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Research on Flexible Data Model of MES System based on Time-series Database

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Abstract

In the process of advancing towards digitization and intelligence in manufacturing, Manufacturing Execution Systems (MES) have gradually become the core of production processes. The design of the data model is crucial as it affects the scalability, maintainability, and stability of the system. This study focuses on addressing issues in MES systems such as high investment costs, imperfect data models, lack of flexibility, and inefficient data flow. It proposes a novel flexible data model based on time-series databases.This paper introduces the definition and characteristics of time-series databases, analyzes the shortcomings of existing MES system data models, and proposes a novel flexible MES data model based on time-series databases. Finally, the practicality and efficiency of the new data model are validated through experiments.

Keywords

Time-series Database; MES System; Data Model; Flexibility.

1. Introduction

1.1. Current Status of Traditional MES System Data Models

With the rise of Industry 4.0 and smart manufacturing, the manufacturing industry is facing significant transformations. In the current era of smart manufacturing, there is a continuous increase in the demand for big data; various workshop algorithms such as workshop scheduling algorithms, labor hour forecasting algorithms, etc., require more flexible data models; data queries demand more comprehensive, accurate, and rapid responses. These challenges are posing a threat to traditional MES systems. Traditional MES systems, due to their small data capacity, are unable to cope with high concurrency, and their rigid data models cannot meet the demands of the current smart manufacturing environment. Therefore, it is imperative to propose a data model for MES systems based on big data that is more flexible, faster, and more accurate.

The traditional MES system data model typically revolves around the enterprise, emphasizing centralized management and control. The data model is primarily constructed around production processes, resources, materials, quality, etc., which are solidified based on a production line, lacking flexibility and adaptability [1].

Table 1 below shows an example of equipment data for a production line.

Table 1. Equipment Data Sheet

Equipment ID	Equipment Name	Responsible Person	Date of Manufacture
001	Lathe	Li Si	2000.1.1
002	Robot1	Zhang San	2000.1.1
003	Robot2	Wang er	2000.1.1

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The traditional MES data model primarily focuses on structured data and lacks sufficient processing capabilities for the massive, unstructured data emerging in modern manufacturing processes [2]. To address this issue, some studies recommend adopting NoSQL databases to better manage unstructured data and enhance data access and analysis efficiency. Additionally, the integration of big data platforms makes storage and processing of these data more efficient.

Regarding the handling of time-series data, traditional MES systems lack effective storage and analysis tools. Facing this challenge, new MES systems are beginning to adopt databases designed specifically for time-series data, such as InfluxDB, and real-time Complex Event Processing (CEP) technologies, enabling efficient processing and real-time analysis of time-series data [3].

The rapid changes in industrial production demand that MES systems promptly adapt to new production equipment and processes, and expand their functionalities. Traditional MES systems with their independent modules hinder flexible functionality expansion [4]. In this regard, microservices architecture provides an effective solution by decomposing MES into multiple small, independent service units, each responsible for different functions, thereby making system modifications and upgrades more flexible and expedient [5].

In summary, the traditional MES data model shows shortcomings in managing structured data, handling time-series data, ensuring system flexibility, and addressing challenges in modern manufacturing. The following section will propose a MES system data model based on time-series databases to address these issues.

1.2. MES Data Model based on Time-Series Databases

Table 2. Time series database comparison table

Database	Advantages	Disadvantages	Applications
InfluxDB	Focuses on storing and retrieving time-series data without external dependencies.	Integration with backend systems may pose challenges.	Monitoring, IoT sensor data storage, etc.
Kdb+	Fastest time-series database with lower operational costs.	Optimized primarily for the financial industry.	Suitable for big data, IoT, IT, and OT sectors.
TDengine	Domestically developed open-source time-series database with extremely high data retrieval speed and SQL query support.	Lower data refresh rates.	Industrial Internet and computer IT applications.
Prometheus	Capable of real-time monitoring of system data.	Slower compared to Prometheus and InfluxDB.	Industrial and computer IT sectors.
TimescaleDB	Supports SQL query language, fully optimized for SQL queries.	Low data refresh rate.	Industrial IoT and computer IT sectors.

Building upon the capabilities of time-series databases, this model enhances the traditional MES data model by introducing dynamic management of process flows[6]. It upgrades the processing capabilities of key modules such as personnel, orders, and equipment from the traditional MES data model, thereby enhancing system flexibility, reducing maintenance costs, and establishing a more versatile data model framework. Leveraging the characteristics of time-series databases, the MES system now efficiently supports operations for writing, querying, and summarizing time-series data[7]. Compared to traditional relational databases, time-series databases exhibit significant advantages in handling time-related data (e.g., temperature, humidity, and vibration data collected by various sensors) [8]. In MES applications, time-series databases provide rapid data storage and retrieval services to meet the demands of high-frequency and large-volume data processing.

Popular time-series databases in the market include InfluxDB, Kdb+, Prometheus, Graphite, TimescaleDB, TDengine, each offering distinct features and advantages.As shown in Table 2 below[9-10].

Considering the requirements of MES systems, TDengine, a domestically developed open-source time-series database known for its steep learning curve, high operational efficiency, and capability to handle large volumes of data, is chosen.

2. Design of Flexible MES System Data Model based on Time-Series Database

2.1. Data Model Design based on Time-Series Database

In traditional MES systems, the data model typically includes modules for equipment data, personnel management, order management, and so on. Designing only these modules has certain limitations and fails to fully utilize the capabilities of MES systems in the era of big data. In a time-series database-based approach, in addition to the aforementioned modules, modules for materials, processes, collection, and resources are expanded.

By expanding these modules, the MES system gains additional functionalities and integrates resources such as big data and algorithms, making it more convenient for users to utilize MES in factory production. This enhances the depth of MES system applications and aligns with microservices frameworks, reducing development complexity and costs. The relationships between these modules are illustrated in Figure 1 below. The subsequent sections will elaborate on the advantages of expanding these modules.

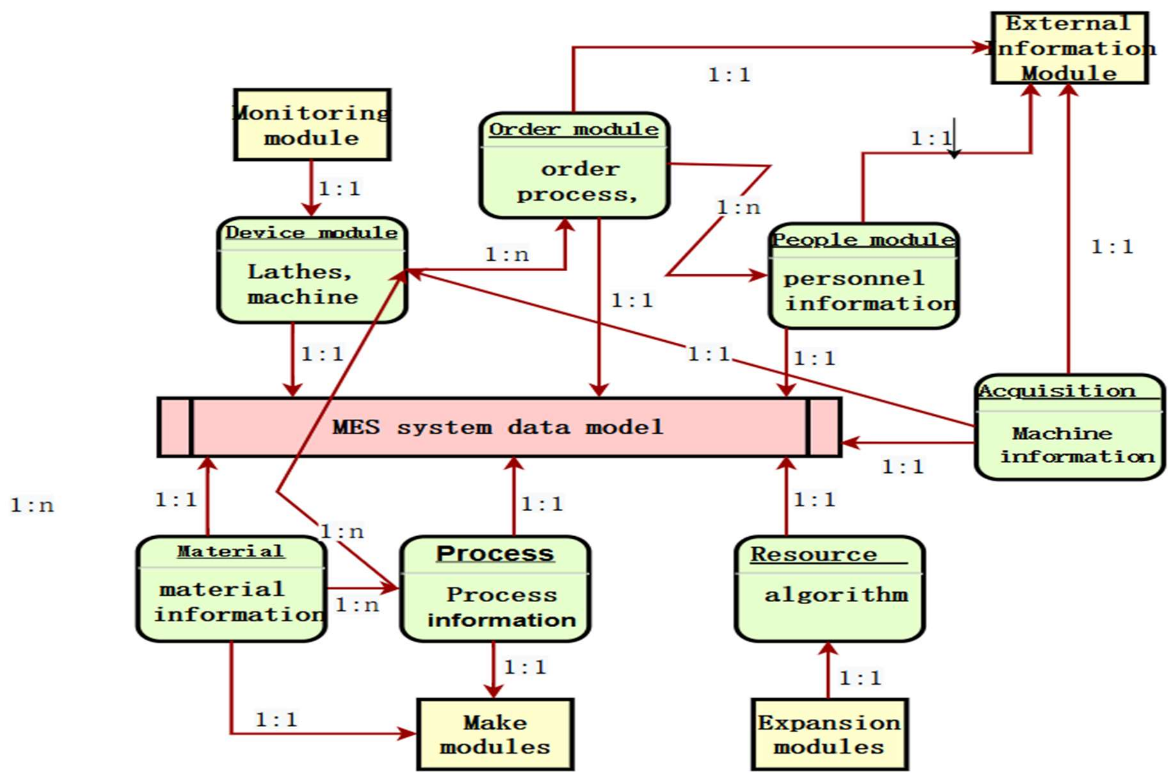

Figure 1. Module Relationship Diagram

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In traditional manufacturing execution systems (MES), the material management module primarily focuses on basic material information maintenance, inventory tracking, and demand planning, lacking flexibility to adapt to rapidly changing production demands and complex supply chain environments. The material management module can benefit significantly from utilizing a time-series database for storage, enabling real-time tracking of material flow from receipt to consumption and final product. Leveraging the advantages of time-series data allows precise recording of every movement and status change of materials, associated with timestamps. This not only records extensive material data but also provides a rich foundation for subsequent analysis of material-related insights.

In existing MES systems, the process management module faces several critical challenges: static management of process data without dynamic adjustment capabilities for production changes, inflexible configuration of process parameters making it difficult to adapt to diverse production needs, and limited optimization potential of process workflows, hindering continuous improvement driven by data.

To address these issues, adopting a time-series database enables dynamic recording and tracking of process parameter changes. By continuously updating process data in real-time, it enhances responsiveness to production changes. Simultaneously, storing vast amounts of process data allows engineers to swiftly adjust and optimize process parameters based on actual production demands, thereby enhancing production flexibility and efficiency.

In the collection and resource management modules, the collection module stores real-time data from machine tools. Analyzing this data in real-time enables various functionalities such as machine tool operating time, total downtime, and utilization rate. Using a time-series database for storage reduces computational errors and processing time. The resource module includes uploads and downloads of data such as CAD drawings, tables, documents, as well as algorithms and equipment models. Storing this diverse data in a time-series database accelerates the intelligence of MES systems, contributing to their advancement towards smart manufacturing.

For equipment data, designing a data model based on a time-series database enables effective support for high-frequency data read and write operations, particularly for monitoring operational states such as temperature and vibration sensor data. Real-time updating and recording of these data in a time-series database ensure their immediacy and accuracy, providing robust support for equipment failure warning and maintenance decision-making.

2.2. Design based on Flexible Data Model

In terms of flexibility in MES systems, it mainly involves the order management module, personnel management module, and equipment data module. To enhance the dynamism of MES systems, it is essential to strengthen the flexibility in the design of these three aspects of data models, with a particular focus on the equipment data module.

In traditional MES systems, the order management module primarily maintains information and status of production orders. However, this module typically does not include management of order hours and audit processes. This limitation reduces the module's flexibility, making it more challenging to adapt to and adjust production processes.

To enhance the flexibility of the order management module in traditional MES systems, improvements are proposed. By expanding the functionalities of order management to include order generation, auditing, issuance, as well as forecasting and tracking of work hours, a more comprehensive order management model is provided. This approach allows better control of production processes and enables advanced prediction and resource planning.

By analyzing historical order data and current production capacity, and integrating workshop scheduling algorithms for estimating work hours, orders are entered into the system only if they can be completed within the specified time frame, as depicted in Figure 2 below.

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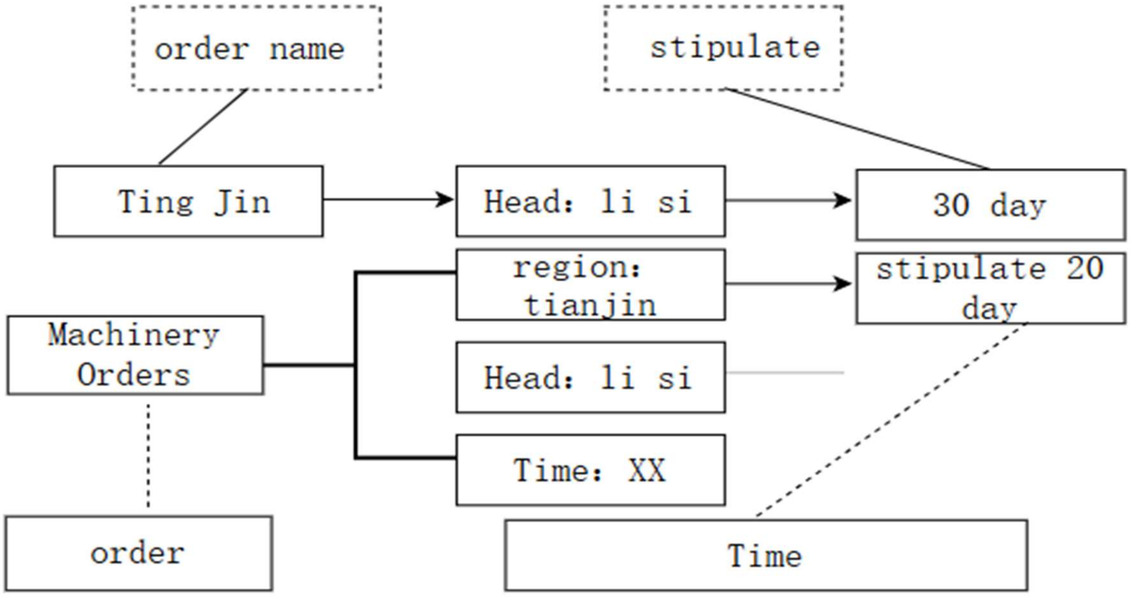

Figure 2. Module Relationship Diagram

In traditional MES systems, the personnel management module typically handles basic personnel information and permissions allocation, which can be too rigid in rapidly changing industrial environments. To address this issue, a more flexible personnel management data module is proposed. This module not only manages traditional static information but also integrates dynamic factors such as skill development, job efficiency, and on-duty status of employees. Additionally, a dynamic skills management module is introduced to update employee skill levels and training progress in real-time. Storing and processing these time-varying data effectively using a time-series database supports rapid retrieval of employees' skill development history, thereby providing data support for manpower planning and optimization.

In traditional MES systems, the equipment data module usually adopts a static data structure, limiting adaptability and flexibility during equipment changes and production processes. To tackle this issue, enhancements are made to the equipment data module to improve system responsiveness and maintenance efficiency.

Table 3. Add data structure table

Attribute Name	Description	Format	Example
STATE	Equipment operational state	INT	0 for operational, 1 for non-operational
TIME	Start time of operation	Timestamp	2023-1-1
ENDTIME	End time of operation	Timestamp	2023-1-2
NUM	Material inventory count	INT	123
MATERIAL_TIME	Timestamp of material	Timestamp	2023-12-1

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The structure of equipment data is designed for dynamic configuration, enabling adaptation to changes in production lines such as equipment updates, replacements, or process improvements without requiring extensive system-wide reconfiguration. Introducing modular and microservices concepts, a new equipment selection module is added, allowing independent updating and maintenance of equipment units, thus making them adaptive to production lines. This approach reduces the complexity and time required for system upgrades and maintenance. To differentiate from traditional data models, the newly added data structures are stated as follows.

Table 4. Comparison Table of Lathe Data under XML

Traditional MES System Lathe Equipment Data	Lathe Equipment Data Based on Time-Series Database
ID-01 Description- Name-CNC lathe Properties ID-CNC lathe Description - milling machine Value-2 NMU-5	ID-01 Description- Name-CNC lathe TIME-2024-04-12 ENDTIME-2024-04-13 Properties ID-CNC lathe Description - milling machine Value-2 Choice-0 NMU-5 Algorithm-Workshop scheduling Internet of Things- model Upload-CAD Run Time-56 hours Utilization rate-fifty percent
	Utilization rate-fifty percent

3. Experimental Results

Table 5. Database speed comparison table

Database Name	Data Size Added	Time Required
TDengine	Add 5000 sets of data	0.2 seconds
	Add 50000 sets of data Query 5000 sets of data Query 50000 sets of data	2seconds 10 seconds 100seconds
Mysql	Add 5000 sets of data Add 50000 sets of data Query 5000 sets of data Query 50000 sets of data	10seconds 500seconds 15000 seconds 5700seconds

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In comparing the storage speeds of time-series databases and relational databases, 5 sets of data of varying sizes were simultaneously stored. The specific experimental results are shown in Table 5 below.Acknowledgements

Comparing these five sets of data, the time-series database demonstrates a speed advantage over relational databases, particularly in querying and adding data, as evidenced by approximately 200 times faster speed when querying 50000sets of data. This highlights the superiority of time-series databases, especially in handling large-scale data.

4. Conclusion

This article primarily discusses the construction process of a flexible data model in MES systems. The model covers key modules such as personnel, equipment, orders, materials, and processes, and provides corresponding entity-relationship diagrams for databases. In the long term, adopting time-series databases significantly reduces data retrieval times, offering new perspectives for handling big data and transitioning towards intelligence in MES systems. Moreover, introducing flexible data models enhances the adaptability and flexibility of MES systems.

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