Development of a human-centric knowledge management framework through the integration between PLM and MES

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Abstract. Data management systems represent a powerful tool for collecting and managing real-time data in a company. One-of-a-Kind Production (OKP) firms, which leverage on their knowledge about past products and manufacturing processes to reduce lead time, are the ones which can potentially benefit the most from deploying systems like PLM and MES.

However, the benefits arising from data management systems are still limited due to the scarce integration among them. In particular, for OKP companies it is crucial to be able to collect and formalize the knowledge generated by operators during the manufacturing process, in order to constantly improve the design process. In this way, the iterations of trial and error can be reduced, saving time and costs.

This paper proposes a framework (i.e., a Knowledge Base System) for the integration of a PLM software used for product design and production cycle definition, and a MES software able to collect operators' feedbacks about manufacturing criticalities. The integration is realized by means of a centralized database, able to receive data from both systems and to relate them to generate useful information. Finally, a case study developed on a car prototyping company is presented to exemplify the advantages of systems integration.

Keywords: PLM, MES, Industry 4.0, Knowledge Management, Human-centric production.

1 Introduction

The many challenges faced by society at a global level, (i.e., the climate change, the Covid pandemic and Countries' political tensions) demonstrated the fragility of existing production models. As a consequence, the European Union deemed Industry 4.0's paradigm (I4.0) inadequate for the achievement of its strategic goals, including the 2030 Sustainable Development Goals [1]. In fact, despite being born to satisfy economic and ecological requirements, I4.0 evolved over time to become technology-focused and efficiency-driven, proving to be unsustainable in the long term from all critical points of view: social, economic, and environmental [2].

For this reason, in 2021 the European Commission elaborated a new paradigm called Industry 5.0 (I5.0). I5.0 builds upon I4.0's technologies while stressing the role played by innovation and research in the achievement of a competitive sustainability [2]. The most important element introduced by this paradigm is the triple bottom line: resilient value creation, human well-being and sustainable society [3].

The European Commission also recognized the role of industry as pivotal to the concretization of each of these three dimensions [2]: industry needs to be sustainable in the long-term, resilient to external shocks and human-centered. This last definition means that, differently from I4.0, technology is now required to adapt to human needs and not the other way around. In fact, in the previous paradigm human and technological components were considered separately and almost in conflict with each other. Taking Zero Defect Manufacturing (ZDM) as an example, most approaches are currently based on the idea of removing and substituting human workers with technologies like machine learning and robots.

The underlying philosophy is that operators contribute to most of the mistakes made in manufacturing (up to 90% of the total) while robots are able to perform repetitive tasks with lower variability. However, recent studies [4] suggest that superior performances are achieved not when removing humans from the production lines, but rather when integrating and empowering them using technologies like cobots and Augmented Reality. This is a perfect example of the purpose of the new European policy: it is not aimed at proposing a new set of technologies (especially because I4.0 technologies' adoption was still below 30% in most industries in 2020 as stated by IOT Analytics), but rather at redirecting their usage toward more sustainable applications.

One of the technologies introduced in the smart revolution is the Information Systems (ISs) integration. It consists in the creation of data exchange channels and interaction modalities between ISs to increase efficiency, foster collaboration and improve productivity, but also to integrate data from multiple sources to extract previously unknown or implicit knowledge [5]. In this way, integration assumes a strategic role because it may contribute to the creation of a sustainable competitive advantage based on the company's know-how.

The three most common and used production ISs are the Enterprise Resource Planning (ERP), used to manage and integrate different business functions and for resource planning, the Manufacturing Execution System (MES), used to monitor and control production and resource usage, and the Product Lifecycle Management (PLM), used to collect, manage and distribute product data [6].

Regarding the existing integrating architectures among these ISs, the PLM-MES integration is the least established, especially if compared to the ERP-MES which can already benefit the ISA 95 – IEC 62264 standard for the data structure [7]. However, thanks to the information flow it creates between design and manufacturing phases, it represents an interesting opportunity for those company which base their competitiveness on the experience and knowledge acquired over time (e.g., One-of-a-Kind-Production or OKP companies, whose products are customized on a single customer's demand).

This article will present a framework for PLM-MES integration inside an OKP company. The two ISs interact through a centralized database called Knowledge Based System (KBS) by using inter-systems interaction flows. The purpose is to present an industrial solution and to demonstrate how an I4.0's technology can be applied in an I5.0's perspective.

The rest of the paper is organized as follows. Section 2 presents the analysis of the existing literature on integration solutions and its benefits. Section 3 describes the proposed PLM-MES knowledge management framework and the inter-system interaction flows. Section 4 discusses a case study on the implementation of the system in an OKP firm and it also reports the benefits of the proposed system in the context of human centricity. Finally, Section 5 draws conclusions and outlines future research directions.

2 Related works

Despite the growing interest on the topic, the literature produced over the past four years regarding integration between PLM and MES is surprisingly scarce. This may be partially due to the limited PLM diffusion (the "*Before PLM era"* will not end until 2040 [6]) which may hinder research on the topic. PLM's low adoption is also the reason why the standard for ERP-MES integration does not include PLM applications and delegates the product data management to the other two systems [7].

The most important reference on PLM-MES architecture is represented by Ben Khedher et al (2011) [7]. Starting from the analysis of the lifecycles of the data exchanged (i.e., product object, product instance, manufacturing system and purchase order) and the types of activities, it defines the areas of responsibility for each system. The same work also proposes an ontology-based integration.

When analyzing the PLM-ERP integration for OKP companies Bruno et al. (2020) [8] proposes an integration based on a centralized database (i.e., the KBS) able to store and integrate the data produced by both systems and to redistribute it to workers and designers, implementing in this way the feedback mechanism.

The same topic is also analyzed in a study presenting an application of the technology to an aeronautical OKP company [9]. This implementation complements the data provided by the MES by means of technologies like RFID for product tracking and a control system.

An integration based on international standards for PLM and MES has also been proposed [10]. This research proposes a neutral information model for product, process, and resource data exchange. It also allows to transfer and comment 3D files between systems.

Similar systems minimize the chances for errors allowing for smoothly transferring and sharing information from product development to manufacturing, as demonstrated by Stolt and Rad [11]. Although this study focuses on the PLM-ERP integration, similar considerations can be made for the PLM-MES interconnection. However, data integration is only part of the benefits this framework delivers. In fact, this architecture facilitates the creation and management of new knowledge. The relationship between PLM as product data repository and Knowledge Management (KM) has been demonstrated by Folkard et al [12]. In this study, researchers identified the PLM as a key enabler of KM because of the role it plays in knowledge reuse through the provision of repositories to enable collecting, sharing and distributing information.

All studies mentioned above explain the expected operational and knowledge management benefits created by this technology. However, little information is provided on the topic of human centricity. In order to study this aspect, it is necessary to start from an analysis of the I5.0's implications. Ivanov (2022) [3] analyzes the effects of the new policy on Operations and Supply Chain Management. In this study the major technological principles of I5.0 possible ways to enhance human centricity at the plant level can be analyzed.

Finally, a literature review on Human Centric ZDM [4] explains how technology can enhance operators' and engineers' capabilities; as such, it represents a useful example to lead future research on different applications.

3 Knowledge Management Framework

The proposed framework aims to integrate PLM and MES systems through the KBS, as shown in Fig. 1. A preliminary implementation of the framework was proposed by Bruno et al. (2020) [8]. The PLM application is used for the management of product, equipment, and process data, and for enhancing collaboration and coordination during the design and the industrialization phase. Inside the PLM, products and production routes can be defined and made available inside the KBS. Instead, the MES is employed for planning, monitoring, and controlling production, but also for collecting the operators' feedback. The KBS is a centralized database able to store and integrate data from both systems. It acts as a mediator and can make available information both to PLM and MES, thus allowing the reuse of knowledge. The allocation of the activities between the MES and the PLM is compliant with the solution proposed by Ben Khedher et al. (2011) [7].

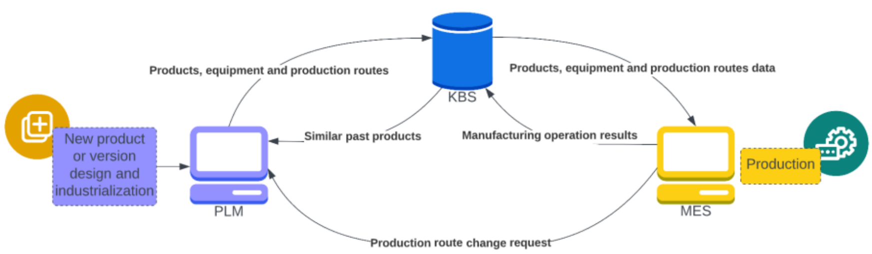

Fig. 1. Interaction flows between PLM, KBS and MES.

3.1 The KBS

The KBS data structure is shown in Fig. 2, according to the UML class diagram formalism [13]. It has been designed to meet the needs of an OKP company. In fact, for this type of organizations, it is necessary to correctly store information about all the product and production routes' versions, in order to be able to store a complete record of the design process history. In this diagram, blue classes belong to PLM and yellow ones to MES (the two green classes refer to ERP, where data related to the customer orders are inserted).

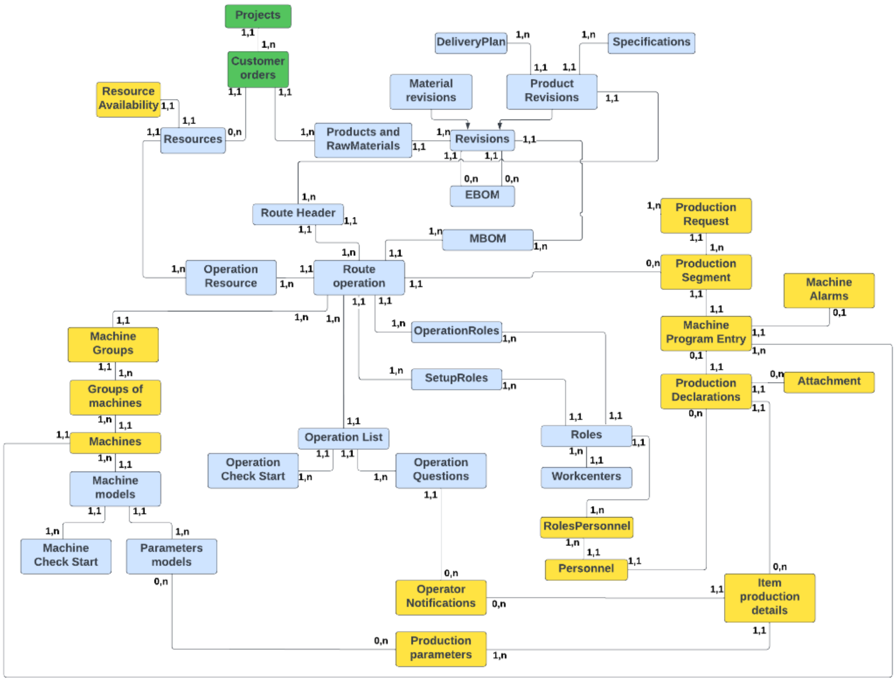

Fig. 2. UML class diagram of the KBS

In the PLM, the process starts when the company receives a project, which is made of multiple customer orders. Each order corresponds to one product, one raw material and multiple resources. Each record of product or raw material may have multiple versions, each with their own sets of specifications, BOM, delivery plan and versions of the production routes. Only one production route will be flagged as active for each revision of a product; however, the full revision history is stored in the database to be later used as a knowledge source. The production route is divided into route header, which stores the general information about a route, and route operation, which contains the sequence of operations required to produce a specific revision of a product. The route operation table is connected with revisions (in order to construct a MBOM), machine groups (an entity storing dynamic groups of machines), operation roles and setup roles (to identify the kind of operators required for the operation itself and for the setup), operation resource (where the resources required to perform a specific operation can be stored) and operation list. The operation list reports a list of generic operations; in this way, it is possible to define controls to be made before the operation (i.e., operation check start) and after (i.e., operation question).

In the MES, multiple production requests can be generated for each production route. The planning of each request is made using production segment, which is related to route operation. Machine program entry stores the specific machine used to perform the operation and is directly related to the production declarations, which contains information about the production progress. More detailed information can be found inside the item production details. This last table has associated the parameters used during the operation and the answers given by the operator to the standard questions provided inside operation questions, in this way a more detailed analysis of the problematic operation can be made.

The KBS, other than facilitating system intercommunication, has the role of repository of integrated data which can be later analyzed to extract knowledge. Therefore, it can be used for multiple purposes:

- to find the similarity between a new product and the existing ones, in order to provide information about the design process, the production route and the issues occurred in the past. This helps the company to anticipate design problems and solving them before they emerge, thus saving time and money.
- to run cluster analysis on products, defects and solutions used. In this way, the KBS can provide quantitative data to support the development of organizational best practices.
- to provide more accurate forecasts of time and cost thanks to the analysis of past experiences, which can benefit planning accuracy and customer relationships.
- to reduce the dependency on key knowledge-holders, a common problem for OKP companies. Since part of their knowledge can be stored and retrieved, the firm becomes able to contain the know-how loss in case one of their employees leaves.
- to identify potential areas of improvement both in design and manufacturing, enabling continuous improvement.

3.2 The interaction flows

One of the most crucial elements in PLM-MES integration is the definition of the interaction flows among the systems, especially the feedback flow from production to design. Two kinds of flows exist (see Fig. 1).

- Flows from PLM to MES. Product, equipment, and process data are defined in PLM and then exported to the KBS, where MES can read it.

- Flows from MES to PLM. The information about operation results is exported into the KBS and made available to the PLM, where designers can use them to improve products or equipment design and industrialization.

More precisely, the PLM-MES flow can be further divided into two types, depending on the timing. The first type transfers data concerning the type of operations, the machine models, the production parameters model, the checks to be made before and after the operation and a list of questions to be answered after each process. These can be considered static data, since they define the characteristics of the plant and the production, thus is not very frequent. The second type of flow is instead continuous, and it is designed to systematically insert product, equipment, and process data from PLM to MES. This data is highly dynamic and subject to endogenous and exogenous changes. In order not to limit the organization flexibility, information updates on a single production route must be communicated to the MES system as soon as possible. The many changes to be reported and the number of orders processed at once by companies allow us to consider this flow continuous.

The MES-PLM flow represents the most important advantage provided by the integration, because it makes possible the storage and reuse of the historical knowledge, by formalizing the trial-and-error process typical of an OKP company. The MES-PLM flow can be further classified in two types according to the path used for the interaction; both are necessary to deploy the feedback mechanism between manufacturing and design. The first type has the role of summarizing the data collected in production to produce information about the product revision; in particular, it moves data about production results (e.g., number of conforming, number of scraps, unsuccessful operations, issues found), from MES to KBS and, after a processing operation aimed at improving readability, ultimately to the PLM. The second one deploys a real-time mechanism to simultaneously stop the production from using the inappropriate cycle and to trigger a second industrialization phase in the PLM. Therefore, it is a more direct form of interaction between MES and PLM (but simultaneous with the previous one) and it is needed to deploy proper and timely change management processes. In an OKP company the production route may go under several changes during manufacturing; therefore, their revision and approval requires a formal process. This must be triggered by the MES (i.e., the production, where the route incompatibility is discovered); however, since the industrialization is part of PLM areas of responsibility, the change process must be managed inside the PLM. This problem is solved by using the concept of lifecycle, as described in the next section.

3.3 Entity lifecycle

A lifecycle is a sequence of states an entity (i.e., a data object) may be in. The states, represented as nodes, are connected by arcs, which allow to move a data object from one state to another following one of the paths allowed. The changes of states are entirely managed by PLM as part of the product data. However, transition actions may be triggered by the MES system when needed.

The concept of the lifecycle has already been used for PLM-MES integration [7] focusing on the product macro phases. On the contrary, in this framework the focus is on detailing the design and manufacturing phase. Two different but interacting lifecycles have been designed, one for the product (in this case, for the revision of the product) and one for the production route, as shown in Fig.3. Given the business model of an OKP company, the Product revision (i.e., the customer's product specifications) dominates over the Route header; a change in the former's information creates the need for the latter's reevaluation.

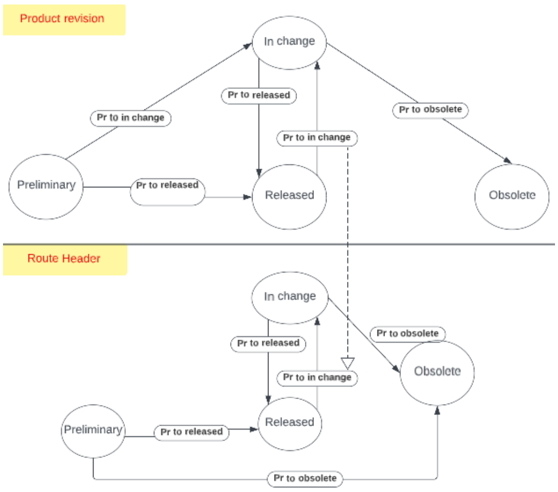

Fig. 3. Lifecycles of product revision, production route their interactions.

Both the product revision and the production route are created in state Preliminary. A Route Header cannot be created until the Product revision's information is validated i.e., Released. Once the product is released, a Route Header can in turn be generated and released. When parts and routes are released, they cannot be modified without a formal change management process.

In case an issue emerges during production such that a change to the route is required, the MES immediately requests the promotion of the route to the In change state This action activates a change process, which in turn informs all the responsible entities and activate a formal workflow to coordinate the re-design of the route. Along with the promotion to the In change state, an indication about where to find in the KBS the specific production declaration reporting the problem can be included. Depending on the entity of changes required, the change process may lead to two alternative outcomes: if a minor change is needed (e.g., adding detailed work instructions to an operation) the Route Header can be simply released back; instead, in case of major changes (adding or removing resources, modifying the operations order) a new version must be generated. .

When a product faces a revision (i.e., a new data object of type Product revision is generated), it must be first moved to the In change state to be evaluated; this causes the promotion of the latest Process Plan to In Change and, of course, the activation of a Change Workflow. Once accepted, a new version of Product Revision can be generated, while the old version is promoted to the Obsolete state. This promotion is triggered inside the PLM system and is essential to ensure instantaneous communication between the otherwise siloed departments of Design and Production.

4 Implementation and discussion

4.1 Implementation of PLM-MES integration framework

The proposed framework has been implemented within an Italian OKP company which produces car body parts some of the most important global producers. The proposed solution employs open-source software for most of its components.

The PLM application is Aras Innovator, released by Aras Corporation [14]. Multiple data objects and relative forms were created, replicating the data structure shown in Fig. 2. Aras also allows to associate to each data object a lifecycle. Using this function, the lifecycles reported in Fig.3 for Product revisions and Production route were implemented. The same lifecycles were connected by means of C# codes activated on the promotion event.

The KBS was implemented by using PostgreSql [15], according to the diagram shown in Fig. 2. The commercial MES system Jpiano was implemented by the AEC company [16].

The flow from PLM to KBS was deployed by means of Node-RED, a visual programming tool that allows online service communication [17]. For some entities this flow is activated periodically; in some cases, it can be activated when specific events (like the Product revision promotion on Aras) occur. The second activation mode is designed to improve the timeliness of communication among the systems; in fact, in this way the MES system can be readily informed in case a change occurs. The flow from MES to PLM exploits a HTTP request sent by Jpiano directly to Aras' server which activates the promotion of the item specified in the request body.

4.2 Contribution to human-centricity and Industry 5.0

The exposed integration contributes significantly to the achievement of human-centricity in production and to the transition toward I5.0. In fact, some of the most important I5.0's technological principles are collaboration, coordination, and communication [3]. Thanks to the data migration and the interaction flows, communication between two typically departmental steps of design can rise in frequency and quality, thus improving the coordination at the organizational level. A timely feedback and knowledge sharing between design and manufacturing is particularly critical for OKP companies since, thanks to this practice, they can significantly reduce the amount of design iterations, thus reducing the lead time and costs. Finally, the PLM itself represents an important tool for collaborative design.

The PLM-MES integration plays a peculiar role when analyzed under a human-centric perspective. It allows to formalize the manufacturing experience and knowledge created during operations (that would otherwise remain implicit in operators' heads) and to make the information about the problems occurred and the solutions adopted in the past directly available for the design of similar components. Therefore, this solution enhances designers' capabilities by enriching their personal experience with historical data about defects and choices made on similar products. To extend this concept, the knowledge reuse feature can complement the results obtained from traditional software tools such as simulations, by providing real manufacturing examples, thus overcoming software's inherent limitations, and providing better guidance for designers in their decision-making process. .

Furthermore, the PLM-MES integration can be framed within the lean manufacturing approach, and in particular ZDM, which is now considered to be one of the key enablers of I5.0 [4]. By making immediately available to operators drawings, work instructions and stamping simulation results, it provides key information about possible failures and areas to focus on during quality control. In this way, a proactive approach can be taken by workers during manufacturing, who can implement the necessary actions to prevent defects before they occur, making a further step toward ZDM even in the OKP's unpredictable environment.. The lesson learning mechanism presented creates the conditions for the continuous improvement of both the worker and the process.

This integration also makes the whole organization more resilient to changes. As mentioned, the historical knowledge is formalized and stored in a database, so that it could be made available immediately to anyone. Traditionally, this form of information remains in workers' heads; as a result, when employees leave the organization, the latter loses an important part of its know-how which is a critical dimension of the contemporary competitive advantage. Thanks to this technology, the knowledge can not only be saved in similar situations but can also be distributed to new hires in order to reduce their learning curves. Overall, the whole system becomes more flexible and resilient.

5 Conclusions

In this paper, an improved framework for PLM-MES integration has been proposed. This framework presents multiple benefits for all kinds of production but especially for OKP companies, which in this way can formalize and store the knowledge produced during their activities and reuse it when new similar products must be designed and redistributed.

The framework has been implemented using a centralized database to convey data from both systems to integrate and reuse it. The designed interaction flows create immediate feedback between production and design, improving the effectiveness of this solution. The communication channel established between these two departments also demonstrates the conformity of the technology to I5.0's requirements.

Future research should focus on the introduction of the ERP system, whose functions are currently played by the PLM. The full integration benefits can only be generated when all information sources are integrated correctly in order to generate knowledge.

Another area requiring further analysis is the formalization and representation of manufacturing knowledge; ontologies can be employed on this aspect for the definition of the concepts' taxonomy and relationships. Finally, it is necessary to understand how the data generated during production can be processed to present only the most meaningful and representative information to workers, to avoid information overload.

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