edge layer: The edge layer, which is located between the device layer and cloud computing layer, is the layer closest to the original data at the factory side. Edge managers are mainly deployed around factory equipment and connected to production equipment via a wired network or local area network (LAN). Edge managers mainly refer to exchangers, routers, and other intelligent terminals, with specific computing power, communication capability, and storage capacity, and work between the cloud computing layer and the terminal device layer. As the members of the distributed network, edge nodes provide computing, storage, and network services for terminal devices and serve as a significant guarantee for data security and privacy. The edge gateway takes charge of the access of the terminal nodes at the device layer, cooperates with the cloud computing layer in applying edge computing [8-9], and provides services like protocol conversion, data acquisition, edge computing load, data storage, and processing and collaboration application. Moreover, the edge gateway supports a two-level device model, where the first-level device model faces the device access, describes the communication capability of terminal nodes, and covers original data information like physical communication port, communications parameters, and data protocol address. The second-level device model faces the cloud-edge collaboration, describes the functions of terminal nodes, and provides normalized data objects for cloud computing and edge computing.

Cloud computing layer: The cloud computing layer consisting of high-performance servers integrates powerful cloud storage, cloud computing, and cloud analysis capabilities, and it is able to screen, store and analyze the data acquired by production equipment and provides remote services for cable production procedures. The platform supports cloud-edge collaboration, in which the cloud computing layer performs the total life-cycle management of the edge gateway from creation until configuration, unloading, updating, and monitoring, arranges the processing strategies and model training for the edge-side data, and transmits the configuration information, models and applications to the edge gateway for updating and execution. There are two important data flows between the cloud computing layer and edge layer: First, the acquired data is cleansed and preprocessed from bottom to top at the edge layer, the irrelevant parameters and data are excluded, and the key information extracted through filtering is pushed to the cloud computing layer, thus reducing the transmission bandwidth. Second, the complex computing task executed by the cloud computing center is disassembled from top to bottom, the data without real-time requirement in the business system is saved, computed, and uniformly arranged at the cloud end, while that with the high real-time requirement is disassembled to the edge side of the factory side, and the decision is executed by edge
computing. The effective division of work between cloud computing and edge computing is adopted on this platform to handle the loads under different scenarios, which not only completes the functions and services requiring timeliness but also makes the work simple and lowers the deployment, operation, and maintenance costs.

Application layer: The cable production procedures include test and detection, warning, fault diagnosis, equipment maintenance, real-time monitoring, order management, and audit encryption. Relevant personnel can use the related functions by logging in to the system platform to intuitively and timely get the production data, which can considerably improve the production efficiency and production quality. The platform supports multi-user management with multiple safety guarantees: First, the data transmission is encrypted using TLS, ensuring high-intensity data storage and transmission encryption. Second, safety protection is executed for the network side, edge gateway, and data applications through firewalls. Third, the platform provides an audit log interface, and saves and manages audit logs.

The edge intelligence architecture design solves the real-time heterogenous data connection problem between different systems at the factory side, performs the decentralized management of devices and enhances their safety, and realizes the asynchronous and concurrent data storage of multiple production procedures.

3. Application Design of Edge Computing Technology in Production Procedures

3.1 Factory-side data cleansing
The electrical equipment category management center realizes the application of edge computing by deploying edge nodes, captures the production data, test data, and surveillance video data of all the production procedures, i.e. the value data-carrying business tags, in the cable production flow using edge nodes, processes the captured data through filtering rules, then captures, analyzes, judges and verifies the real-time production data using data acquisition transformation, clustering analysis, and other techniques, and effectively identifies and restores incomplete data and inaccurate data.

The invalid redundant parameters and data are processed through the process management of factory-side data cleansing links, including four data cleansing steps: data preprocessing, missing data processing, data format processing, and data logic processing. In the data preprocessing link, the captured data is filtered, the repeating data is excluded, and the problem data to be processed is found, including but not limited to improperly named data, wrongly written data, and mistakenly input data. In the processing link of missing data, the missing data is complemented or deleted, e.g., finding vacant date value or index value, or supplementing the missing data by means of re-extraction or artificial supplementation, interpolation and deletion. As for the data format processing link, the formatted data is corrected, e.g., the numerical data is input with full-width numerical characters or there is an error of data format. Moreover, the unified management and maintenance of field attributes are done by setting a data dictionary, the boundary and specification of fields are defined, and the wrong data formats are consistently processed through the field attribute rules. In the data logic processing link, the contradictory values and outliers in numerical values are identified, corrected, processed, and confirmed according to the Pauta criterion, which is then effectively trained and supplemented through the resulting feedback. Generally speaking, data logic processing involves business data restructuring. To facilitate the full data analysis and processing based on production links, partial data structures should be carried or the data structures under different business scenarios should be merged to ensure the retention of high-value information data.
After the factory-side data was cleansed, the key information data filtered and extracted was then pushed to the electrical equipment category management center platform to generate authentic and valid original datasets of power cable production and manufacturing for the follow-up quality analysis.

3.2 Formulation of the quality evaluation rule engine

In the power cable production process, numerous production indexes affect cable quality. Even the same measurement index may have different connotations in different production requirements, and the indexes are associated to some extent. Some key qualitative indexes can be hardly quantified, but exert important influences on the production quality, so they are worthy of high attention. Given this, the quality evaluation based on cable production procedures is not only of high complexity but with degraded quality analysis efficiency. In this study, the information reflected by original variables was included to the greatest extent by summarizing and extracting core indexes and comprehensive variables, and then quantified with a more appropriate mathematical model.

Based on the data-driven process quality evaluation strategy model designed under the edge computing framework, a total of 23 key evaluation indexes were extracted from six production process capacity factors—personnel, machine, material, method, environment, and measurement—and then embedded into the rule engine. The indexes of the personnel capacity factor were quantified by centering on operators' professional titles, years of related work experience, and operating time. The indexes of the machine capacity factor were evaluated according to the equipment value level, the number of equipment faults, and years of equipment operation. The indexes of material the capacity factor were analyzed through the brand of raw material, material usage, and mechanical properties. The indexes of method capacity factor were converted according to the production procedure, procedure precision, and standard requirements [10]. The indexes of the environmental capacity factor were quantitatively compared based on the temperature, humidity, and dust-free degree of the production environment. The indexes of measurement capacity factor were measured and evaluated through the DC resistance, compliance rate of voltage-withstanding duration, and the magnitude of partial discharge obtained in the predelivery test. The detailed index descriptions and index conversion methods are seen in the following table.

| S/N | Production process capacity factor | Name of evaluation index | Index conversion method |
|-----|-----------------------------------|-------------------------|-------------------------|
| 1   | Personnel                         | Operator's professional title | Conversion method for operator's professional title: Senior professional title (senior technician) =1, medium-grade professional title (technician) =0.9, junior professional title (senior worker) =0.8, others=0.7; doctoral degree=1, master's degree=0.9, bachelor degree=0.8, others=0.7 |
| 2   | Years of related work experience  |                         | Conversion method for years of related work experience: \( Y_X/Y_M \) |
| 3 | Operator's operating time | Where, $Y_M$ is the maximum years of related work experience of the operator completing the procedure. |
|---|--------------------------|---|
| 4 | Equipment value level | Conversion method for equipment value level: $= V/V_M \times 80\% + (N/N_M) \times 20\%$ Where, $V_M$ is the maximum value of production equipment and $N_M$ is the maximum number of production equipment of the same model in the industry. |
| 5 | Number of equipment faults | Conversion method for the number of equipment faults: $= 1 - \text{number of faults}/10$ The index is taken as 10 when the number of faults is greater than 10. |
| 6 | Number of equipment operation years | Conversion method for the number of equipment operation years: $= 1 - T/T_M$ Where, $T_M$ is the maximum number of years in which the equipment of the same model and category can be put into use. |
| 7 | Brand of raw material | As the material-related evaluation indexes are all qualitative and the requirements for different materials are different, it is difficult to establish the same baseline for the quantitative comparison. The characteristic indexes, expected goals, and data values are associated by means of fuzzy matter-element to obtain accurate analysis results. Conversion method: $= \mu(x)$ Where $M$ is a characteristic index, $C$ is the value of index data, and $\mu(x)$ is the value of the corresponding fuzzy characteristic quantity. |
| 8 | Specification of raw material | |
| 9 | Material usage | |
| 10 | Mechanical properties | |
| 11 | Surface quality | |
| 12 | Production procedure | The related procedure indexes of method dimension are converted according to the conversion method for the process capacity index, namely, the influence factors of procedural process capacity are decomposed layer by layer, and the factors in each layer are refined to constitute a factor set influencing the procedure capacity. Conversion method for process capacity index: $= \frac{USL - LSL}{6\sigma}$ Where, $USL$ and $LSL$ are the parameter upper limit and lower limit in the standard requirement of the index, and $\sigma$ represents the sample standard deviation. When the calculation result $< 0.67$, the index is converted into 0; When $0.67 \leq \text{calculation result} \leq 1$, the index is converted into 0.5. |
| 13 | Procedure precision | |
| 14 | Standard requirement | |
| 15 | Parameter upper limit | |
| 16 | Parameter lower limit | |

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When $1<\text{calculation result} \leq 1.33$, the index is converted into 0.75;
When $1.33<\text{calculation result} \leq 1.67$ and when the calculation result $>1.67$, the index is converted into 1.

| No. | Description                                                      | Conversion Method                                                                 |
|-----|------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| 17  | The temperature of the production environment                     | $\frac{T - T_0}{T_M - T_0}$                                                      |
|     |                                                                  | Where $T_M$ and $T_0$ are the maximum and minimum values of environmental temperature upon the task completion in this production procedure, respectively. |
| 18  | The humidity of the production environment                       | $\frac{H - H_0}{H_M - H_0}$                                                      |
|     |                                                                  | Where $H_M$ and $H_0$ stand for the maximum and minimum values of the humidity upon the task completion in this production procedure, respectively. |
| 19  | Dust-free degree of the production environment                   | $1-U/U_M$                                                                        |
|     |                                                                  | Where $U_M$ is the maximum degree of dust fall.                                  |
| 20  | Percent of the pass in the process test                          | Conversion method for the percent of the pass in process test:                  |
|     |                                                                  | The index is 1 if the test result is qualified and 0 if the result is disqualified. |
| 21  | DC resistance in the predelivery test                            | Conversion method for the DC resistance in the predelivery test:                 |
|     |                                                                  | The index is 1 if the test result is qualified and 0 if the result is disqualified. |
| 22  | The compliance rate of voltage-withstanding duration             | Conversion method for the compliance rate of voltage-withstanding duration:      |
|     |                                                                  | The index is 1 if the compliance rate is 100%;
|     |                                                                  | The index is 0.8 if 100% > compliance rate of voltage-withstanding duration > 99.9%;
|     |                                                                  | The index is 0 if 99.9% > compliance rate of voltage-withstanding duration.     |
| 23  | The magnitude of partial discharge                               | Conversion method for the magnitude of partial discharge:                       |
|     |                                                                  | The index is 1 if the test result is qualified and 0 if the result is disqualified. |

The computational analysis of evaluation indexes was carried out via edge computing technology, and the computing results were fed back to the platform system and synchronized to the corresponding production equipment to implement real-time control, optimization, and decision-making. The production process was timely monitored, and the production management was managed. The quality warning rule was set in the platform, so once the edge computing result was not within the expected reasonable range, a warning would be sent to the production department and supervision department to realize effective risk prevention and control.

4. Application Scenarios of Edge Computing Technology in Quality Control

4.1 Business process arrangement based on edge computing results
According to the research findings regarding the quality evaluation of power cable production, the
cable quality is influenced not only just by cable production materials but also the production process, detection method, etc. [11]. During the cable production and manufacturing process, the production processes vary, and the process parameters involved vary with the production procedure. The cable quality is the result of the accumulative superposition of all production procedures [12]. The production process parameters should be combined for the sake of effective evaluation and analysis.

In this study, the quality evaluation was performed for the cables produced by the suppliers gaining access to the electrical equipment category management center platform with the help of edge computing technology. Next, given the inclination of edge computing technology to executing predictive tasks, the real-time mass data was computed, with attention paid to the speed, memory usage, and energy efficiency of the algorithm execution framework in the prediction process. An edge computing-based evaluation framework for electrical equipment was specially developed to ensure value maximization. This framework contained four major links: data acquisition, model training, quality prediction, and quality application.

![Fig. 3 Working Mechanism of Edge Computing-based Evaluation Model](image)

Data acquisition: The data acquired by the platform included raw material data, production data, video data, etc., which were large but with just a few characteristic dimensions, and no definite relationships were found between the characteristics. After the factory-side data was cleansed through edge nodes according to the data cleansing process, the abnormal data was checked and the missing
data was complemented, and all the acquired characteristics were taken as effective characteristics.

Model training: The index quantification models (like process capacity index model, fuzzy matter-element model, and linear model) applied in the process quality evaluation strategy model were preliminarily adjusted. The optimal segmentation point was sought, the optimal structure tree generated by each training process was added into the model until the target error reached the minimum value, and whether the model achieved the optimal level was judged by setting a validation set.

Quality prediction: The optimal values of process aggregation parameters were set to improve the product quality, including the homogeneity of products, percent of the pass, and service life. Next, the data quality in the test set was predicted through the prediction model, and the model prediction result was reflected directly by the accuracy.

Quality application: The key characteristics of product quality were monitored, the technological process was optimized, and the order of operating procedures was adjusted or the operating parameters of the manufacturing unit were regulated to improve the production efficiency. Edge computing could realize the characteristic deployment of different products and production lines, link the upstream and downstream supply chains, coordinate department needs, and promote the optimization and fusion of enterprises' ecological chains at the edge.

On this platform, a data-driven process quality evaluation strategy model was established based on edge computing, followed by a comprehensive analysis of factors of different dimensions. Next, the variable data of each procedure was input, the final output result was calculated according to the variable calculation, and the business was rearranged through the output data, expecting to acquire the optimal value. Besides, the cable production equipment was automatically controlled, the data analysis and self-processing capabilities were strengthened, and the relevant risk early warning was given, thus helping production enterprises and power enterprises to control the risks, and optimize the equipment performance status, process parameters, technological process, and finally the total value chain of production in the whole cable industry.

4.2 Data analysis of old equipment by combining edge computing and OCR image

Not a few factories have gradually started the informatization construction. However, the related production equipment used has not kept up with the digitalization development. A lot of factories still use traditional video monitoring equipment, most of which are already old and not timely updated, and consequently, the data stored in old equipment cannot be effectively read. Besides, the built-in computing power of front-end cameras is insufficient, and the mass videos stored cannot be timely invoked. The reconfiguration of intelligent video monitoring systems or the replacement of cameras is an enormous challenge faced by factories. On the one hand, the cost is extremely high, and on the other hand, the intelligent processing capacity can hardly reach the expected level.

To solve the problems of the factory monitoring platform (like difficult video transmission, great video analysis, and processing difficulty, and high storage cost), the edge computing model and video monitoring technology were integrated according to the features of edge deployment position adjoining the data source side. Then, the OCR technology was combined to transfer the monitoring video analysis and preprocessing to edge nodes. Subsequently, an intelligent video monitoring service platform based on an edge computing framework was constructed, and the key frame extraction and filtering algorithm of edge nodes was designed. By identifying target videos, the video images were preprocessed to remove the redundant information and screen out and upload valid videos. Next, an edge node task scheduling algorithm was designed to improve the intelligent processing capacity of front-end cameras in the video monitoring system. If the edge nodes were not used to identify images and videos, the video load pressure was high, the transmission bandwidth required was large with a long-time delay, and the mass videos lost the significance of effective monitoring. Moreover, the risk points could not be identified without the input of a lot of manpower and material resources.

The edge computing framework provided an effective preprocessing platform for video monitoring in the factory avoiding problems such as the limited computing power of servers in cloud computing
centers. The specific operating steps were as follows:

1) Improve the overall network performance. The old network was extended and renovated, and the bottleneck links and nodes encountered in the data transmission were reduced;

2) Accelerate the video analysis speed. Partial or all videos were analyzed by the edge nodes. A platform with the preprocessing function was provided to the video monitoring system to perform the real-time extraction and analysis of behavioral characteristics in videos and implement the processing mechanism for the behavioral perception data on monitoring scenarios;

3) Improve the memory utilization rate of video data. A behavioral perception-based elastic storage mechanism of video monitoring data was constructed to conduct the real-time adjustment of video data, which could not only reduce the storage of invalid videos and reduce the memory space but also maximize the storage of "in-process" evidence-type videos and enhance the credibility of evidence information.

When applied, the video monitoring technology lowered users' construction and maintenance costs. The centralized computing and storage mode strengthened the security and reliability of video data. In this way, the valid videos saved were reduced, and the memory space was reduced. Moreover, the "in-process" evidence-type video data was maximized, thus enhancing the credibility of evidence information and improving the utilization rate of memory space for video data. Based on the intelligent processing function, the "in-process" event monitoring and "in-process" event reporting functions were added to timely and effectively transmit the response message to users.

5. Conclusion

Under the technological development background of comprehensively interconnected industrial internet, the data-driven mode was combined with edge computing and big data analysis technique to perform a full range of data sampling and analysis of cable production procedures. Moreover, the process cleansing steps and rules were established for the factory-side data rinsing, and the quality evaluation rule engine was studied and designed, followed by the process control and quality evaluation of cable production. The evaluation result served as a significant link in the feedback to implement the real-time monitoring and warning of cable production and manufacturing, and substantially improve the transmission efficiency and cost control for production enterprises. It is predicted that with the continuous development and iteration of technologies in the future, edge computing technology may gradually realize edge autonomy, dynamically realize self-optimization, and finally automatically realize the business logic analysis. Furthermore, the indexes triggering decisive factors in the production procedures should be discovered to facilitate the deep analysis. On this basis, the control and optimization of production procedures can be promoted through the closed feedback loop of quality monitoring effect.

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