PLM-MES INTEGRATION TO SUPPORT COLLABORATIVE DESIGN

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Abstract

In order to deal with global competition, manufacturers have to develop innovative, sustainable, high added-value, high quality products. Cooperation among companies is necessary to share product development capabilities, costs and potential risks. Information systems such as PLM, ERP and MES must be deployed and reciprocally integrated to improve the efficacy of this collaboration. In this paper, we focus on PLM-MES cooperation: the former system manages relevant product information to meet client specifications; the latter analyzes real-time data collected at the shop-floor (e.g. through a set of sensors installed on the machines) and extracts useful data concerning the "as-is" state of the process or product. The information generated by MES can be used as a feedback to redesign or revise manufacturing operations, in order to enhance the quality of the product and the performance of the production process. This experience-driven knowledge must be integrated in the PLM, to be available for future production, even in different places or for cooperating companies. In this paper, we show an application in the field of aeronautics, in which produced parts must meet very high quality.

Keywords: Product lifecycle management (PLM), Manufacturing Execution Systems (MES), Knowledge management, Integrated product development, Design practice

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

In recent years, worldwide manufacture entered a mutation period, characterized by sustained but modest growth, a renewed focus on product and process innovation, and extended collaboration across the value chain. Manufacturers have developed frameworks and tools to improve transparency and mitigate risk across the supply chain, as well as the global enterprise; further, they are continuously adjusting their business models, since the market dynamics quickly change.

Today, a sharp cost management is necessary but not sufficient to deal with global competitors. The market is demanding innovative (or even disruptive) products: in this regard, alliances among companies are increasing, with the aims of sharing product development capabilities as well as costs and potential risks. Thus, instruments to support this kind of cooperation are necessary and strongly required (KPMG, 2012).

One way to support such inclusive approach is the deployment of information systems to efficiently manage design and production operations, and to maximize the efficacy of the available data. Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES) are among the mostly deployed systems in modern manufacturing companies (Ben Khedher et al., 2011).

PLM is a strategic business approach that supports the collaborative creation, management, dissemination and use of product definition information across the extended enterprise from concept to end of life (Gecevska et al., 2011); it is an information-driven strategy that allows information and knowledge sharing within and between organizations (Sudarsan et al., 2005). The aim of PLM is to ensure the fast, easy and troublefree finding, refining, distribution and reutilization of the data required for daily operations (Saaksvuori and Immonen, 2008).

ERP systems are software programs deployed at the company management level with the function of integrating and coordinating information in every area of the business. ERP provides a unified enterprise view of the business which encompasses all functions and departments, and an enterprise database in which all actions concerning finance, sales, marketing, purchasing and human resources are traced (Umble et al., 2003).

A MES is a layer of communication between the management and the production levels; it is a software that allows data exchange between the organizational level, usually supported by an ERP, and the shop-floor control systems, in which several, different, very customized software applications are employed (Meyer et al., 2009). The aim of a MES is twofold. First, the system has to plan the production processes according to the requirements given by the organizational level. Thus, the MES has to evaluate the optimal sequence planning taking into account the basic features of the process, such as processing and setup times, and workstations capacity; the system also has to manage and allocate resources such as the personnel and the material necessary for the manufacturing process. The second aim of a MES is the management of the bottom-up data flow: information can be collected at the shop-floor level to assess product quality and process performance. Such data are analyzed by the MES, and the results are provided to the organizational level and used to control the process. The functionalities of a MES have been grouped in 11 categories by (MESA International, 1997); further, the tasks for each enterprise layer and, in turn, for each kind of information system are listed in the ISA95 – IEC62264 (2013) standard. This standard also provides definitions for the data structures to be exchanged among information systems aiming to enhance their integration; however, it mainly focuses on ERP-MES-Shop floor integration.

Nowadays, there exists a large variety of methodologies to deal with the top-down data flow and the problem of the finest production planning (Harjunkoski et al., 2009, Rolón and Martínez, 2012, Valckenaers et al., 2007, Verstraete et al., 2008); further, several commercial software that can be tuned according to the necessities of a company are available (Saenz De Ugarte et al., 2009). On the other side, few tools to extract information from shop-floor data have been developed. Existing software mainly focus on product quality and process performance monitoring, deploying techniques such as the control charts; however, a huge variety of heterogeneous quantities can be measured: recently, monitoring and control systems to be integrated into manufacturing machines assumed a relevant role in the improvement of production processes. The demand of such systems is increasing, because of the development of low-cost, small, easily available sensors. These measuring devices should be supported by mathematical techniques able to real-time integrate and analyze data collected from several heterogeneous sources, to provide a complete picture of the current state of the process

and make available useful indications to improve the process itself. Examples of real-time monitoring systems integrated in MES are given in (Arica and Powell, 2014, Snatkin et al., 2013, Zhong et al., 2013).
A successful integration between PLM and MES can play a key role in process performance and product quality improvement. The integration among these two information systems allows to close an information loop between design and manufacturing: the continuous flow of shop-floor data collected by the MES can be used to adapt process parameters, machine programs or task sequences. Changes must then be stored into the PLM, which is the information source containing the complete process and product descriptions (Tech-Clarity, 2011).
Up-to-date, few work in the field of PLM-MES integration has been done. A first attempt has been made by Ben Khedher et al. (2011): they analyze the data exchange between the PLM and MES systems; they also propose a model for this integration. Nevertheless, this general model lacks of validation since no evidence of application is shown.
The original contribution of this paper provides both a theoretical framework for the cooperation between the two systems and an industrial application. In section 2 the case-study is introduced: it consists in a manufacturing process for spur gears production in the field of aeronautics. The features of PLM systems are overviewed and a focus on the PLM structure deployed for this work is given. Then, the monitoring and control system integrated into the case-study machine is described. Furthermore, the methodologies to explain how it is integrated with a MES and how the MES cooperates with the PLM are explained. Finally, in section 3, some results for the case-study and concluding remarks are provided.

2 CASE-STUDY

The case-study chosen to deal with the integration between PLM and MES is in the field of spur gear production. The industrial partner of this research project is a manufacturer of aeronautical components. The accuracy required for its products is very high; further, the unitary cost of these workpieces is very high, thus the process must be finely tuned in order to minimize scraps and losses. In the following subsections, an exhaustive description of the case-study will be provided; we will mainly focus on the PLM perspective, on the deployed monitoring and control systems, and on the integration among information systems.

2.1 The role of Product Lifecycle Management

Product design is a highly involved, often ill-defined, complex and iterative process; the needs and specifications of the required artifact get more refined only as the design process moves toward its goal (Chandrasegaran et al., 2013). Moreover, due to fierce market conditions, the design process should be completed in a reduced quantity of time. In order to accelerate time to market, product and process design must be developed simultaneously rather than sequentially (Abdalla and Knight, 1994).
During product definition and realization, information is shared by designers and used by manufacturers to produce the part; then it is deployed by metrologists, during verification, to create measurement programs and analyze results. The management of product information management is further complicated by the need to handle changes that may occur along the product development. It should also be considered that, in current conditions, companies operate in several continents: a designer in one country can specify a product that is then made in another and probably assembled yet in another.
In such a global market and in such operational constraints, PLM is the only stable channel of communication. PLM integrates a consistent set of methods, models and IT tools for managing product information, engineering processes and applications (Abramovici, 2007). An effective PLM system aims to streamline product development and boost innovation in manufacturing (Sudarsan et al., 2005).
As stated, in this work we are concerned in gear manufacturing. Gears provide a unique contribution to the operation of so many machines and mechanical devices; thus, they have received special attention from the technical community for more than two millennia (Davis, 2005). Gears are machine elements that transmit rotary motion and power by the successive engagement of teeth in their periphery. A designer must remember that the main objective of a gear drive is to transmit higher power with smaller overall dimensions; it must be produced with the minimum possible

manufacturing cost, it must run reasonably free of noise and vibration, and require little maintenance (Maitra, 1994). These features have an essential role today, since new engines should be sound, economically viable, environmentally clean and reliable. Furthermore, high quality of manufactured parts leads to engine efficiency improvement, thus to a reduction of fuel consumption and pollutant emissions.
In the field of aeronautics, gears undergo exceptional conditions: peripheral speed of these gears is usually beyond normal standard values; furthermore, they must resist high temperatures.
In Figure 1.a, a spur gear constructed in one piece with the shaft is shown. Typical specifications (form tolerances) that are critical for gear body are shown. Circularity tolerances are prescribed for the bearing seats and the gear; planarity is prescribed for the side surface. Such tolerances are defined in the standard ISO 1101:2012.

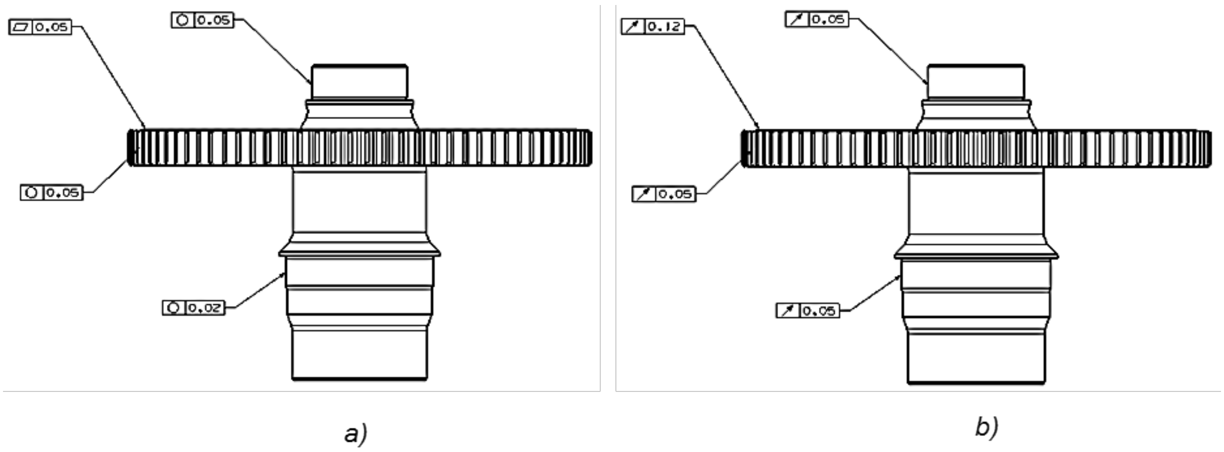

Figure 1. The two design versions for the spur gear deployed as case-study.

Consequently, the design information is communicated to the manufacturing engineer who decides the manufacturing process suitable to produce the part. The first executed operation for gear production is roughing. Then, the workpieces experience heat treatment to achieve the necessary surface hardness and through-toughness. During this process, some form distortions are introduced; thus, in order to produce a gear with the necessary accuracy, a grinding operation is necessary.
However, since grinding is a costly operation (with respect to other machining processes), it should be performed under optimal conditions (Alagumurthi et al., 2006). Therefore, workpiece positioning in the grinding machine must be accurate: even small misalignments can affect the result of the process, leading to the rejection of the part. Since the heat treatment leads to form distortions, the definition of a new reference system is necessary before grinding the gear. Up-to-date, this operation is a manual task based on the experience of the operator; to improve the result of the alignment, an innovative machine has been developed: it is equipped with a monitoring and control system able to measure a set of points on the surface of the spur gear, and automatically evaluate and perform two corrective rotations that result in the best alignment of the workpiece with the machine axis. After this centering process, the countersinks of the gear are finished; they will define the axis of the workpiece for the subsequent grinding of the gear teeth.
The change in the traditional process, due to the introduction of the new machine, requires an adjustment to the form tolerances applied in the design. Since the machine attempts to align the workpiece to the machine axis, it is not necessary to measure the overall roundness (circularity); conversely, the run-out tolerance helps to limit the axis offset of the gear with respect to the machine axis. The new design version is shown in Figure 1.b.
All the information generated in the design and manufacturing phases should be managed in a secure and reliable way. Moreover, product information should be connected to its production process. PLM allows to link defined processes to the product and to provide constraints on the order of process execution.
In Figure 2 a simplified representation of the spur gear design and the process to manufacture it in a PLM system is shown. As stated before, the product at study has two design revisions. The latter is then connected to a specific production process. Next, the process is divided into operations which are

steps that are normally executed in one work area and using one machine. In fact, the information about the employed resources (fixtures, workstations, tools, parameter, CNC programs, work areas) can also be linked to the process if they exist in the system. If necessary, operations can be splitted in smaller operative actions.
By linking the product to the process, PLM is able to inform the process owner, through the Configuration and Change Management (CCM) process, whether a further change to the design is necessary and evaluate how this modification would impact the established operations. However, processes may also have their own revision history independently of the product, in response to feedback from the shop floor personnel when executing the process.

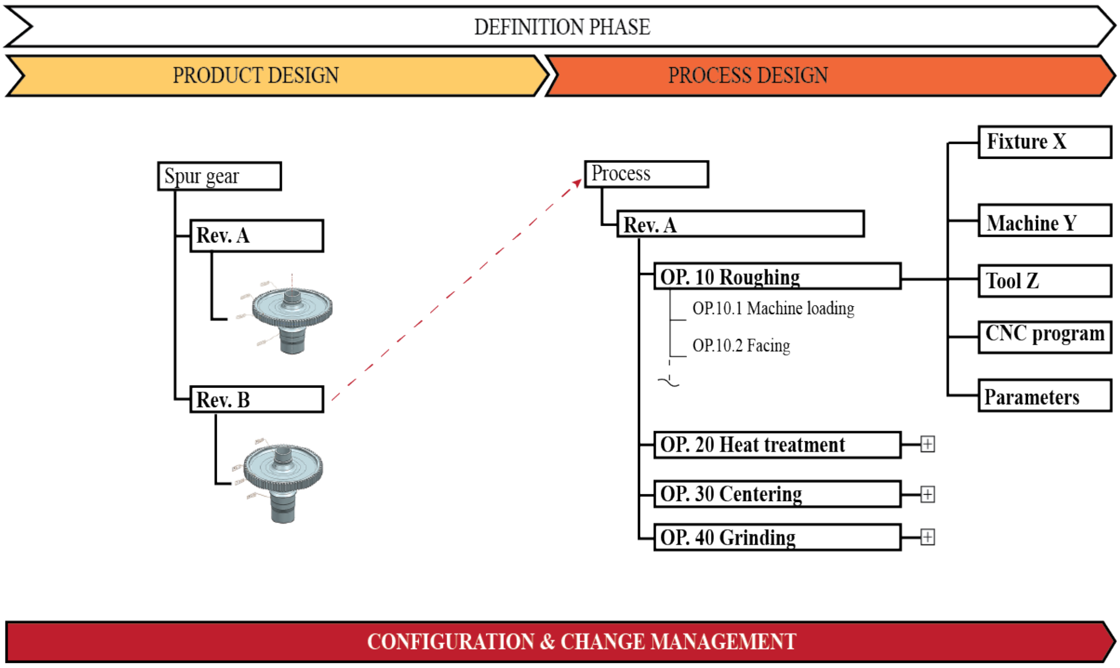

Figure 2. Schematic representation of the Product Lifecycle Information

In the aeronautics market, traceability is a highly important requirement: the manufacturer should guarantee at any time accurate information about the product, processes, materials, stocks, etc. The process defined in the PLM system identifies the resources that are ideally employed to produce the part. Nevertheless, processes may vary according to the location of their execution, availability of resources, and time constraints. For example, the machine assigned to the roughing operation could be down due to programmed maintenance operations and a replace machine should be used. In that case, product operations traceability is lost. Hence, there is the need to associate the physical product information (MES) to the related product data (PLM).
A possible methodology is the use of RFID technology during the production phase to find, differentiate and trace every product. The use of this technology neutralizes the physical separation of product components and the related information (Erkayhan, 2007). Recording the unique product number on a RFID tag allows to quickly access related product information previously entered in an IT application.
In a general scenario (Figure 3), a customer order is entered into the ERP system by sales and marketing department. A production is planned by the MES, using the information stored in the PLM system, with batch sizes, start and end dates, etc. Subsequently, the MES assigns an individual RFID tag to every product and links real-time manufacturing information, performs inventory control, and schedules activities.
The connection between the three systems (ERP-PLM-MES) with the support of the RFID technology ensures that the client will always have accurate, reliable, up-to-date information, and that any change will be correctly managed and made permanently.

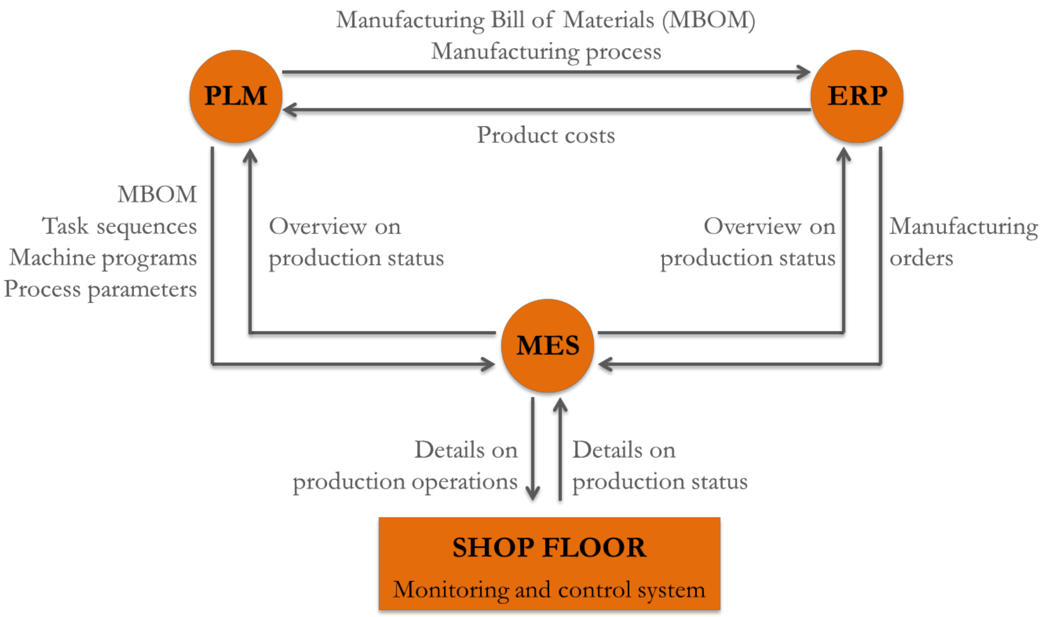

Figure 3. Data flows among connected information systems. Picture adapted from (Ben Khedher et al., 2011).

2.2 The monitoring and control system

The machine that performs the centering operation has been equipped with a monitoring and control system consisting in measurement sensors, a control unit, a rotary table and transducers to automatically correct the position of the gear.
When the gear is loaded into the machine, a measurement system acquires a set of points on workpiece surface. It is composed of four displacement transducers with touching probes: three of them are able to move along the radial direction, to measure the distances from the machine axis to the bearing seats surfaces and to the pitch circle of the gear. The fourth transducer moves along a direction parallel to the machine axis to measure the run-out of the side surface of the gear. The sensors set is shown in Figure 4. The choice of the features to be measured is strictly tied to the tolerances introduced in section 2.1 and in Figure 1.b.

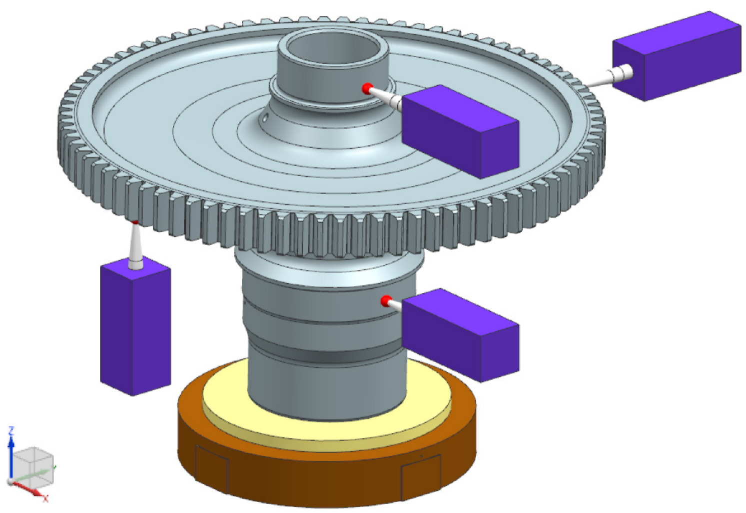

Figure 4. Representation of the monitoring system integrated into the machine.

The data acquired by the measurement system are transmitted to the control unit, and are real-time processed by a mathematical algorithm. The machine is able to perform two corrective workpiece rotations to change the position of the gear: the algorithm calculates the two values for such rotations that allow to minimize the residual positioning error of the gear. This mathematical technique is described in (Barbato et al., 2015); it is also able to predict whether, after the repositioning operation, the configuration of the workpiece will satisfy the tolerances or not. In case the new configuration is not acceptable, a second algorithm is run: it is based on the Iterative Closest Point (ICP) technique (Besl and Mckay, 1992), which allows to simulate the manual centering operation. This task is performed because in the manual operation, a greater number of degrees of freedom is available, and it is possible to better deal with workpiece form error. In case the result of the ICP technique is acceptable, the gear is manually placed into another machine for countersinks finishing, and centered through dial indicators. In case even the second algorithm does not find a gear positioning able to satisfy the prescribed tolerances, the value for the planarity error of the side surface is calculated. If the planarity error is high, a reworking operation is performed: the side surface is finished again to reduce the form error; then the gear centering process is restarted. Otherwise, if the value of the planarity error is low, the form error may be due to misalignments between the bearing seats, or because the side surface is not orthogonal to the axis of the gear. A flow chart of the operations performed by the monitoring and control system is shown in Figure 5.

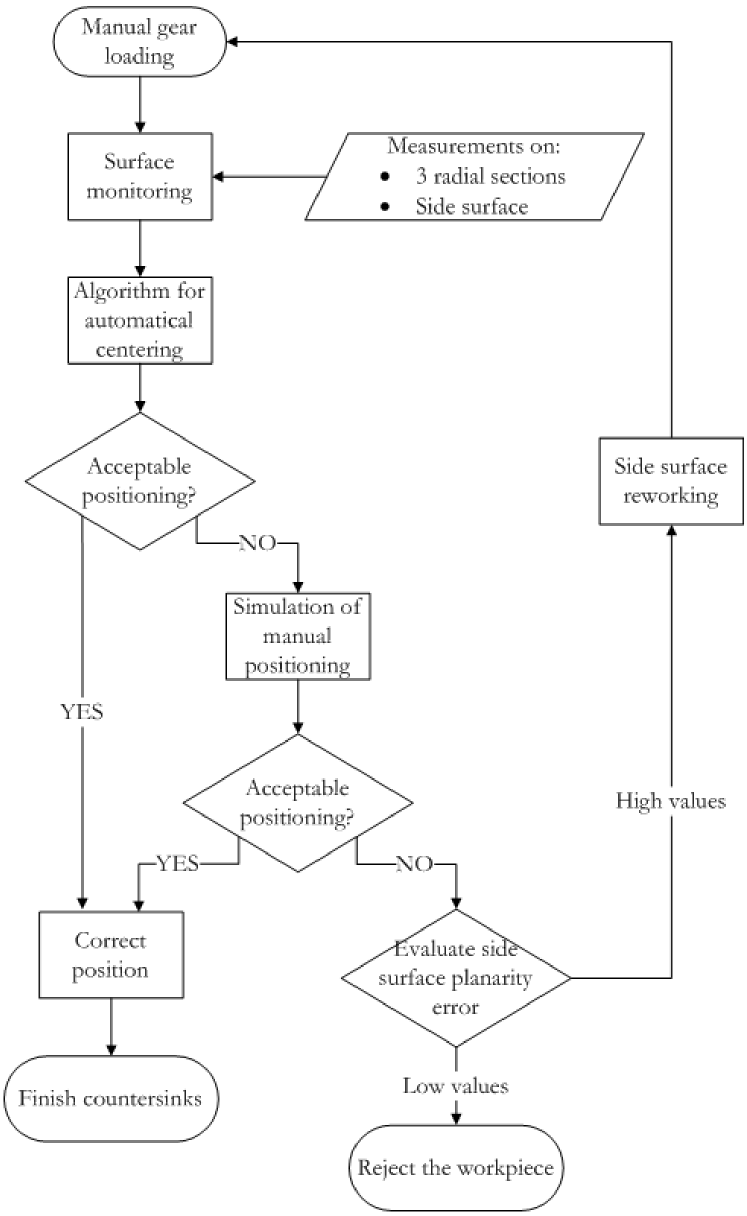

Figure 5. Flow chart of the operations performed by the monitoring and control system.

2.3 Integration between the monitoring and control system and a MES

The methodology described in section 2.2 can be fruitfully integrated into a Manufacturing Execution System. The algorithm has been designed to real-time analyze geometrical data, with the aim of ensuring the quality of the finished parts and to identify in advance possible criticalities. However, the methodology is also able to deal with other functionalities of a MES. First, it can be deployed for product traceability: each workpiece is identified with a unique ID number; information concerning each gear, such as the time at which the centering operation occurs and the expected results of the alignment, can be collected and stored into a database. These information can be useful to monitor the results of centering process over time, and identify possible decays or drifts. The algorithm can also be enriched with functionalities for maintenance planning: it can trace the performed recovery operations and the number of workpieces manufactured after the last setup; thus, it can generate alert signals when an intervention (for example, a tool replacement) is almost necessary, in order to best plan the workflow. The monitoring system can also be able to extract indicators such as cycle times, downtimes, production efficiency, reworking and scraps rate, to evaluate the performance of the process; however, a careful analysis of these data is necessary, since the causes of issues identified on the centering machine can be due to inefficiencies in the upstream workstations.

2.4 Integration between MES and PLM

In the previous sections, we introduced the functionalities of PLM and MES, and the benefits that result from their deployment. The two information systems have different functionalities: PLM contains information concerning the to-be product and the production process; conversely, as-built data are stored in the MES. The integration among these two systems allows to create a feedback information mechanism that can enhance the performance of the production process and the quality of the manufactured parts.

When a new product or production process is released, the PLM contains all the information that, according to the project, allow to meet the required specifications. Then the ramp-up phase is run, and a tight monitoring is necessary to detect any difference between the real products and the expected output. A careful analysis of the data collected in this phase is necessary: they can be rich of useful indications to optimize process and product design, allowing to improve the performance of the production process and the quality of the manufactured parts. The deployment of a MES is also useful after the ramp-up phase, when a steady state is reached: a continuous analysis of shop-floor data allows to monitor the behaviour of the process and detect systematic trends, criticalities or deviations. For example, the MES can trace process variability: as machines get aged, the quality of the products can be lower and machined parts may result out of tolerances. The results of such analysis have to be used to identify strategies or practices for performance and quality improvement. These actions lead to redesign or revise some operations: such changes must be integrated into the PLM system, in order to store this experience-driven acquired knowledge, and make it available for the future production. A system for product traceability, based, for example, on RFID tags, would enhance this task: correlations between the state of the process and the quality of the products can be extracted, and the causes that led to a specific kind of issue can be detected. Furthermore, the knowledge collected by the PLM can be shared even among several different plants or with different suppliers; thus, the expertise acquired in one place can be standardized and made available elsewhere.

3 RESULTS AND CONCLUSION

The monitoring and control system described in section 2 has been tested on the machine for automatic centering with a set of spur gears produced in the same lot. In Table 1 the results concerning 12 pieces are synthesized: the automatic centering algorithm provides a result that satisfies the prescribed tolerances for 5 parts; this operation does not lead to acceptable results for three workpieces, but the manual positioning leads to an acceptable configuration. Finally, the positioning of four gears out of twelve is not acceptable neither with the automatic operation nor with the manual one. One of them is affected by a high value for the planarity error of the side surface; thus this feature must be finished again, to reduce the form error before countersinks grinding. The three remaining workpieces exhibit low values for the planarity error, and the non-acceptable centering can be due to form error of the bearing seats or a deformation of workpiece axis: because of this, these three part are rejected.

Table 1. Application of the algorithms integrated into the MES on a sample of 12 spur gears: synthesis of the results.

	1	2	3	4	5	6	7	8	9	10	11	12
Automatic positioning acceptable?	NO	YES	NO	NO	YES	NO	NO	YES	YES	YES	NO	NO
Manual positioning acceptable?	NO		YES	NO		NO	NO				YES	YES
Planarity error	LOW			LOW		HIGH	LOW					

The first advantage expected by the deployment of the monitoring and control system is product quality improvement: sensors allow to detect, measure and monitor variables, events and situations that affect process performance or product quality. Compared to the currently used manual procedure performed at the end of the production process, this continuous quality control permits to reduce the quantity of defective products, wastes and scraps and, in turn, to reduce production costs. The efficacy of the quality control is enhanced by product traceability: in case a product is not in compliance with the specifications, the causes of the defect can be quickly detected in the process and new process knowledge is acquired; this information is then integrated into the PLM system, and is available for further product and process improvement.

The collected data and the results of the analyses can also be employed to plan innovative strategies, make decisions for a better and faster reaction to market changes and to improve the competitiveness of a company: production cost and cycle time can be reduced thanks to defects and product variability lessening, while the productivity and the capacity to manufacture high-quality innovative products can be increased. To this purpose, the integration among different information systems allows a more effective data exchange within and between companies, leading to enhanced company agility and improved quality of transmitted information.

The PLM-MES integration is also helpful to improve process sustainability. The deployment of a monitoring and control system allows to predict the quality of the produced parts, to avoid useless operations, and to focus reworking actions. The reduction of defective products allows to decrease energy consumption and reduce the environmental impact (for example, material usage, water consumption, emission of pollutants). In the near future, actions to enhance sustainability will play a strategic role and provide a competitive advantage. For example, European Union is fostering the reduction of environmental impact through the 20-20-20 program. Further, storing into a PLM the results of the analyses performed by the MES allows to share such knowledge wherever it can be useful, to support people in making aware decisions, and to undertake continuous improvement practices.

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