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Design And Implementation of a Digital Traceability System for Lithium-Ion Battery Assembly and Dispatch Management

Vishal Gupta[1], Payal Jain[2], Kartik Gupta[3], Shreeyansh Saxena[4], Nitesh Singh [5]

[1-5] New Product Development Department Maxvolt Energy Industries Limited, Ghaziabad India.
Correspondence: article@maxvoltenergy.com.

Abstract
The rapid expansion of the usage of lithium-ion battery technology in electric vehicles and energy storage systems has raised the need to ensure the highest level of traceability and transparency in the battery assembly process. The purpose of the proposed research is to design and implement a digital traceability system that can track the entire assembly process of the battery from the registration of the individual cells to the dispatch of the final battery product. The proposed digital solution is based on integrating real-time tracking, inventory management, quality control, and packing verification through a single software platform. The proposed solution will be able to track the entire assembly process of the battery through the assignment of unique identification to the individual cells and the final battery assembly, which will enable the genealogy tracking of the battery assembly process. The proposed digital solution has been experimentally implemented in the assembly process, and the results show the benefits that can be achieved through digital manufacturing solutions in the assembly process of the lithium-ion battery.

Keywords: MaxTrace, Digital Traceability system, Assembly Process, Supply Chain Management, Digital Manufacturing.

Nomenclature

Abbreviations

LIB	Lithium-ion Battery
BMS	Battery Management System
DTS	Digital Traceability System
EV	Electric Vehicle
QR Code	Quick Response Code

1. Introduction

With the shift in the global energy sector towards electric vehicles and renewable energy storage, lithium-ion battery manufacturing is growing exponentially. Thousands of individual cells are connected in complex structures to form a battery pack, used in vehicles, storage systems, and consumer electronics. To ensure the reliability and safety of battery systems, it is essential to implement strict quality control and traceability in the manufacturing process [1]. In traditional battery manufacturing systems, many operations are manually handled or implemented in separate databases, making it challenging to trace the product and identify the causes of failures. This becomes a serious problem in the case of product recall or quality issues [2].

Digital manufacturing technologies, as inspired by Industry 4.0, create opportunities for overcoming these challenges. For example, the integration of barcode or QR code technology, cloud-based database technology, and process monitoring technology can create opportunities for the development of digital traceability technology for battery manufacturing processes. Such technology can record all the manufacturing steps involved in battery production. The current research aims to develop a digital traceability system for lithium-ion battery assembly and dispatch processes [3]. In the proposed system will integrate cell-level traceability, module assembly monitoring, quality inspection records, packaging monitoring, and dispatch records in one system. The main aim of this research is to design and validate a digital traceability system for lithium-ion battery manufacturing processes.

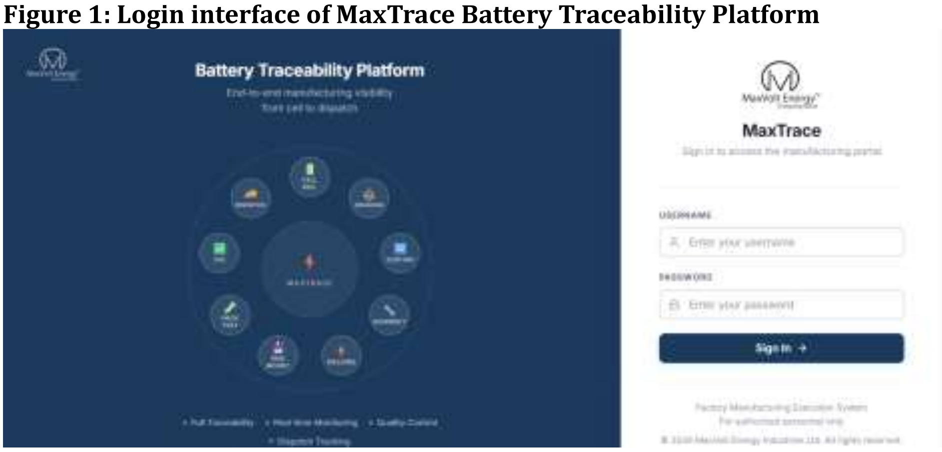
Some benefits that can be achieved when implementing the digital traceability system in the assembly line of lithium-ion batteries include the capability to perform battery genealogy tracking, which is essential in identifying all the cells, modules, and components used in the assembly of the battery pack. This is particularly important when performing root cause analysis in the case of product defect issues [4]. The system also has the capability to improve the management of the inventory and logistics, which is essential in the operation of the assembly line. The digital system also has the capability to reduce human error, which is common when using manual documentation methods. The digital traceability system also has the capability to support the implementation of data-driven strategies in the operation of the assembly line, as it can provide valuable information concerning the production process [5].

Despite the increasing significance of traceability in the field of battery manufacturing, many of the current systems are still not equipped with an integrated digital system for traceability. In many cases, traceability data is scattered among different databases or is isolated in different manufacturing systems. This is hindering the ability of the manufacturers to have a holistic view of the manufacturing process and is affecting the quality assurance process as well. Hence, there is a great need for a digital system that can manage the entire process of lithium-ion battery assembly and dispatching [6].

The major contributions of this research are:

- The development of a digital traceability architecture for battery manufacturing.
- The integration of real-time production tracking and inventory management.
- The implementation of battery genealogy tracking from cells to packs.
- The evaluation of system performance in a controlled assembly environment.

Figure 1: Login interface of MaxTrace Battery Traceability Platform



The figure 1 shows the login interface of MaxTrace Battery Traceability Platform, developed by MaxVolt Energy Industries Ltd. to manage and document the lifecycle of batteries across production lifecycle. It enables manufacturers and energy providers to ensure transparency, compliance and safety in battery operations through end-to-end traceability.

The design emphasizes:

- **Traceability** → Every step is logged and connected
- **Process integration** → All manufacturing stages are unified
- **User control** → Secure login ensures restricted access

In simple terms, MaxTrace acts like a digital backbone for battery manufacturing, ensuring every component can be tracked, monitored, and verified throughout its lifecycle.

2. Literature Survey

The rapid growth in the development of lithium-ion battery manufacturing, particularly for electric vehicles and energy storage systems, has created a need for effective monitoring and traceability systems in the manufacturing process. Lithium-ion battery manufacturing is a complex process that includes multiple stages, such as electrode, cell, module, and battery pack manufacturing. Each stage in the process results in the generation of large amounts of manufacturing data, which must be effectively recorded and managed to ensure product quality and safety. Researchers have stressed the need for traceability systems in lithium-ion battery manufacturing, stating that traceability systems are required to record the generated data in the manufacturing process, thereby establishing the relationship between manufacturing parameters and product performance, enabling the manufacturer to obtain datasets in the process chain, thereby supporting process optimization, maintenance, and data-driven manufacturing [7].

Traceability is critical in the battery manufacturing industry due to the safety risks that may befall the public as a result of the failure of lithium-ion batteries. Inconsistencies that may occur in the battery manufacturing process, such as electrode contamination, electrolyte unbalance, and electrode coating failure, can cause battery degradation and thermal runaway. In an effort to solve these problems, several authors have proposed the application of tracking and tracing technologies in the battery manufacturing process. This will enable the identification of faulty components and the improvement of quality assurance in the battery manufacturing industry [8].

Component identification is a technological requirement that has been identified as critical in the application of traceability technologies in the battery manufacturing industry and other industries with complex production processes. Various component identification technologies, such as barcodes, QR codes, and RFID tags, have been used in the identification of components and the tracking of the production process in the battery manufacturing industry. The application of optical component identification technologies, such as two-dimensional data matrix codes, is critical in the battery manufacturing industry due to the density and speed of the scanning process that can be achieved with the application of this technology in the industry [9].

Recent advancements in Industry 4.0 technologies have enhanced the capabilities of traceability in advanced manufacturing systems. Industry 4.0 technologies incorporate cyber systems, the Industrial Internet of Things (IIoT), cloud computing, and data analytics into the industry. These technologies enable the monitoring and tracking of the production process in real-time and the automatic recording of production data. Traceability systems based on Industry 4.0 technologies enable the tracking of materials and products in real-time and provide real-time visibility to the production process [10].

Another significant research direction in the production of lithium-ion batteries involves the application of data analysis in the production process. Machine learning and statistical analysis methods have gained popularity in the analysis of data generated during the production process of lithium-ion batteries. Researchers have successfully applied machine learning methods to analyze the relationships between the parameters of the production process and the performance characteristics of the battery. However, the application of such methods is highly dependent on the availability of production data, which can be achieved through the application of digital traceability methods [11]. Besides the application of digital technologies in the production process, researchers have also applied digital technologies in the enhancement of transparency in the entire supply chain of lithium-ion batteries. Blockchain technology has gained popularity as a digital technology that can be applied in the enhancement of transparency in the supply chain of lithium-ion batteries. Blockchain technology can be applied in the recording and verification of information concerning the supply chain of the battery, including the raw materials, production process, transportation, and recycling process [12].

Despite these developments, certain limitations are still present in the current traceability systems for the manufacturing of lithium-ion batteries. For example, many of the current traceability systems are designed to support the manufacturing process of individual lithium-ion battery cells, whereas the manufacturing process of battery packs and dispatch is still not supported adequately in these systems. Additionally, in many manufacturing systems, the manufacturing data is still scattered and present in independent software systems, hindering the ability to perform analysis of the manufacturing process as a whole. Hence, there is a need for a unified digital traceability system for the manufacturing of lithium-ion batteries, where component identification, production monitoring, quality inspection, and dispatch can be performed in a single system. The current research aims to fulfill this need through the development of a comprehensive digital traceability system for the manufacturing of lithium-ion batteries and dispatch management [13].

3. Digital Traceability System Architecture

The proposed Digital Traceability System (DTS) aims to perform end-to-end monitoring and tracking of lithium-ion battery component parts through the entire manufacturing process, from incoming cell inspection to dispatch of the finished battery pack. The system architecture will incorporate software platforms and database systems to ensure that all manufacturing activities are digitally recorded and associated with certain battery components. This system will establish a genealogy for all the components involved in the manufacturing process of the battery pack, enabling the manufacturer to trace a battery pack back to the individual cell parts used in the process.

The system architecture is based on a multi-layer system design with five main functional layers: the data acquisition layer, identification layer, database layer, application layer, and visualization layer. Each of these layers has a distinct role in the entire system of traceability and is aimed at facilitating real-time monitoring of battery assembly process activities.

3.1 Data Acquisition Layer

The data acquisition layer is in charge of acquiring real-time production information from the battery assembly line. This layer comprises diverse hardware tools, such as barcode scanners, QR code scanners, operators' terminals, and inspection tools placed in different stations in the production process. In the process of battery manufacturing, operators are required to scan the battery cells, modules, and battery packs before the process begins. This information is sent to the system server, where it is saved in the product manufacturing record. Other information, such as results from testing tools, including voltage, internal resistance, and function tests, can be automatically collected by the traceability system. The main aim of this layer is to ensure the precise and continuous collection of production information, excluding any manual recording process.

3.2 Identification Layer

The identification layer deals with the identification of all the components involved in the battery manufacturing process. A unique identification number is assigned to the components based on the identification codes. This enables the identification system to track the movement of the components through the manufacturing stages.

The identification system in the battery manufacturing industry includes the following:

- Cell Identification (Cell ID) – A unique identification number assigned to the lithium-ion cell.
- Module Identification (Module ID) – A unique identification number assigned to the group of cells assembled in the module.
- Battery Pack Identification (Pack ID) – A unique identification number assigned to the battery pack as the end product.
- Batch Identification (Batch ID) – This identification number is assigned for the identification of cells from the supplier batch.

3.3 Database Layer

The database layer is the heart of the digital traceability system. A centralized relational database is used to store all production data generated during the course of the manufacturing process. The database consists of several structured tables, which are as follows:

- Cell table
- Sorting and grading tables
- Battery Model table
- Battery pack assembly table
- BMS table
- Quality inspection table
- Packaging table
- Dispatch table
- Users Management table

Each record in the database has a unique ID, such as the cell ID or pack ID, which allows complete genealogy tracking. The database structure provides a centralized platform to integrate all production data generated during the course of the manufacturing process at different assembly stations.

3.4 Application Layer

The application layer is composed of software modules that handle the operational activities of the traceability system. The modules enable the monitoring of the manufacturing process, validation of the production process, and recording of the traceability information.

The main modules used in the application layer include:

- Production Tracking Module: It is used to track the movement of cells, modules, and battery packs through the production stations.
- Inventory Management Module: It is used to track the real-time availability of the components within the facility.
- Quality Inspection Module: It is used to track the inspection information and ensure that the components reach the next stage of production after passing the inspection.
- Packaging Verification Module: It is used to verify that all the assembly and testing activities have been completed prior to the commencement of the packaging process.

- Dispatch Management Module: It is used to track the dispatch information and link the battery packs with the customer dispatch documentation.

The application layer is also used to execute automated validation rules that prevent the movement of uncompleted and faulty assemblies through the production process.

3.5 Visualization Layer

The visualization layer offers interfaces for production managers, engineers, and quality control personnel. The visualization layer enables users to access production information in real-time or manufacturing history through reports or interfaces. Some of the characteristics of this layer include:

- Real-time production monitoring interfaces
- Inventory tracking interfaces
- Quality reports
- Battery genealogy lookup interfaces
- Dispatch reports

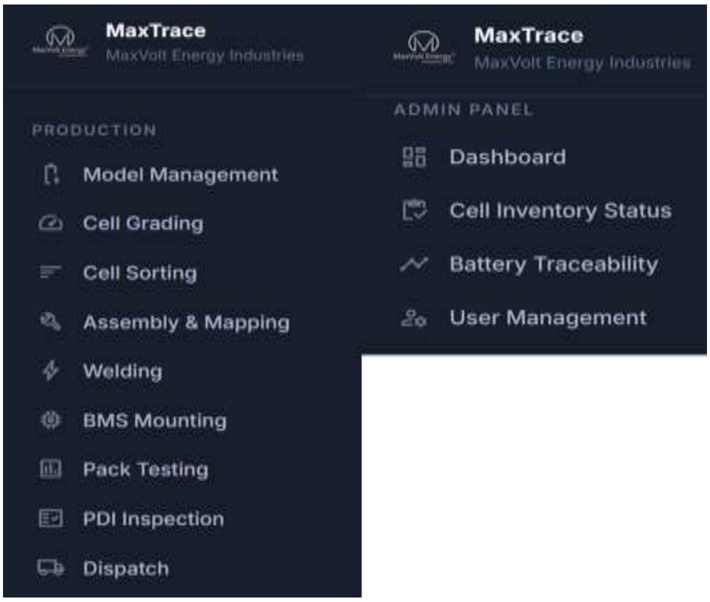
These interfaces allow decision-makers to identify production problems or bottlenecks in production or manufacturing processes, analyze production history, or perform root cause analysis on a defective battery pack.

4. Battery Assembly Traceability Workflow

The battery manufacturing process comprises different production stages in which individual components of the battery, known as lithium-ion cells, are connected to produce a fully functional battery pack. However, in a typical production environment, it is difficult to trace the movement of components from one stage to another due to the lack of proper documentation systems in battery production. Therefore, to overcome this problem, it is suggested that the proposed traceability system be equipped with a structured traceability workflow in which production data is ingested at every stage of battery production.

The traceability workflow starts from the model-driven battery instantiation and extends to different stages of battery production, including grading and sorting of cells, module production, battery pack production, BMS mounting, battery testing, packaging, and dispatch of battery packs from the production site. At every stage of battery production, operational data is recorded using scanning machines connected to the traceability database. Here, the battery barcode acts as a rendezvous point for granular disparate data components.

Figure 2: MaxTrace DTS sidebar



4.1 Model-Driven Battery Provisioning and Management

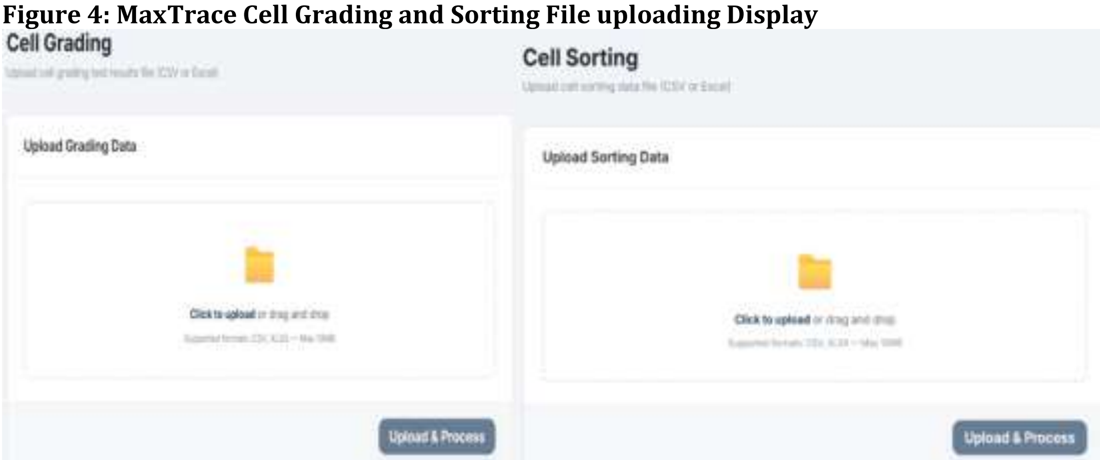
The first stage of the traceability workflow implements a decoupled system architecture where Battery Model metadata is logically separated from physical battery instances enforcing referential integrity and engineering constraints, ensuring that each battery instance inherits the properties of its parent Battery Model. The BatteryModel schema contains immutable parameters, including model name, series and parallel cell configurations, welding methodology and compatible BMS model. It facilitates batch ingestion and instantiation via an OpenXML(.xlsx) payload which is parsed asynchronously into a transient memory buffer. Through this the system temporal time complexity is reduced from O(n) manual entries to O(1) batch transactions. Further, the system extracts the battery_id and model_name key references performing a relational lookup to verify model existence and to detect potential battery_id collisions. This system automates the workflow, mitigating manual entry errors and eliminating data redundancy.

Figure 3: MaxTrace Model Management Display

4.2 Cell Sorting and Grading

The first stage of the traceability workflow implements a decoupled system architecture where Battery Model metadata is logically separated from physical battery instances enforcing referential integrity and engineering constraints, ensuring that each battery instance inherits the properties of its parent Battery Model. The Battery Model schema contains immutable parameters, including model name, series and parallel cell configurations, welding methodology and compatible BMS model. It facilitates batch ingestion and instantiation via an OpenXML(.xlsx) payload which is parsed asynchronously into a transient memory buffer. Through this the system temporal time complexity is reduced from O(n) manual entries to O(1) batch transactions. Further, the system extracts the battery Id and model name key references performing a relational lookup to verify model existence and to detect potential battery Id collisions. This system automates the workflow, mitigating manual entry errors and eliminating data redundancy.

Figure 4: MaxTrace Cell Grading and Sorting File uploading Display



The figure 3 shows the file upload interface for two key stages in the MaxTrace Battery Traceability Platform: Cell Grading and Cell Sorting. These steps are critical in battery manufacturing because they determine how individual cells are evaluated and grouped before assembly.

4.3 Assembly and Mapping

Once cells are sorted and graded, they proceed to the assembly and mapping stage. During this stage, cells are arranged in a deterministic configuration to form a module or battery pack structure. Depending on the battery design, cells may be arranged in series or parallel configurations to achieve the required voltage and capacity levels.

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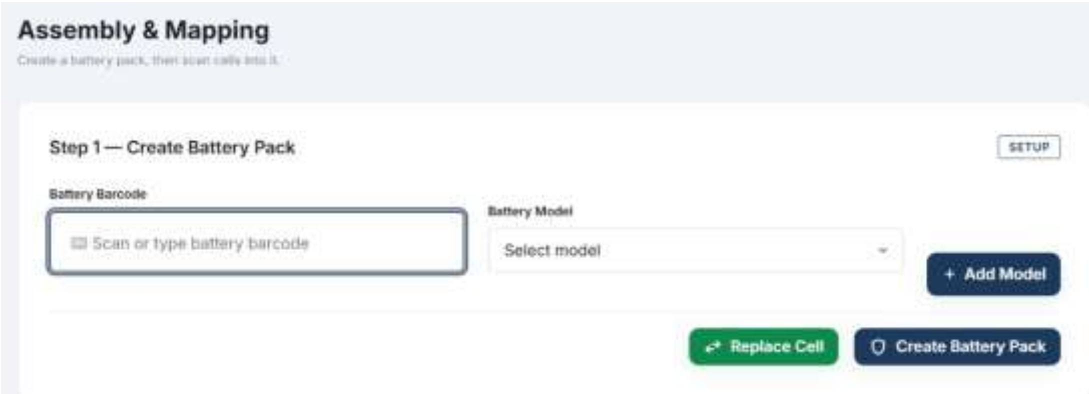
Figure 5: MaxTrace Assembly Mapping Image



The figure 4 shows the “Assembly & Mapping” module in the Maxtrace traceability system. It is used to digitally create a battery pack and map individual cells into it, enabling full traceability from cell level to pack level. This is critical for quality control, safety, and lifecycle tracking.

4.4 Welding

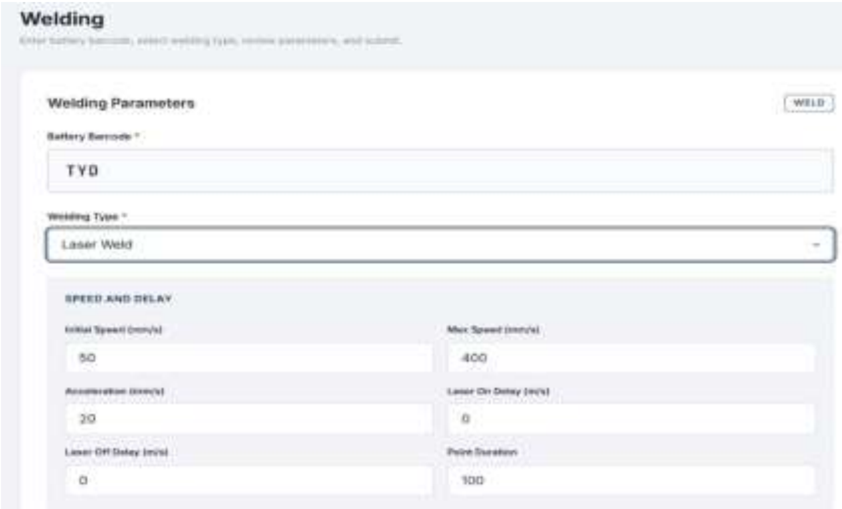
The welding stage establishes electrical connections between cells using conductive connectors such as busbars or nickel strips. Welding processes may involve laser welding or resistance spot welding depending on the battery pack design and manufacturing technology.

During this stage, the traceability system auto resolves the welding methodology and captures records like:

- Welding machine identification
- Welding parameters
- Operator identification
- Welding timestamp

These records ensure that the welding process is documented and that any potential manufacturing defects related to poor electrical connections can be traced back to the specific welding operation.

Figure 6: Maxtrace Wielding parameter Display image



The figure 5 represents the “Welding Parameters” module in the Maxtrace traceability system, used during the battery pack assembly process specifically for controlling and recording welding operations (like tab-to-cell or busbar welding).

4.5 Battery Management System (BMS) Mounting

After the cells are electrically connected, the Battery Management System (BMS) is installed within the battery pack. The BMS is responsible for monitoring key battery parameters including voltage, temperature, and current while ensuring safe operation during charging and discharging.
During the BMS mounting stage, the traceability system performs automated BMS model resolution using Battery Id and records:

- BMS serial number
- Firmware version
- Installation workstation ID
- Operator details

The BMS serial number is linked to the Battery Pack ID in the traceability database, enabling manufacturers to track which control system is installed in each battery pack.

Figure 7: MaxTrace BMS Mounting registration image

The figure 6 represents the “Register BMS” module in the Maxtrace traceability system, where a Battery Management System (BMS) is uniquely identified and linked into the digital manufacturing workflow.

4.6 Pack Testing

After assembly and BMS installation, the battery pack undergoes a series of electrical and safety tests to verify performance and reliability. These tests are essential for ensuring that the battery meets design specifications and safety standards.

Typical pack tests include:

- Voltage verification
- Charge and discharge testing
- BMS functionality verification
- Temperature monitoring tests

The results of these tests are ingested in a batch in an OpenXML(.xlsx) payload to the traceability system and parsed to capture granular data points and to establish a relationship to the corresponding Battery Pack ID. If a battery pack fails any test criteria, it is flagged by the system and removed from the production line for further inspection.

4.7 Pre-Dispatch Inspection (PDI)

Before shipping, each battery pack undergoes a Pre-Dispatch Inspection (PDI) to confirm that the product meets all quality requirements and documentation standards. This inspection stage verifies both the electrical performance and physical condition of the battery pack.

The PDI process includes:

- Visual inspection of pack enclosure
- Verification of labeling and identification codes
- Review of test results (Charge & Discharge) and quality records
- Confirmation of packaging integrity

The system supports batch ingestion of OpenXML(.xlsx) payloads, which are parsed concurrently using ThreadPoolExecutor backed by four OS-level worker threads to address the ASGI (Asynchronous Server Gateway Interface) event loop blocking problem. The traceability system enforces a sequential validation pipeline ensuring that all production and testing records are complete before the battery pack is approved for dispatch.

4.8 Dispatch and Logistics Management

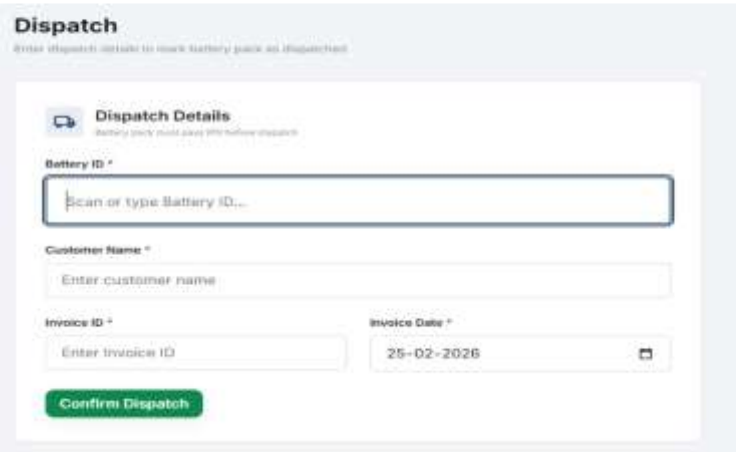
The final stage of the traceability workflow is battery pack dispatch. At this stage, finished battery packs are assigned to customer orders and shipment records. Operators scan the Battery Pack ID to generate dispatch documentation and logistics tracking information.

The traceability system records:

- Customer information
- Dispatch date and time
- Transportation details
- Destination location

By maintaining these records, the system ensures that each battery pack delivered to customers can be traced back to its complete manufacturing history. This capability is essential for warranty management, product recall procedures, and post-market performance analysis.

Figure 8: MaxTrace Dispatch Details



5. Unified Analytical Reporting and Production Analysis

The system incorporates a Unified Report Generation Engine, used to generate a detailed and holistic report of granular disparate data components of different stages related to a Battery Id. The report includes executive summary that captures the terminal state of entire production stages along with data of battery model, assigned cells and their ng count, pack testing and its overall ng status, welding, BMS mounting and dispatch.

By anchoring all historical data points linked to a Battery Id it produces a high-quality audit-trail. It helps in root cause and statistical trend analysis through better visualization using graphs and cohesive separation of datasets.

The system also incorporates an Admin dashboard which uses WebSocket's for real time monitoring of cells, batteries and production stages data including their pass/failure count, pending tests and inspections, inventory status, today's production output and detailed stage breakdown.

Figure 8: MaxTrace Executive summery Report

Figure 9: MaxTrace Unified Report Cells Data with Graphs

Figure 9: MaxTrace Admin Dashboard for Production analysis

6. System Implementation

A prototype of a digital traceability system was implemented in a lithium-ion battery assembly setting using a three-tier architectural stack designed for high concurrency data ingestion and real time data monitoring. The traceability system was built using:

- Python-based backend processing
- SQL database management

- Barcode scanning interfaces
- Web-based production dashboard

At every production station, operators are required to use handheld barcode scanning devices to read the components of the battery to be assembled. The data from these scanning devices is automatically transferred to a database for processing and linking to the production stage.

The traceability system also incorporates validation rules that ensure battery assemblies are not moved to the next production stage unless all components are in place.

7. Experimental Results and Performance Evaluation

The digital traceability system was evaluated over multiple production cycles. Several performance metrics were analyzed.

- Inventory Accuracy: The system improved inventory tracking accuracy from approximately 88% to 99%, significantly reducing misplaced components.
- Error Reduction: Production errors related to incorrect module assembly decreased by approximately 35% due to automated validation checks.
- Low API Latency: The system is optimized to reduce the API latency from ~60ms to ~10ms which results in faster data retrieval and ingestion.
- Batch Ingestion: The system implements Multi-Threaded Execution Model which is capable of handling batch ingestion of payloads using ThreadPoolExecutor and OS-level worker threads which enables parallel processing of records.
- Constant Time Query Optimization: The system is optimized to minimize the number of queries between client and database. If a payload containing records of 40000 cells is ingested then instead of N+1 queries and O(n) database interaction time complexity, the system accomplishes its task in a three query atomic transaction and in O(1) time complexity.
- Optimized Relational Schema and Volumetric Scalability: The database architectural scheme is highly normalized ensuring a high volume of component data is decoupled from production-stage metadata. The tables are linked via indexed foreign-keys which makes it capable to handle data of 50000 cells and datasets from various production stages without any performance degradation.
- Process Visibility: The system enabled real-time monitoring of production stages, allowing supervisors to identify bottlenecks and optimize workflow.
- Traceability Efficiency: Root cause analysis for defective battery packs was significantly improved since the system could identify all component genealogy within seconds.

8. Conclusion

Implementing a digital traceability system has a great potential to improve the transparency of the manufacturing process in lithium-ion battery assembly lines. As battery production increases globally, this kind of digital traceability system becomes more important, as indicated in the experimental results, which showed a great potential in enhancing transparency in the battery production process. The research in this paper focused on the design and implementation of the digital traceability system in the assembly and dispatch management of the lithium-ion battery. The proposed digital traceability system is able to integrate the different stages of the assembly and dispatch management process, including the registration of the cells, the sorting and grading of the cells, the assembly and mapping of the cells, the welding process, the mounting of the BMS, the testing of the battery pack, the pre-dispatch inspection and the dispatch logistics management, among others. The proposed digital traceability system is able to track the history and genealogy of the individual cells, the modules and the battery pack through the assignment of unique identification to the individual cells and the battery pack. The proposed digital traceability system is able to automatically capture the production information through the integration of the barcode scanning technology and the database management tools.

The architecture of the digital traceability system was designed based on the multi-layer model composed of the data acquisition layer, identification layer, database layer, application layer, and visualization layer. This architecture allows for the efficient acquisition of data from the production machines and assembly stations, as well as the storage and real-time access of the traceability information through the user interface. Implementation of the proposed traceability workflow has shown several benefits in the battery assembly process. Firstly, the proposed system has shown its potential in improving the transparency and monitoring of the manufacturing process. Secondly, the digital platform has shown its potential in improving the accuracy of the inventory management process. Thirdly, the validation mechanism has shown its potential in reducing the human error factor in the battery assembly process.

The advantage of the proposed system is its potential in battery genealogy and root cause analysis. In the event of battery failure, the proposed system has the potential in identifying the specific cells and modules involved in the battery assembly process. This advantage is particularly important in the management of product recalls and analysis in the battery industry. Furthermore, the proposed system has shown its potential in generating structured data in the battery assembly process. This data can be used in the development of analytics tools for improving the battery performance and efficiency in the production process.

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