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Manufacturing Execution System as an integration backbone for Industry 4.0

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Abstract. Manufacturing Execution System (MES) has been applied to plan and manage production on the shop floor level. Some of its functions include monitoring output, quality control data, and operator productivity. It works between the automation layer and the administrative IT systems, enabling the vertical integration of information. Although MES has already been applied in manufacturing for many years, we argue that the MES is well-developed to play a central role in Industry 4.0 implementation efforts. Advanced connectivity has allowed the MES to gain more information from the shop floor entities. In this scenario, MES may be an integration backbone for Industry 4.0, connecting machines to the manufacturing control logic, collecting data, and providing information for decision making. This paper aims to discuss an updated view of MES's role in manufacturing as a fundamental enabler for data integration in Industry 4.0 environments. A pilot advanced MES case application in an Industry 4.0 manufacturing environment is developed and described. A learning factory has been selected for the pilot application in this research due to its flexibility to allow the necessary IT system changes. In the developed scenario, an MES is applied to control the manufacturing of a customized product. The MES receives the product configuration data from the ERP system, controls shop floor equipment, and manages operators' activities. Product data is gathered along the process. Based on this case application, current MES potential and limitations are explored.

Keywords: Manufacturing Execution System (MES), Industry 4.0, Product Data Management (PDM), Product Lifecycle Management (PLM)

1 Introduction

Industry 4.0 is an initiative to transform industrial manufacturing through digitization and the application of new technologies [1–3]. The implementation of these new technologies is supported by data carried by the traditional IT systems – PLM (Product Lifecycle Management), ERP (Enterprise Resource Planning), and MES (Manufacturing Execution Systems) [4]. In this landscape, the MES has a critical role in how Industry 4.0 can be implemented. The MES is key to achieving the flexibility and integration envisioned in Industry 4.0 [5–8].

Typically, the MES doesn't have a single function but has many supporting, guiding, and tracking primary production activities [9, 10]. The MES is applied to oversee plant floor activities, for example, scheduling, data collection, and quality control. These systems are used to identify the optimal sequence planning considering the process constraints (e.g., time for setup and processing) and the workstations' available capacity. MES are also used to monitor output, consumable usage, and operator productivity. Therefore, the MES can provide the manufacturer with long-term trends on manufacturing efficiency by considering raw material consumption and the number of parts produced [11].

The MES works between the automation layer and the administrative IT systems like ERP [12]. The ERP is an enterprise-wide information system that integrates and manages business processes across the company [11]. The MES develops physical and logical links between ERP and manufacturing. It enables the information exchange between a company's organizational level and the systems on the shop floor. It also manages the bottom-up information flow, collecting shop floor information and analyzing it through mathematical techniques.

MES systems have been in place for many years as an important enabler for performance, quality, and agility in manufacturing [4, 9, 10]. Although the MES has already been applied in manufacturing for a long time, we argue that it is well-developed to assume a critical role in Industry 4.0 implementation efforts. Industry 4.0 is based on the integration of business, manufacturing processes, and value chain actors [1]. Industry 4.0 envisions a factory floor with autonomous and intelligent entities that are integrated and decentralized [13]. This will allow for a more flexible manufacturing process and the possibility for products to be customizable. Therefore, some of the technologies used are Cyber-Physical Systems (CPS) and the Internet of Things (IoT). Advanced CPS are autonomous systems that can make their own decisions based on real-time data capture, analytical results from machine learning algorithms, and past machine behavior [1]. In this Industry 4.0 scenario, MES may be currently seen as an integration backbone, connecting machines to the manufacturing control logic, collecting data, and providing information for decision making.

This paper aims to discuss an updated view of MES's role in manufacturing as a fundamental enabler for data integration in Industry 4.0 environments. A pilot advanced MES application in an Industry 4.0 manufacturing environment is implemented and described. Based on this application, current MES potential and limitations are explored.

The paper is structured into six sections. After the introduction of the research topic in Section 1, Section 2 discusses a brief understanding of Industry 4.0 and MES. Section 3 provides the research approach developed in the paper. Section 4 presents the MES scenario implementation at a Learning Factory. Section 5 provides a discussion of the results. Finally, the conclusion and an outlook on further research needs are discussed in Section 6.

2 MES in the Industry 4.0 context

Industry 4.0 is a broad concept that encompasses several enhancements in manufacturing strategy and environments, including increased flexibility to support product customization [5, 14] and advanced connectivity [1, 15].

Production flexibility levels required by Industry 4.0 demand a decentralized MES configuration [4]. It will still be a single data structure, but it will allow decentralized data capture and processing by Cyber-Physical Systems [8, 16, 17].

Every CPS will need to have the intelligence to identify itself and connect to a centralized system, providing that system with its position and state. The associated computing power can be elsewhere [18, 19]. Information will be provided from each entity and relayed to the MES, where this information can be gathered and shared. This allows each product to have its unique transformation process, leading to the needed flexibility for product customization to be carried out [13].

As discussed on ISA-95, there are different levels of integration in the manufacturing system. The MES is positioned as the third level of integration, connecting the production and control environment and allowing the operations management [20]. Besides, as proposed in the MESA c-model, the MES should be responsible for collecting operations information over the different manufacturing systems and components [21].

Advanced connectivity has allowed the MES to gain more information from the shop floor entities [5–8, 13, 16, 22, 23]. This advanced connectivity means the MES does not require complex systems and interfaces on the operational front, so staff can instead use more adaptable interfaces that can be used more easily and remotely [13].

In this scenario, the MES is crucial to gather a broad range of manufacturing information, analyze it and relay it to the ERP. A continuous information flow between all elements demands both horizontal and vertical integration. Integration of data from different systems is also one of the pillars of Industry 4.0 [9]. Vertical integration allows information flow between CPS and the MES. All services provided by Cyber-Physical Systems should be considered. It ensures CPS makes decisions that comply with the rules set out by the manufacturer [13]. Thus, the activities on the factory floor can be visible, managed, and accurately measured. With the information gathered, optimum parameters can be determined to increase manufacturing efficiency and product quality. The collected information is also important to allow for horizontal integration. Horizontal integration enables the smart supply chain to be transparent as each element of the supply chain's status is visible.

Recent advances indicate that MES could also be integrated with a Digital Twin (DT) to allow further transparency in the manufacturing process. A Digital Twin deals with this physical/digital duet [24–27]. "A digital twin is a digital representation of an active unique product ... that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data within a single or even across multiple life cycle phases" [28]. By integrating the MES with the shop floor, including the Digital Twin, this bilateral communication between the physical and digital objects can exist [29].

3 Experiment setup

In this research, an advanced MES scenario for Industry 4.0 has been implemented and tested in a Learning Factory. Conducting the research on a Learning Factory enabled the necessary freedom to operate technical changes and enhancements on the IT systems and equipment. At the same time, the Learning Factory provided requirements and tradeoffs that mockup a real manufacturing setting.

The selected Learning Factory is located at a university school of engineering in Brazil. It demonstrates the assembly of a customizable skateboard in the context of Industry 4.0. Fig. 1 shows the Learning Factory assembly line with five workstations, numbered in yellow. Each workstation is focused on specific assembly activities: 1) two trucks assembly to the skateboard deck; 2) four wheels assembly to the trucks and quality control; 3) skateboard shock absorber customization; 4) 3D printed options (e.g., rails) assembly and product delivery. Materials are supplied for the workstations with a milk-run cart specially designed for this purpose. Workstation 5 is used to disassemble products for material reuse for further testing procedures. Therefore, it is considered separately from the assembly workflow.

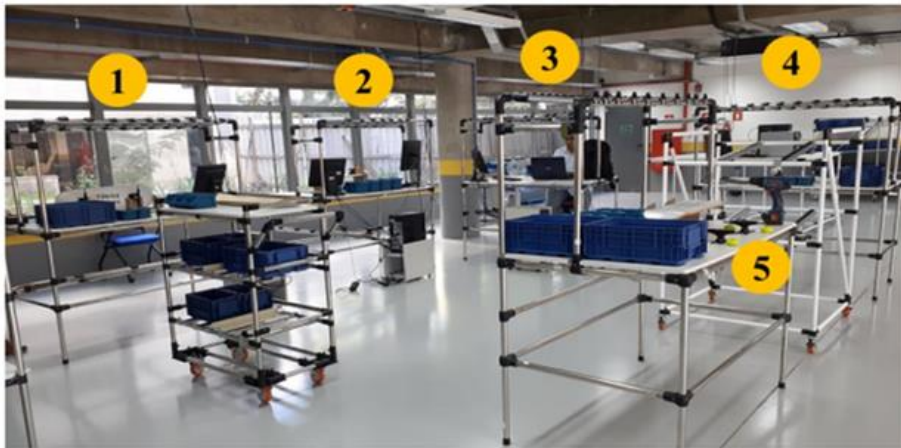


Fig. 1. Learning Factory overview with workstations for product assembly

Besides the assembly line, the Learning Factory also features a production cell equipped with two 3D printers for the production of low-volume and high variety skateboard accessories.

The Learning Factory sample skateboard product can be customized for each production order. The wheel colors can be chosen from a list of available alternatives. Wheel colors can be different for the front and back wheels. The shock absorber can be set on a scale between soft and rigid. This selection results in a torque adjustment on the skateboard truck. Accessories such as 3D printed rails and a connectivity box (for a smart connected product) are available. Fig. 2 presents a schematic view of the product with its main configuration elements.

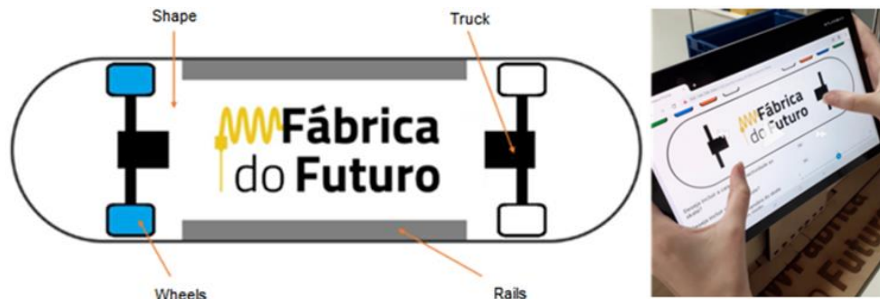


Fig. 2. Skateboard representation and its Product Configurator

The research involved implementing three central manufacturing IT systems: PLM, ERP, and MES. After that, different applications were developed at the individual MES level to show MES integration as the backbone for Industry 4.0.

The PLM, ERP, and MES were implemented on the university cloud services. The PLM system was implemented on a high-performance (8vCPU, 16GB RAM) Virtual Machine (VM) running an SQL Server and structured on a relational database. The ERP system was implemented on a high-performance extra memory machine (8vGPU, 32GB RAM) on a VM running SQL Server running a relational database on a progress environment. Finally, the MES system was implemented on a regular (2vCPU, 8GB RAM) VM running SQL Server and having a relational database on a SQL Server environment [30]. A Java-based Product Configurator (customization interface) was developed to receive the individualized customer request (Fig. 2). The Product Configurator was integrated with the ERP sales and product order module to receive customer orders.

The MES software already had a predefined integration script with the ERP system. This integration automatically captures the XML file from the ERP product order and converts it into the MES database format [30]. Thus, customized customer orders are placed on the Product Configurator interface, resulting in a production order in the ERP system, which is then transferred as an XML file to the MES.

At the Learning Factory, the MES is responsible for managing the assembly activities conducted at the workstation level. When the product assembly is concluded on workstation 4, the assembly data is reported to the ERP system, indicating that the production order has been completed and the product is ready to be delivered.

After implementing the PLM, ERP, and MES systems, three applications were developed and integrated into the MES. The first application integrates the MES with an image processing quality control device (MVISIA ESOS) on workstation 2. The second application connects the MES to the torque wrench device (Atlas Copco ETP STB33) on workstation 3. Finally, the third application connects the MES with a 3D printer (DDDdrop EVO Twin) for the production of optional parts. All three applications have the MES data structure as the backbone for production information, as represented in Fig 3.

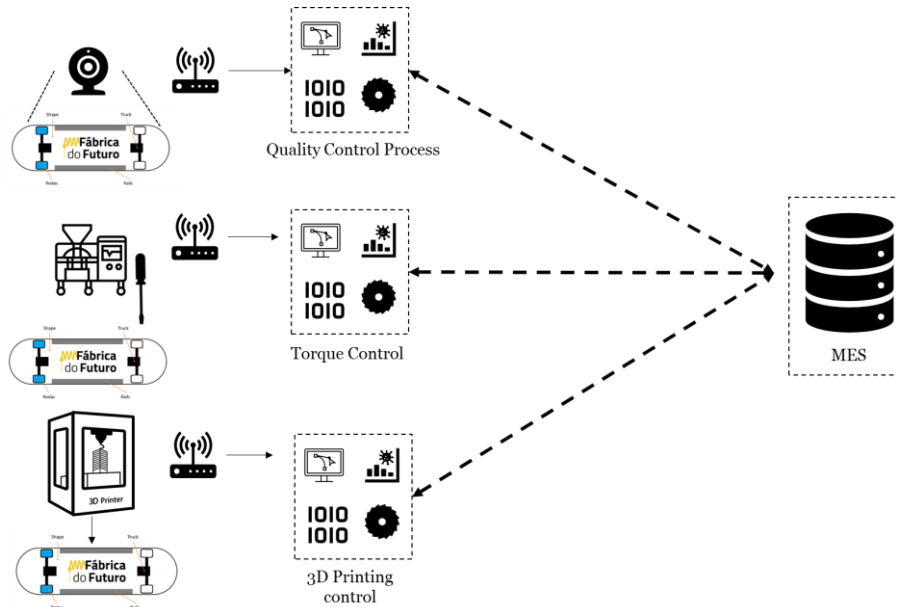


Fig. 3. MES connecting different CPS devices.

Fig. 3 presents a schematic overview of the implemented and tested solutions in this research. This picture shows three independent manufacturing and assembly equipment and applications that receive MES information. The information is order-specific and varies for each product being assembled. The information provided by the MES is needed to trigger the assembly according to the specific production order parameters. When an activity is concluded in a workstation, the order execution parameters (e.g., quality parameters) are sent as new information to the MES system database.

After the implementation, tests were conducted to assess the solution and support discussion on the MES role in Industry 4.0 manufacturing environments.

4 MES as an Industry 4.0 backbone for flexible production

This section details the implemented MES scenario. Therefore, the production order process flow is described. A customized customer order is inputted into the Product Configurator, and a production order is created in the ERP System. Customizable parameters include wheel colors for front and back trucks, the torque applied to the shock absorber (soft to hard), and the optional items selection. The ERP system transmits the production order parameters to the MES via an XML file.

The configuration is sent through the MES to the first workstation, where the trucks are assembled to the skateboard deck. The MES controls a printer used to print a QR code order ID tag, which is attached to the product.

At the second workstation, wheels are added to the truck. The operator receives the information about the wheel color to be assembled on the MES screen. After the manual assembly is completed, an automated quality check is performed. A quality control camera is positioned on the top of this workstation. The quality control camera takes pictures and uses computer vision and machine learning to check if the wheels' positions and colors match the customer order. The computer vision camera information is compared to the MES configuration information, providing automated quality control. The operation can only be concluded in the MES if the quality is approved – Fig. 4 details the implementation.

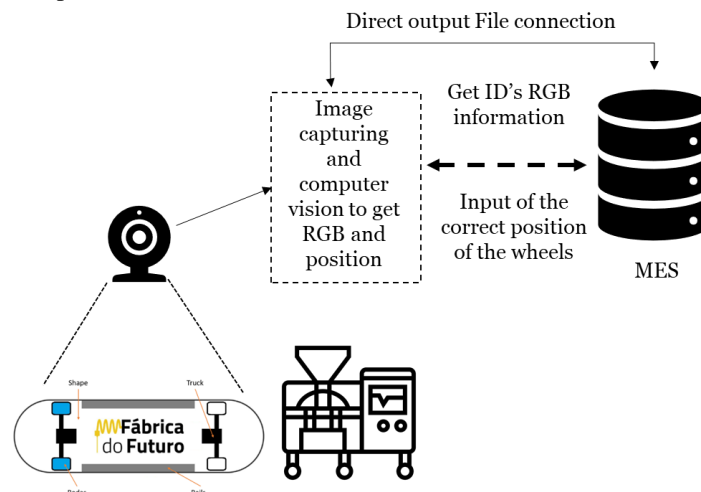


Fig. 4. Image recognition quality control integrated to MES

The camera positioned on the top of this workstation works on the connection. The camera is connected to the internal data network. The camera connects with the MES data structure to get the product configuration data based on the product ID. The camera then collects pictures of the assembly. The RGB of each wheel is identified with a computer vision algorithm. The identified colors are compared to the ones requested by the MES. All the data is remotely processed on the CPS. The MES provides the requested colors and receives the quality control information (approved/not approved). If there is a mismatch between the production order data and the assembly, the errors are pointed out for the operator, including wheel color and position. The quality control data (time, operator, inspection result, etc.) is registered in the MES for traceability. Fig 5 presents a screenshot of the implemented solution.

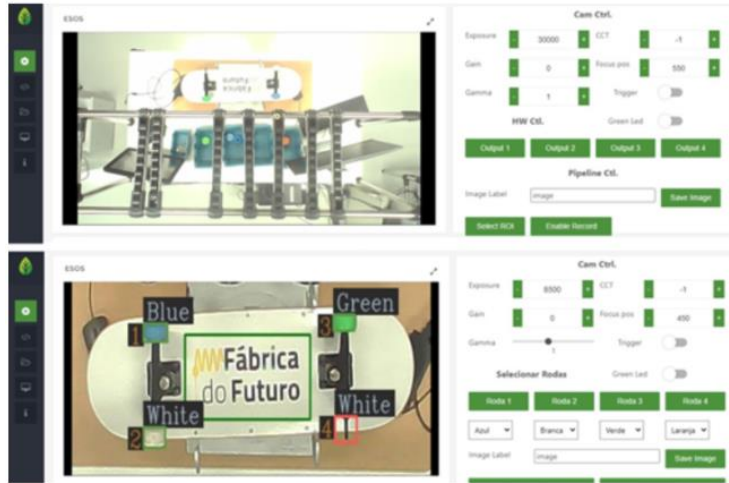


Fig. 5. Image recognition quality control implemented.

At the third workstation, a torque wrench is used, providing customized torque to the truck shock absorber. The torque is informed by the MES to the torque wrench controller. Then, the actuator transforms this information into the application. The actual torque is informed to the MES for information tracking. The integration follows a more traditional approach – Fig. 6 shows the implementation model – the torque is read at the MES database, and a serial communication is started with the controller.

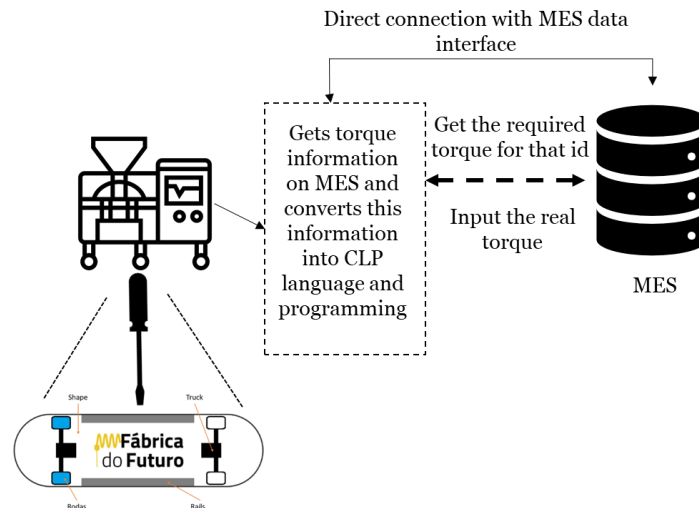


Fig. 6. Torque control system integrated to MES

Finally, at workstation 4, accessories can be applied as per the customer order. These accessories are produced using the two 3D printers available on the shop floor. As accessories are low volume and potentially high-variety items, additive manufacturing is suitable [31]. In the scenario, the 3D printers are started by the MES when a new customer order including 3D printed items is updated at the MES database. The MES also receives and registers progress information from the machines – Fig. 7 details the implementation model.

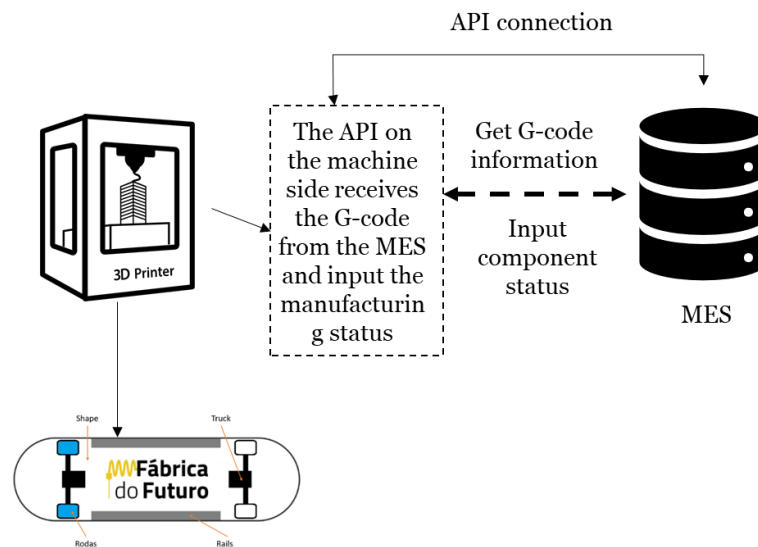


Fig. 7. 3D printing implementation model integrated to MES

The connection, in this case, is allowed by a python odbc connected with the MES and a Java API on the client-side of the 3D printer. The basic principle of the API is to send a request to the machine containing the G-file requested for the part's manufacturing. On this file, the machine's initial setup, as temperature, layer thickness, etc., is given to the machine. On the MES side, the API requests the manufacturing state to update the system's information. Finally, the part status is changed to ready after the machine indication and the production is updated.

The information flow on the implemented scenario has been represented in Fig. 8. It demonstrates that the MES has a central role in manufacturing. The MES connects the production information with the management systems while predicting and controlling the steps that need to be performed to complete the manufacturing process.

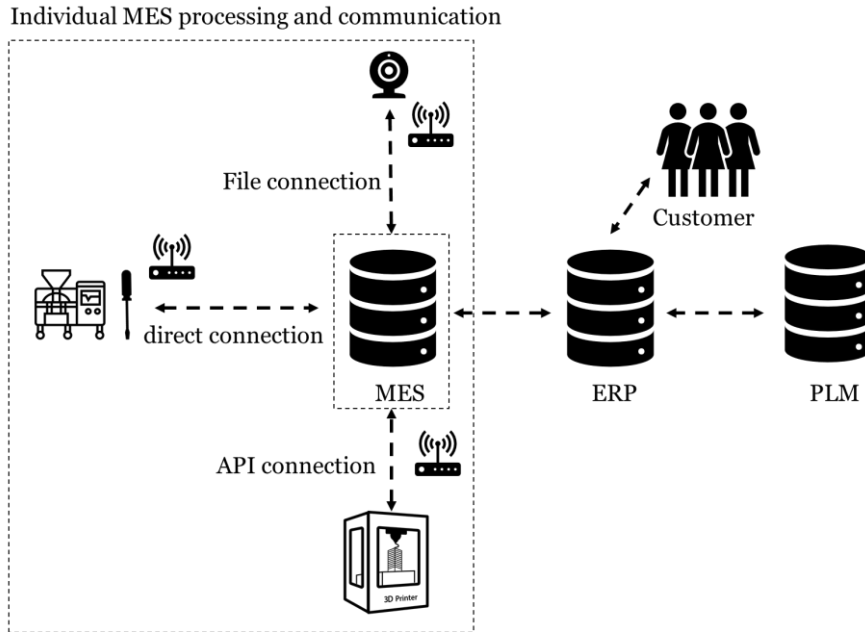


Fig. 8. Information flow

5 Discussion

In the Industry 4.0 MES scenario application presented, it was possible to identify two MES developments. First, even though MES continues to be the way to bridge data from the shop floor to the management levels, it now has a central role in manufacturing. The MES connects product information to manufacturing and management systems, enabling real-time decisions. Second, MES now represents an integration platform for different applications and manufacturing equipment at the production level. These applications are single connected nodes that receive data from the MES and send new inputs for the system.

The MES possesses the central data structure in the shop floor and can, indeed, serve as the backbone for Industry 4.0 IT transformation. This vision has already been discussed in previous works [4, 8, 13, 16, 22, 23].

The MES position has been evolving from a manufacturing system that oversees the production and coordinates the manufacturing to integrating the data of different connected and distributed systems, becoming the backbone of the entire manufacturing environment [27].

Through this integration, the MES can help provide greater flexibility to allow for one-of-a-kind production [5–8]. This is demonstrated through the customizable elements (wheel colors, torque applied, optional items selection) in the implemented MES scenario. Therefore, this research expands previous efforts by demonstrating an imple-

mentation exploring the MES integration potential. In this research, the MES also connects decentralized manufacturing equipment. However, this integration is realized to a central decision-making logic. The MES evolution and role in a decentralized decision-making scenario remains open for further research.

6 Conclusion

This paper discusses an updated view of MES's role in manufacturing as a fundamental enabler for data integration in Industry 4.0 environments. The paper presents a pilot advanced MES application in a Learning Factory. The pilot application explores MES potential to link product and manufacturing data and equipment.

The implemented scenario demonstrates that MES may be a key enabler to Industry 4.0 initiatives in manufacturing. The tested application indicated that the MES enhanced flexibility for product customization. Moreover, it played a significant part in data collection and decision support. The studied MES application enabled integration between the individually connected equipment and management systems, connecting the shop floor with the ERP and supporting a continuous flow of information between the different control levels.

Besides, the MES must be prepared to connect with different types of information and protocols. It can be through an API, as in the 3D printer model, a direct connection, as in the torque wrench, a file exchange, as in the computer vision, or any other connection protocol. In this way, the MES works as a platform to connect various individual data processors to the whole manufacturing environment.

This research has limitations regarding the use of open-source platforms for integration and a Learning Factory scenario for implementation. At the implemented Learning Factory scenario, future steps may include integrating the information of multiple applications to test the distributed MES system's latency and robustness. This experiment will evaluate the capacity of distributed communication between systems and machines. The Learning Factory implementation may also be enhanced to explore the MES role in a decentralized decision-making scenario. Future research work may also assess the evolving MES role in the industry. Therefore, case studies of advanced MES adopters and even a survey research approach may be conducted.

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