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Modular Semi-Automated Assembly System with Real-Time Data Traceability for the Automotive Industry

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ABSTRACT

Every electrical network experience various power quality disturbance that necessitates meticulous planning, preparation, measurement, and, most crucially, the ability to promptly identify issues as they arise. Currently, the system faces limitations in remote data access and experiences delays in identifying disturbances due to the manual analysis required once disturbances are detected. The objective of this research is to integrate IoT technology to enhance the system by enabling real-time remote data access and automated classification of disturbances. The methodology of this project involves three main stages: first, generating power quality disturbance signals using Simulink software; second, developing a disturbance classification system on Arduino; and finally, designing and implementing a monitoring system on Arduino using ThingSpeak as the IoT component. The results demonstrate the successful detection and classification of the tested power quality disturbances by the developed monitoring system.

1. Introduction

The automotive manufacturing industry has made notable progress in the development of assembly systems. The industry is increasingly focused on achieving improved efficiency, accuracy, and adaptability, making the development of innovative assembly systems crucial. Contract assemblers, particularly in Malaysia, often faces the challenge to balance between consistency in quality and technological standardization from the manufacturer which requires comprehensive approach to assembly management. This work explores the creation and use of a semi-automated assembly system, with a specific focus on modular and reconfigurable systems to enhance flexibility, efficiency, and scalability.

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2. State of the Art

The use of automation in automotive production systems has received increasing attention in recent years, driven by the demand for enhanced efficiency, precision, and flexibility in car manufacturing. This section summarizes the important achievements and approaches in the industry, laying the groundwork for understanding the design and implementation of a semi-automated powertrain assembly system.

2.1 Manufacturing Execution System (MES)

A Manufacturing Execution System (MES) facilitates the integration of enterprise-level planning systems (like ERP) with the shop floor, providing real-time data and control over manufacturing operations. This integration ensures the coordination of production activities, which is vital for achieving efficiency, quality, and traceability throughout the manufacturing process, particularly in the highly complex and precision-driven automotive industry [1]. The layer of the systems in the manufacturing environment is summarized in Figure 1.

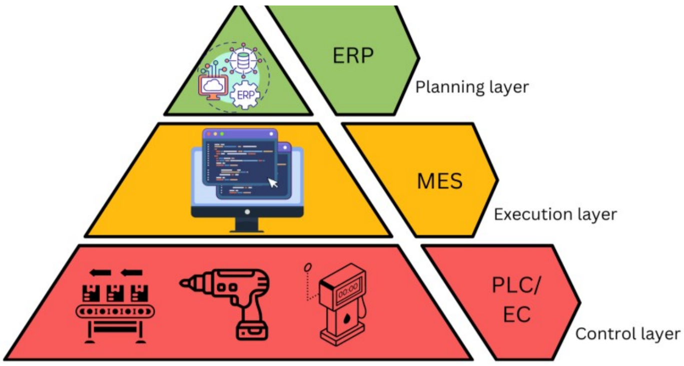

Fig. 1 The layer of manufacturing systems

MES consists of essential elements such as production planning, real-time data collection, work order management, quality control, inventory management, performance analysis, reporting, and traceability. Production planning and scheduling encompass the generation and supervision of production orders, guaranteeing compliance to planned schedules and the effective distribution of resources, machines, and personnel [2]. Continuous monitoring of production status and adherence to predefined standards and tolerances is crucial for maintaining the high standards required in automotive manufacturing [3]. Real-time data collection from machines, sensors, and operators enables this monitoring.

Work order management in a MES involves providing operators and technicians with detailed instructions and overseeing the sequence of operations and material flow throughout the production process [4]. Quality management tools facilitate inspections, tests, identification and management of non-conforming products, and corrective action implementation. Inventory management capabilities involve the ability to track raw materials, work-in-progress (WIP), and finished goods in real-time. These capabilities are often integrated with warehouse management systems to ensure a smooth flow of materials [5]. The performance analysis and reporting features enable the calculation and tracking of important performance indicators like Overall Equipment Effectiveness (OEE), cycle time, and production yield. The dashboards and reports offer the ability to customize and provide both real-time visibility and historical analysis of production performance. Having detailed records of the production history of each product, including materials used, process parameters, and quality inspections, is crucial for ensuring compliance and quality assurance [6].

Optional features for a MES can greatly improve its capabilities. These features encompass advanced analytics and AI, energy management, integration with the Industrial Internet of Things (IIoT), supplier and customer integration, labor management, and augmented reality (AR) and virtual reality (VR) applications [7]. Integrating with IIoT devices improves data collection and process control, while edge computing minimizes latency in decision-making. The labor management features help with shift scheduling and skill tracking, ensuring that the appropriate personnel are assigned to tasks. AR and VR applications have proven to be valuable tools for training and simulating production processes, improving operational efficiency, and reducing training time [8].

However, integrating a MES with existing enterprise systems like Enterprise Resource Planning (ERP) and Supply Chain Management (SCM), as well as shop floor equipment such as sensors and machines, can be a challenging and resource-intensive task. Developers need to use a variety of strategies to ensure smooth communication between different systems and technologies. Current setups often lack the necessary strategies for effective data storage, processing, and analysis, which can be overwhelming due to the sheer volume of data generated by MES. Also, adapting MES to industry needs while ensuring scalability presents extra hurdles. Industries that have distinct processes may face challenges when using generic MES solutions that do not fully cater to their specific requirements. Developers must create user-friendly interfaces that are easy to navigate and include modular components to address these limitations.

To effectively utilize advanced analytics and artificial intelligence (AI) for predictive maintenance and process optimization, it is necessary to have sophisticated algorithms and high-quality data. However, this data may not always be structured and ready for implementation. In addition, the integration of IIoT has not been fully utilized since managing connectivity and data in a complex environment is challenging. As sustainability becomes more important, several nations are enacting strict regulations concerning energy consumption and emissions. By incorporating energy management into MES, manufacturers can easily meet regulatory requirements using real-time monitoring and reporting features. However, efficiently monitoring and improving energy usage throughout all production processes poses a considerable obstacle that must be tackled.

Overall, a properly executed MES is a crucial asset for contemporary manufacturing operations, particularly for automotive contract assemblers. It offers extensive control over production processes and seamlessly integrates with other enterprise systems. Although there are significant challenges to implementation, data-driven solutions can achieve a balance between consistent quality and the technological standardization necessary for a successful assembly system.

2.2 Modular and Reconfigurable Systems (MRS)

In the framework of modern manufacturing, the goal of efficiency, flexibility, and market response has resulted in considerable improvements in production systems. MRS has been developed as a transformational technique in this field. These systems are intended to respond to changing production requirements and technological advancements with minimal downtime and cost.

MRS is founded on the concepts of modularity and reconfigurability. Modularity refers to designing a system using interchangeable components or modules that can be independently developed, modified, replaced, or upgraded. Modularity enables systems to be built up of different, interchangeable modules that may be independently developed, modified, or replaced. For example, in the automobile industry, businesses have built modular production lines that allow multiple car models to be produced using the same fundamental framework by simply swapping out modules for certain functions. The modular design also reduces the need for extensive retooling and allows for the incremental addition of capacity or capability [9]. MRS is also scalable, which allows the production capacity to be readily altered by adding or deleting modules. This is especially advantageous in sectors with changing demand. For example, in the electronics industry, modular assembly lines allow for rapid scaling of production for new product releases, as shown in the practices of businesses such as Foxconn [10].

Reconfigurability, on the other hand, is the ability of a system to rapidly change its configuration, structure, or functionality in response to new requirements or operational conditions. They have various unique qualities that make them ideal for modern manufacturing contexts such as modularity, scalability, flexibility and ability to be customized [11]. According to Morgan *et al.*, [12], there are six original core characteristics of reconfigurable system: modularity, integrability, customization, convertibility, scalability, and diagnosability, with two desirable characteristics: mobility and adaptability. The overview is shown in Figure 2. These reconfigurable fundamentals are represented in both the state of-the-art domains of Operational Technology (OT) for machine control, and Integrated Technology (IT) for machine Intelligence; as distributed and decentralized environments, which are horizontally and vertically integrated.

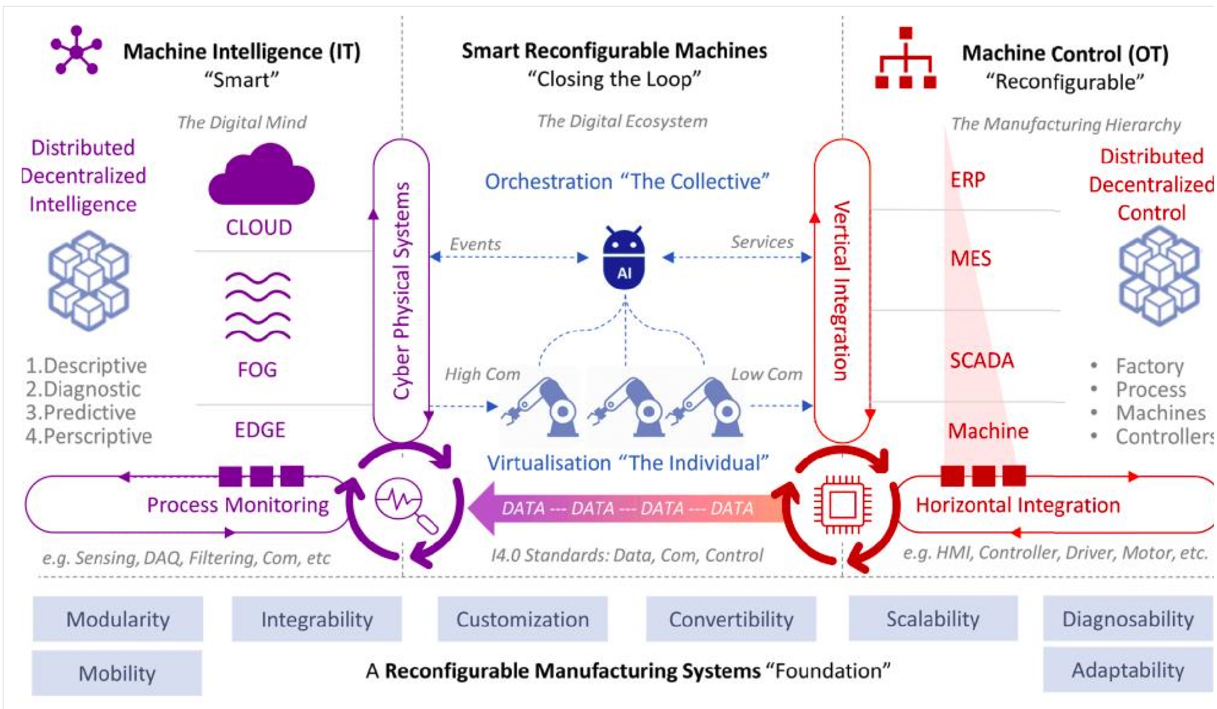

Fig. 2 The foundation of reconfigurable manufacturing system [12]

Adaptability is another important feature, allowing systems to acclimatize to new products or changes in manufacturing processes easily. In the aerospace industry, businesses such as Boeing use reconfigurable manufacturing systems to tailor the manufacture of various aircraft components to specific design specification [13]. Quick reconfiguration also minimizes production interruptions, enhancing OEE [14]. Customization, the fourth attribute, allows for tailored setups to fulfill specific production requirements. In healthcare, MRS are utilized to manufacture medical devices, allowing for rapid adaptation to regulatory changes and technological improvements. Manufacturers can also respond more effectively to market demands and technological advancements, maintaining a competitive edge [15].

Despite their advantages, the implementation of MRS poses several challenges. Designing MRS requires advanced engineering and careful planning to ensure the compatibility and functionality of modules. The Boeing 737 production line, for example, employs a modular method to produce a wide range of aircraft models. Modules have been meticulously developed and integrated to ensure smooth functionality and interoperability, allowing Boeing to adapt to new models and market demands readily [16]. Furthermore, the absence of industry-wide standards for module interfaces and communication may impede interoperability and scalability. Modules from different manufacturers, or even product lines within the same firm, may not be interoperable if standard interfaces are not used, which results in considerable delays and additional costs [17]. This complexity can deter companies from adopting MRS, particularly those with limited technical resources.

Therefore, it is essential that the development of a powertrain assembly system falls under the purview of MES and MRS. For a contract assembler, the capability to assemble a wide range of products significantly enhances their revenue potential. Consequently, incorporating modularity, scalability, flexibility, and customizability into the system as well as bridging the gap between comprehensive planning and standardization is imperative to achieving these objectives.

2.2 Human Machine Interface (HMI) and User Experience

The essential feature in automotive assembly is the Visual Production Guide (VPG), which is an instance of Human-Machine Interface (HMI), prominent for a successful implementation and operation of automotive assembly. Effective VPG design enhances user experience, leading to improved efficiency, safety, and satisfaction for operators, process engineers, maintenance engineers, logistic engineers, and line leaders. The design principles for effective HMI, as illustrated in Figure 3, emphasize the importance of user-centric design [18]. The VPG should be tailored with the end-user in mind, considering the specific tasks and workflows of operators and engineers. Achieving this involves comprehensive user research, iterative prototyping, and continuous testing. Operators, for instance, need simple interfaces to work efficiently. Large, clear touchscreen buttons and visual indications are vital for quick control and information access. This design keeps operators on task without delay or confusion. However, line leaders need HMIs that cover the entire manufacturing line. This includes machine status, output rates, and bottleneck identification to help them manage operations and meet production targets.

Interfaces should display only the relevant information in a clear format. This method lets people focus on their jobs by removing extraneous data. Access to essential information and navigation should be simple. Screens should have a clear function and only items that assist it. Logical layout grouping of similar information and controls improves usability. Consistent interface design and terminology enable users easily learn and use the system, reducing learning curve and errors. Quick responses to user inputs enable immediate feedback and keep users informed of system status and operations [19]. Finally, interfaces should be configurable to fit user demands and preferences. This versatility lets users customize dashboards and controls to suit their operations, improving productivity and pleasure.

Fig. 3. HMI design principle

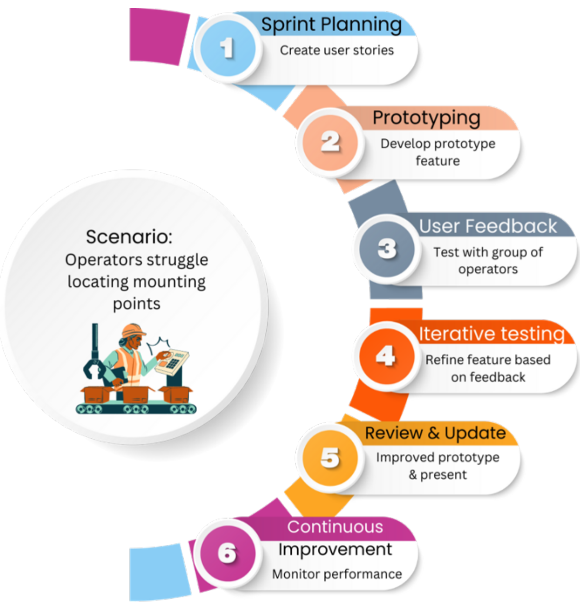

Fig. 4. Agile VPG development scenario

As previously mentioned earlier, the agile approach [20] to developing the assembly system is crucial especially in a tailored system. An example of the scenario involved in the agile approach of the VPG development is summarized in Figure 4. The VPG is developed with user research as means to initiate sprint [18]. User research shows that operators have difficulty finding the mounting points in the assembly. Developers can understand the needs, pain points, and workflows of operators and engineers through interviews and observations. User stories are created based on research findings to define the requirements and expectations of the end-users. The stories guide the development process to address real user needs.

Then iterative development begins. Rapid prototypes of VPG functionality and interface concepts are created. These prototypes provide concrete representations of concepts that consumers may study and test. Then, users are invited to evaluate the prototypes and provide input on usability, functionality, and overall experience. This feedback is critical in identifying areas for improvement and ensuring that the design satisfies user expectations. Finally, an iterative testing process is set up in which prototypes are constantly refined depending on user feedback. Each iteration should focus on specific concerns while improving the VPG's usability and clarity. Throughout the development process, cross-functional teams, including designers, developers, process engineers, and operators, should work together to create the VPG. This collaborative approach guarantees that multiple viewpoints are considered and included into the VPG design, resulting in a more robust and user-friendly solution.

Regular review sessions with stakeholders to assess the progress and alignment of the VPG with the overall project goals are vital. These reviews provide valuable opportunities to make necessary adjustments, prioritize features based on user needs and feedback, and ensure that the project remains on track. By incorporating feedback continuously, the development team can address issues promptly and refine the VPG to better meet user requirements. Improvements of VPG, when needed should be released in incremental updates. This updates of the VPG, which include new features and improvements in small, manageable chunks, allows for the continuous delivery of value to users. This iterative approach facilitates swift adaptation to changing requirements and ensures that the system evolves in response to real-world usage and feedback.

At the conclusion of this process, it is essential to ensure that the VPG is adaptable to different user roles and production scenarios. This flexibility enables the system to cater to various tasks and workflows without overwhelming users. By accommodating the specific needs of different user groups, the VPG can enhance efficiency, reduce errors, and improve overall productivity in the powertrain assembly process [21].

3. Methodology

The powertrain assembly system is built with MES and MRS in mind. The use of agile approaches was critical to this development since it allowed for iterative improvements and adaptation to changing requirements. The design process emphasized modularity and reconfigurability, allowing the system to handle a variety of engine types and manufacturing volumes. Without the necessity of re-inventing the wheel, this system follows closely the proposed ISA-95 based architecture by Remli et al. [22], with the addition of torque controllers which communicated through serial communication to the application server.

3.1 System Architecture

The assembly system consists of a two-level conveyor which is controlled by a master Programmable Logic Controller (PLC) with an Open Platform Communications – Unified Architecture (OPC-UA) server, an oil filling machine controlled by a slave PLC, a tightening system with torque controllers, barcode scanners, Radio Frequency Identification (RFID) controllers, visual production guides, a Message Queuing Telemetry Transport (MQTT)-based conveyor dashboard, an Andon TV and a mobile inspection system. Figure 5 depicts the system architecture of the powertrain assembly system.

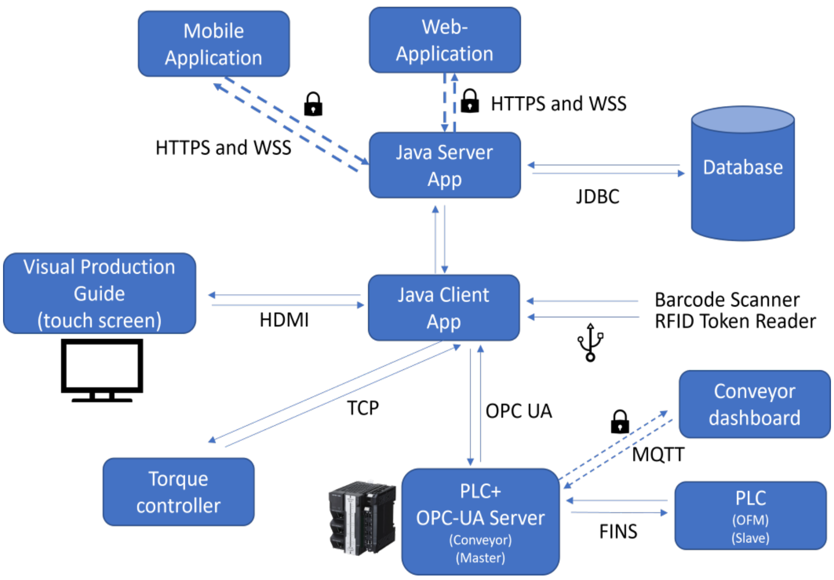

Fig. 5 System architecture

At the core of the system lies the Java Server Application, functioning as the central communication hub. This application interfaces with a centralized database, facilitating efficient storage and retrieval of production data. It also interacts with the web application, enabling real-time updates and control functionalities, thus ensuring that all data collected during the assembly process is systematically organized and easily accessible for monitoring and analysis. The Java Server

Application leverages the JDBC protocol to seamlessly manage and retrieve data from the database. The Java Server Application interacts with the web application, enabling real-time updates and control functionalities. The entity-relationship (ER) model for the database is presented in Figure 6. This ER model is applied in the context of a powertrain assembly system, where it facilitates detailed tracking of production schedules, logging and monitoring of assembly processes and worker activities, as well as integration of different processes (e.g., scanning and tightening) to ensure comprehensive data management. Each entity is endowed with distinctive attributes. By systemically structuring these entities and their interrelationships, the proposed model facilitates the development of an efficient database design and operational management system for the powertrain assembly.

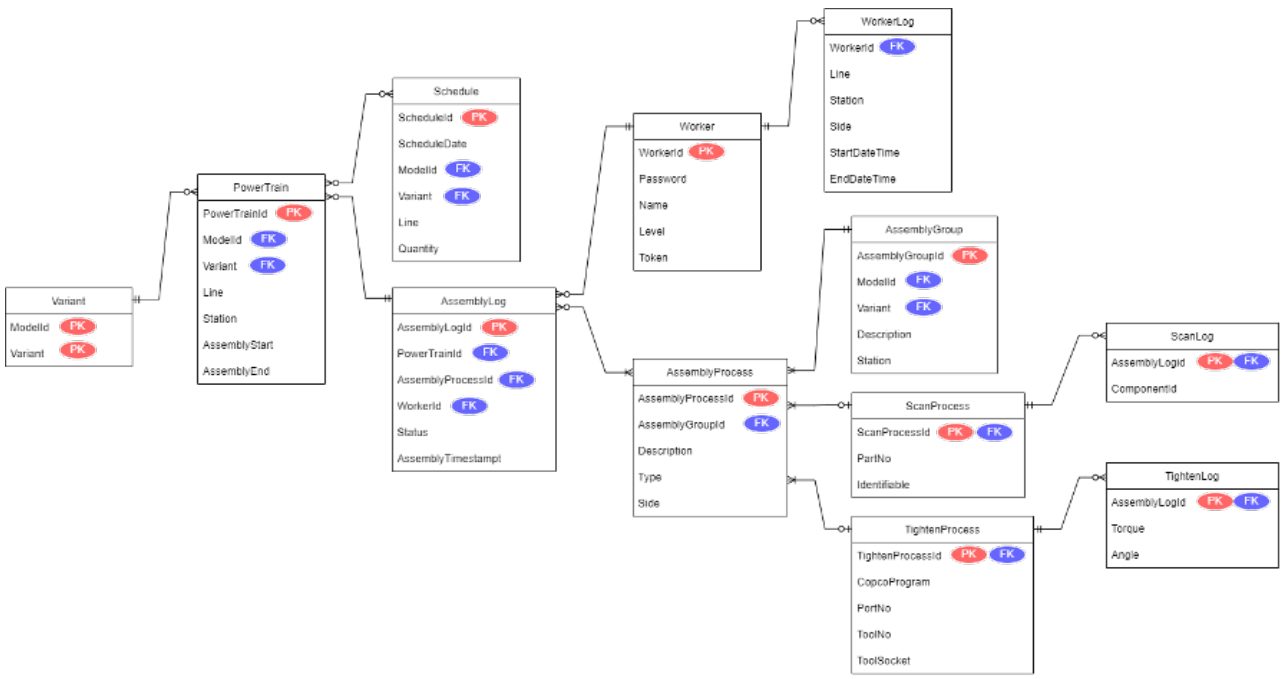

Fig. 6. Entity-relationship model of the system database

The Java Client Application is the main interface for the assembly process. It receives data from the Java Server Application to control and monitor the assembly line. This app interfaces with torque controllers and the VPG. The Java Client Application ensures availability of the latest production data and instructions which improves not only tightening processes but also manual assembly tasks with clear, detailed instructions. Operators and line leaders can acknowledge manual assembly completion and navigate other options for seamless operation and coordination.

The VPG uses torque controllers to navigate assembly processes for specific models and variants and validate the tightening process. Real-time feedback ensures that each component is assembled to the specified torque requirements. The web-application on the other hand, provides an interactive platform for users to monitor and control assembly operations in real-time. It communicates with the Java Server Application using secure HTTPS and WSS protocols, ensuring data integrity and confidentiality. The web application displays key metrics, assembly logs, and integrated production schedules, offering a comprehensive overview of the assembly process to production managers and engineers.

These integrated components of the system become the backbone of the material handling system, ensuring the work-units are correctly assembled before transport. The two-level conveyor utilizes PLC with an OPC-UA server for real-time control and data exchange with the conveyor systems. The PLC manages the operational parameters of the conveyor, while the OPC-UA server facilitates secure and reliable communication between the PLC and the Java Client Application. This setup ensures that conveyor operations are continuously monitored and controlled, optimizing material handling and palette reutilization processes. Additionally, the conveyor can be closely monitored from an MQTT-enabled dashboard, allowing for system overrides in the case of emergencies. MQTT is a lightweight, publish-subscribe network protocol optimized for low bandwidth application. The MQTT protocol facilitates the aggregation of data from multiple sources into a centralized dashboard which can be accessed ubiquitously from various devices (e.g., desktops, tablets, smartphones) by subscribing to relevant topics.

To enhance flexibility and mobility, the system also includes a mobile application. This application allows operators to capture and upload images for post-assembly inspection and verification. It communicates with the Java Server Application, enabling real-time data updates and task management. The mobile application ensures that operators can efficiently document and verify assembly processes, even from remote locations. By integrating these components and leveraging advanced communication protocols, the system architecture supports a robust, flexible, and efficient assembly process with real-time data traceability, enhancing overall productivity and operational excellence in the automotive industry.

3.2 Work-Unit Handling System

The two-level conveyor is operated by a Master PLC with a built-in OPC-UA server. It is a roll-to-roll chain conveyor with two electromechanical drivers for large load transfer. There are always five assembly pallets on the conveyor. Four assembly pallets are located at the upper level, from Station 0 to Station 3. Another pallet is placed at a lower level for quick reuse. Pallet at station 0 ready to receive new work unit from logistic cart. The lower-level pallet is always empty, indicating that the lower-level conveyor is only used to recycle the pallet to Station 0. The home position is shown in Figure 7.

The conveyor system operates through well-defined steps for efficient and precise material movement. The process starts with system start-up and component initialization. The Java Server Application activates communication with the PLC and ensures sensor and actuator readiness. It performs self-checks and establish communication links between the server, client applications, and hardware components. The powertrain units are loaded onto pallets using an overhead hoist once the system is operational. The loading mechanism securely places each powertrain unit on a pallet with a fixed conical mount for transport through the assembly line.

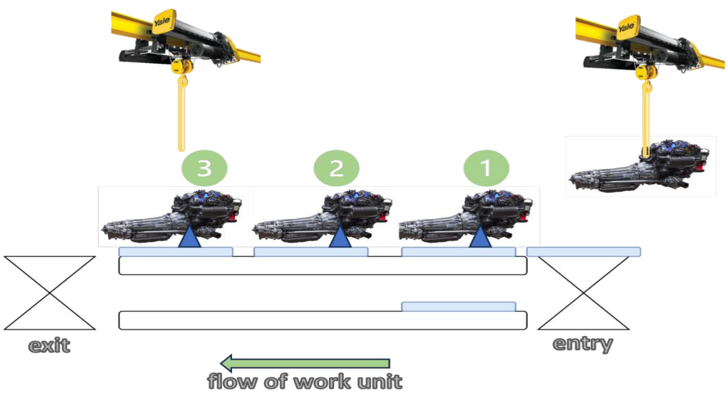

Fig. 7. Assembly pallets in home position

Operators at Station 0 start assembly work after loading and the operators at different stations along the conveyor perform various assembly operations simultaneously. The VPG provides real-time instructions to operators via a touchscreen interface. The screen moves to the center of the conveyor during assembly and returns to the side when finished. After the assembly processes are completed, operators manually activate the completion from the conveyor system, which moves the pallets to the correct positions along the assembly line. This step is crucial for powertrain unit movement between assembly operations.

Pallets must be realigned to the home position in case of system reset or emergency stop. The home position is defined by five pallets in specific locations, detected by photosensors. The system checks stoppers and sensor outputs before resuming automatic mode. The system can be monitored and controlled from a MQTT-enabled dashboard during emergencies.

3.3 Visual Production Guide (VPG)

The VPG is essential for powertrain assembly operations ensuring operators receive precise, real-time instructions and feedback, enhancing assembly efficiency and accuracy. It is a touchscreen interface connected to an Industrial Personal Computer (IPC) hosting the Java client app, providing a user-friendly platform for operators. VPG operation follows the flowchart in Figure 8 for efficient assembly and accurate logging.

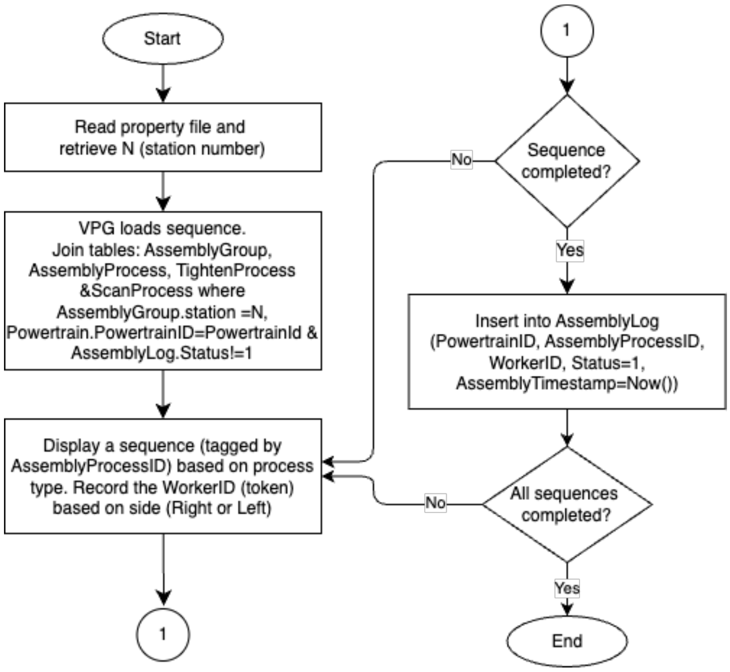

Fig. 8. Loading and logging sequence

The process starts when the Java client app reads the property file to retrieve the station number, N, for each station. It identifies the workstation where the assembly process is happening. The app loads sequences by joining tables from multiple databases. Retrieval is filtered by station number (N), Powertrain ID, and AssemblyLog status. The VPG displays the sequence to the operator and captures relevant data. The system displays instructions and prompts based on the process type (manual, scan, or tightening). The operator's token is recorded based on their working side. The display shows torque settings and prompts the operator to confirm completion for a tightening operation. The system checks if the current sequence has been completed and verify that all steps in the process have been executed correctly, all data entries have been made, and any required confirmations have been logged. The system inserts an entry into the AssemblyLog once a sequence is confirmed as complete. This log entry includes the PowertrainID, AssemblyProcessID, WorkerID, Status (1 for completed), and completion timestamp. The system checks if all sequences for the current station and powertrain unit have been completed and return to the sequence display step if any sequences remain incomplete. When all sequences are completed, the VPG prompts the operator to press a manual push button on the VPG structure to complete the assembly process for the station.

3.3.1 VPG common page

Upon initialization, the VPG presents a common desktop application page that includes initial page and operator identification as shown in Figure 9. Initial page displays basic system information and allows operators to log in and access different assembly tasks. Each operator's identity is confirmed through tokens inserted to a token slot that houses the RFID controller and presence sensor. The operator's name will be highlighted in green, if the token is valid, to indicate active status.

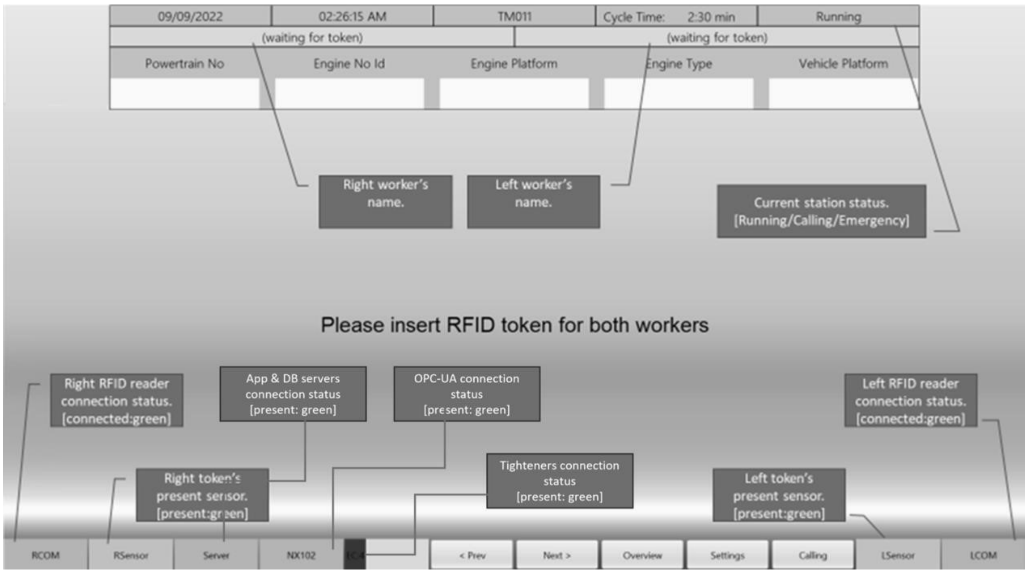

Fig. 9. Common page of the VPG

The common page displays system integration information, including the connectivity status of the Java Client App to the Server App and Database, OPC-UA connectivity status, Java Client App to torque controller connectivity status, and valid RFID token status. Checking the connectivity status between the Java Client App and the Server App/Database ensures uninterrupted real-time data exchange which is critical for data accuracy and timeliness in the assembly process. OPC-UA connectivity status indicator ensures reliable PLC communication, correct functioning of control commands and data exchanges. Operators can quickly identify communication breakdowns, enabling prompt troubleshooting and maintaining material handling integrity. It improves the assembly line's responsiveness and adaptability to real-time conditions, increasing efficiency.

The torque controller connectivity status ensures accurate monitoring and recording of torque values. Real-time connectivity enables immediate feedback from torque controllers, allowing maintenance personnel to quickly adjust settings if discrepancies are detected which reduces defects and rework, enhancing assembly process efficiency and quality. The token status display validates authorized personnel for accessing and operating assembly stations. It helps track operators performing tasks, ensuring accountability and traceability, preventing unauthorized access and operations, enhancing security and integrity of the assembly process.

3.3.2 Scanning, tightening and manual assembly operation page

The VPG facilitates barcode scanning operations, as illustrated in Figure 10, which are essential for verifying the utilization and accurate tracking of components. The barcode scanners are interfaced with the USB port of the IPC that runs the Java Client Application at each workstation. Given that each barcode is linked to distinct components and assembly instructions, the validation of the barcode is imperative as it ensures the system loads the correct instructions and settings corresponding to that specific component. This process mitigates the risk of errors and guarantees adherence to the prescribed assembly sequence.

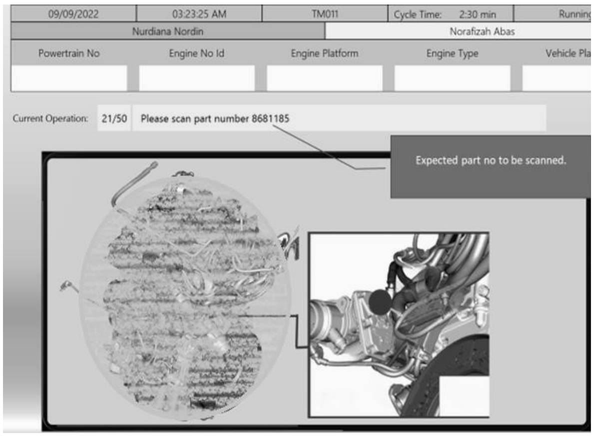

Fig. 10. Scanning operation page

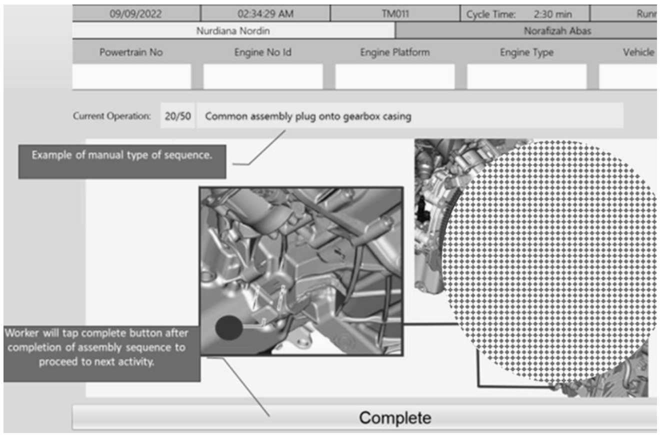

Fig. 11. Manual operation page

The VPG also offers the manual operation page as shown in Figure 11. It is developed to cater for assembly operation that doesn't require any tightening or scanning but is important to be validated. Certain assembly operations, such as hose assembly, involve manual tasks that cannot be automated or controlled through standard scanning or tightening processes. The manual operation page provides specific instructions and validation steps for these tasks.

The tightening operation page on the VPG as depicted in Figure 12 provides tightener's specific tool and torque specification as well as real-time feedback for operator's reference. The torque values are loaded from the database based on assembly process sequence of the model and variant. Integration with torque controllers allows for real-time monitoring and recording of torque values, ensuring that specifications are met. This detailed logging creates an audit trail that can be reviewed to verify compliance with assembly standards.

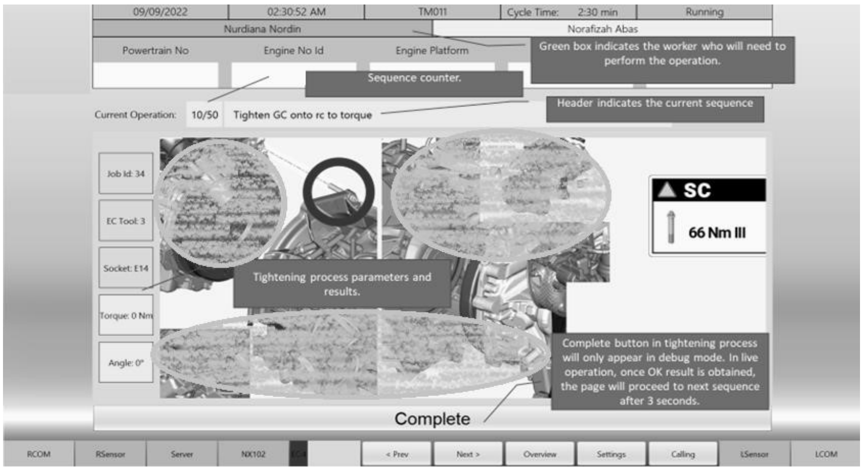

Fig. 12. Tightening operation page

3.4 Web-Application

The web application that accompanies the VPG in the powertrain assembly system is designed as an MES interface which is to provide comprehensive management, monitoring, and control functionalities. It serves as a central platform for process engineers, supervisors, and line leaders to manage assembly tasks, view real-time data, and ensure the smooth operation of the assembly line. The application features the assembly log page, performance metric page, traceability records page, tighteners log page, user-activities log page, schedule page, assembly process page, worker settings page, station page and web-Andon page. The following sub-sections explain prominent features for the web-application.

3.4.1 Assembly process page

The assembly process page is shown in Figure 13 and is accessible from the top navigation menu when “Assembly Process” is clicked. For each process, users can customize the assembly process by adding new groups or modifying existing ones. This flexibility is crucial for adapting to changes in production requirements or introducing new product variants. The page integrates seamlessly with other components of the MES, such as scheduling, worker management, and audit logging. This holistic integration ensures that all aspects of the assembly process are coordinated and managed effectively. The interface is also designed to be user-friendly, with intuitive navigation and clear, concise information. This reduces the learning curve for new users and enhances overall efficiency.

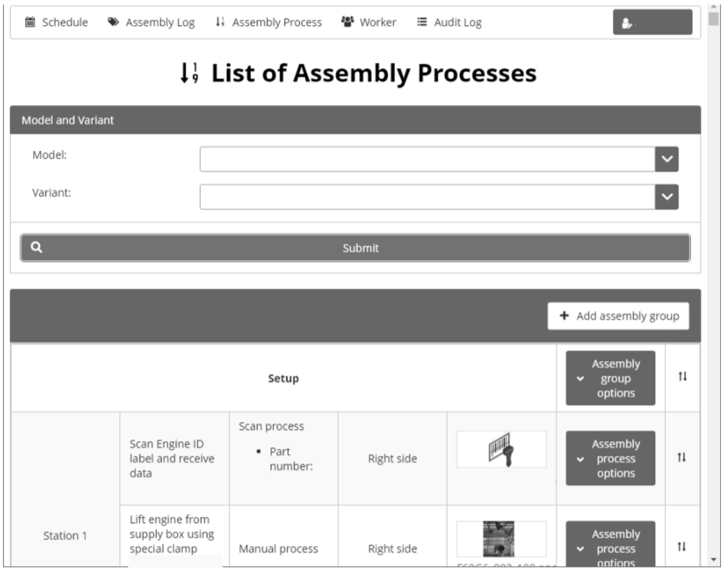

Fig. 13 Assembly process page

3.4.2 Schedule and station page

The scheduling page allows users to view and manage production schedules for the powertrain assembly process. The interface is designed to ensure that production schedules are organized and easily accessible, enabling efficient management of the assembly process as shown in Figure 14. The station page in Figure 15 displays current WIP at each station according to the production line number. The information of the powertrain ID, model and variant for the specific unit at each station is retrieved seamlessly from the Java Client App at each station. By providing real-time visibility into the status and activities of each station, the Station Page enables supervisors and operators to quickly identify and address issues, optimize workflows, and ensure that production targets are met.

An “+ Add Test Unit” button is prominently displayed to enable authorized users to add test unit as shown in Figure 16, which can be used to test run an assembly process of a powertrain variant. This is important procedure to check the sequence of the assembly process and at the same time test workability of tighteners and corresponding socket. The ability to add and manage test units directly from the Station Page supports robust quality assurance practices. This ensures that any issues are identified and addressed before affecting the main production line.

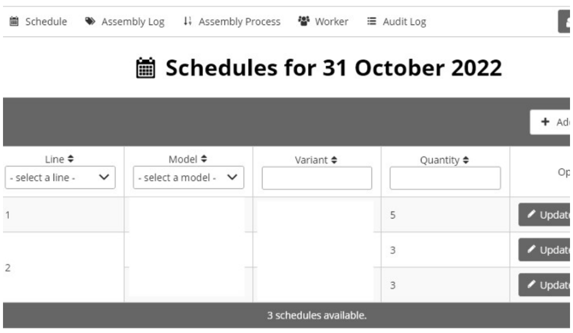

Fig. 14. Schedule page

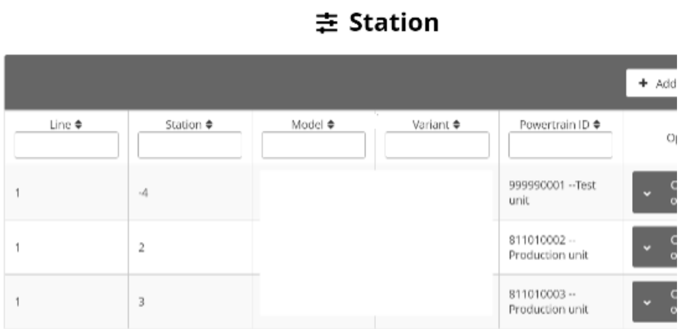

Fig. 15. Station page

3.4.3 Tighteners, user Activities, assembly log page

The log page presents a comprehensive record of assembly sequences, tightener's job and user activities that have been initiated and completed. The tightener's log page monitors and ensures torque consistency and reliability in the assembly process. Timestamps and torque values as shown in Figure 16 are recorded. The log is structured by assembly line and station for easy record tracing in case of tool malfunctions. This approach helps identify performance deviations or irregularities that need attention.

The user activities log page, on the other hand, records user actions like adding or deleting schedules, logging in, and logging out as depicted in Figure 17. This functionality tracks system changes, especially those affecting production schedules. Each entry links an action to a user which is crucial for accountability and auditing. The user activities page monitors IP addresses and timestamps to detect unauthorized access or suspicious activities, enhancing security and compliance with internal policies.

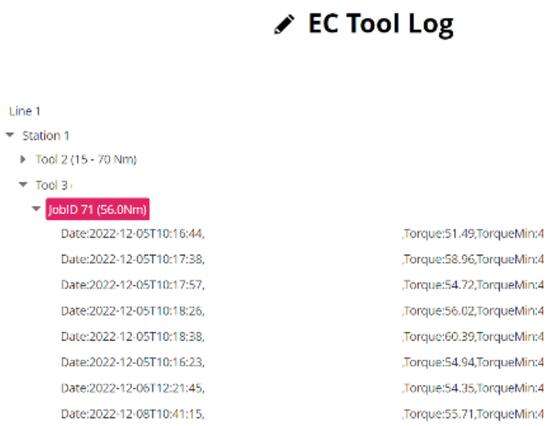

Fig. 16. Tightener's log

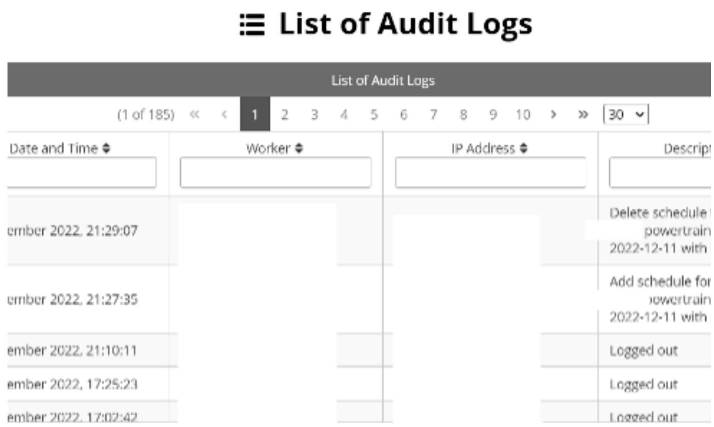

Fig. 17. User activities log

Assembly log encompasses detailed information, including the sequence of the assembly process, the identity of the operator executing the task, the date and time of the task, the component identification number, and the status of the operation. This detailed documentation of assembly activities serves to ensure both traceability and accountability. Figure 18 shows an example of tightening assembly log.

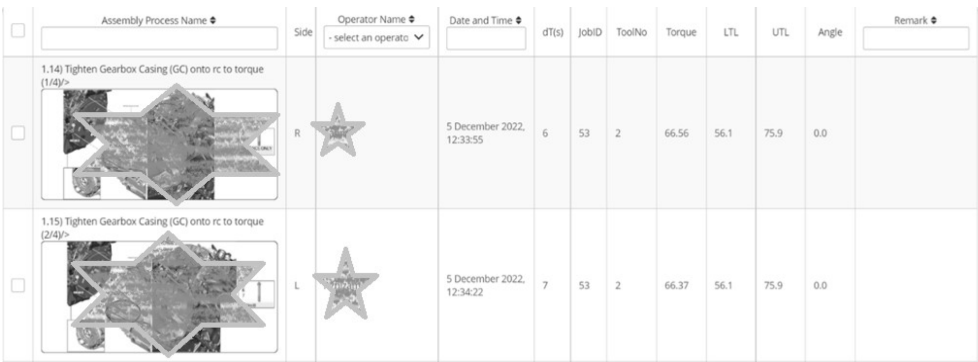

Fig. 18. Example of tightening log (detail retracted for privacy purposes)

3.4.2 Performance metric page

The performance metric page facilitates a comprehensive understanding and enhancement of the efficiency of the assembly process by identifying where delays occur and which stations require improved time management or process optimization, as illustrated in Figure 19. The data obtained here is directly fed by the Java client app at each workstation. The Gantt chart illustrates the temporal distribution of tasks across various stations, thereby facilitating the identification of potential bottlenecks where activities may be experiencing delays. Additionally, the cycle time bar chart offers a comparative analysis of the duration each station takes relative to its target time, thereby pinpointing sectors where efficiency enhancements may be warranted. For example, Station 3 substantially exceeds its target time, indicating a potential area for process optimization.

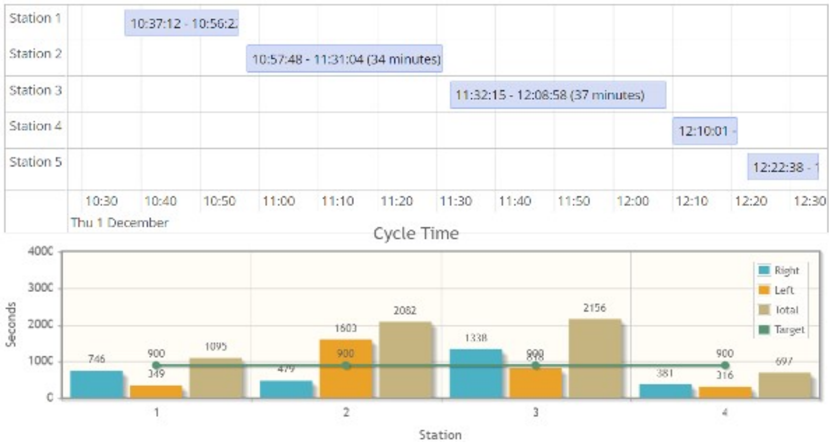

Fig. 19 Performance metric page

3.5 Mobile Application

PDI is a critical stage in the powertrain assembly process to ensure the final product meets quality standards before delivery. The Android app captures real-time photos of powertrain units during the PDI which includes images of components, assemblies, and unit conditions. Photos in the app are automatically stamped with the time and location of the inspection for precise documentation of inspection details. Android app photos and data sync with MES web application which allows centralize access of all inspection data for analysis and reporting. The Android app reduces reliance on manual documentation and improves inspection accuracy, resulting in cost savings for rework, warranty claims, and quality issues. Figure 20 summarizes the Android app implementation.

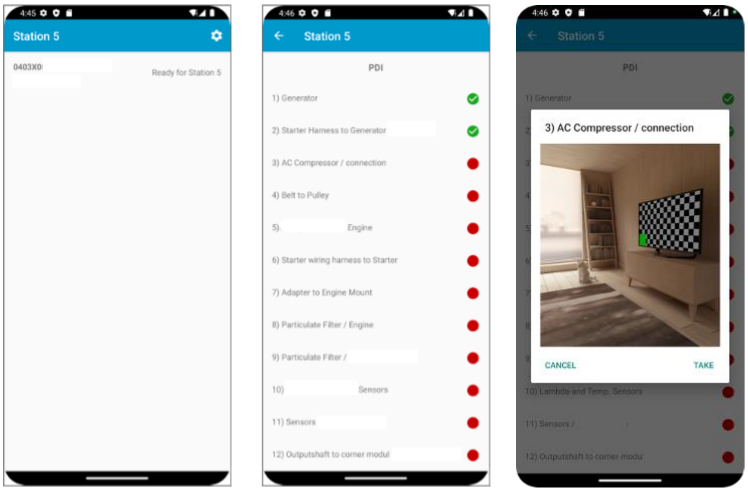

Fig. 20 Mobile application (from left: Main screen, Detail PDI Process, Capture Window)

Other pages in the web application includes Web-Andon page and Worker Management page which are not included in this subsection due to page limitation. The Web-Andon replicates the Andon TV display at each production line to enable quick view of the production update without the necessity to go to the production line while the worker page manages workforce details, roles and responsibilities, ensuring the assembly operations are staffed appropriately and efficiently.

4. Discussion

The implementation of a semi-automated powertrain assembly system as a proof of concept for MES and MRS, which currently reaches level 8 at Technology Readiness Level (TRL), aligns well with contemporary trends in manufacturing. It provides real-word evidence of the benefits of MES and MRS, such as improved traceability, flexibility, and efficiency. It validates the theoretical advantages of these systems, making a strong case for their broader adoption in the manufacturing industry. The Powertrain Web Application deploys the MES role as the central hub for integrating various processes in the powertrain assembly. It provides real-time monitoring, control, and data collection across different stations. This ensures that the assembly process is efficient, consistent, and meets quality standards. It also enables traceability by recording data at each stage of the assembly, which is crucial for ensuring compliance, quality control, and quick response to any issues that arise.

Simultaneously the system wears the MRS coat in terms of flexibility and scalability as it allows the powertrain assembly system to adapt to different production volumes and variations in product designs. The assembly system can also be customized and reconfigured to accommodate new technologies or process improvements. This capability is essential for maintaining competitiveness in the automotive industry. The modular nature of MRS enables faster deployment of new assembly lines or modifications to existing ones, thereby reducing the time-to-market for new powertrain models.

However, the complexity of integrating MES and MRS with existing ERP systems and shop floor equipment remains a significant challenge in terms of communication and data exchange between diverse systems, each with its own protocols, standards, and legacy technologies. In this implementation, for example, no integration with existing ERP system is yet in place.

Ensuring seamless communication between disparate systems and managing the sheer volume of data generated can also overwhelm existing IT infrastructures, necessitating robust data storage, processing, and analysis strategies from the developers. For example, six picture set for PDI purpose, which can consume typically a 2MB space per picture, can take up to 700MB per day if 30 powertrains are assembled per line. Data archiving is implemented in this case, where a tiered storage strategy is used. Frequently accessed data is stored in high-performance storage (hot storage), while less frequently accessed data is moved to cost-effective cold storage solutions. This is automated to ensure optimal storage usage.

The VPG exemplifies effective HMI design, emphasizing user-centric principles. By providing clear, intuitive interfaces tailored to the specific tasks of operators and line leaders, the VPG enhances efficiency and reduces errors. The agile approach to developing the VPG, involving iterative prototyping and continuous user feedback, ensures that the system remains aligned with user needs and evolving production requirements. However, maintaining simplicity and clarity in HMI design while incorporating advanced features like real-time feedback from torque controllers and dynamic operation pages can be challenging. Ensuring that these interfaces remain user-friendly and accessible to all operators, regardless of their technical expertise, is essential in this project.

The integration of advanced analytics and AI for predictive maintenance and process optimization is another area where the system can benefit. These technologies can significantly enhance operational efficiency by identifying potential issues before they lead to downtime or defects. However, implementing sophisticated algorithms and ensuring the availability of high-quality data for these analyses require substantial investment and expertise, which may not always be feasible for all manufacturers and was not implemented in this system.

Future improvements in powertrain assembly systems could focus on enhancing the interoperability of modular components through the development and adoption of industry-wide standards. This would facilitate easier integration and scalability, reducing costs and improving efficiency. Additionally, investing in advanced data analytics and AI capabilities can provide significant benefits in terms of predictive maintenance and process optimization. Finally, maintaining a strong focus on user-centric HMI design, ensuring that interfaces remain simple and intuitive while incorporating advanced features, will be crucial in supporting efficient and error-free operation.

5. Conclusions

The comprehensive integration of advanced methodologies and technologies within the powertrain assembly system has yielded significant advancements in efficiency, quality, and adaptability. This paper has explored the critical aspects of implementing MES and MRS within the context of powertrain assembly, highlighting both the achievements and the challenges encountered. The deployment of MES has revolutionized the management of the assembly process, enabling real-time data tracking and enhanced production control. Additionally, the incorporation of MRS has introduced a level of flexibility that is crucial in the dynamic automotive industry, allowing for rapid adaptation to changes in assembly process and demand. The VPG exemplifies user-centric HMI design, promoting efficiency and reducing errors through intuitive and accessible interfaces. The agile development approach, involving iterative prototyping and continuous user feedback, has ensured that the VPG remains aligned with user needs and evolving production requirements. This alignment has been instrumental in maintaining high productivity and quality standards on the assembly floor.

Despite these advancements, several challenges remain. The integration of MES with existing systems and shop floor equipment continues to pose significant complexity. The need for sophisticated algorithms and high-quality data for predictive maintenance and process optimization presents another challenge. While these technologies hold the potential to significantly enhance operational efficiency, their implementation requires substantial investment and expertise, which may not always be feasible for all manufacturers and were not implemented for this project. To address these challenges and further enhance the powertrain assembly system, several future improvements are suggested. Developing and adopting industry-wide standards for modular components will facilitate easier integration and scalability, reducing costs and improving efficiency. Investing in advanced data analytics and AI capabilities can provide significant benefits in predictive maintenance and process optimization, enhancing overall operational efficiency.

The powertrain assembly system project has successfully integrated state-of-the-art technologies and methodologies to enhance efficiency, quality, and adaptability. By addressing the challenges of integration, data management, and user-centric design, and by implementing the suggested future improvements, the system can achieve long-term success and competitiveness for any contract assemblers in this country. The continuous evolution of these systems will ensure that they remain at the forefront of manufacturing innovation, driving the industry towards greater heights of productivity and quality.

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