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Reference architecture for the industrial implementation of Zero-Defect Manufacturing strategies

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Abstract

In recent years, digitalization has enhanced the implementation of more complex architectures for the management and control of manufacturing systems. In particular, Manufacturing Execution Systems (MES) acquired relevance as central software module for the application of advanced Zero-Defect Manufacturing (ZDM) strategies, aiming at achieving improved production quality performance at industrial level. ZDM-strategies ground on the gathering of production and quality data from heterogeneous sources and on their integration with information at multiple factory levels. This paper presents a reference architecture and the related software modules to properly support the implementation of advanced ZDM strategies in complex industrial contexts.

Keywords: Architecture; zero-defect manufacturing; cyber-physical systems.

1. Introduction

Manufacturing companies have recently faced major steps in the digitalization of software architectures for the management and control of manufacturing systems. Already existing management softwares for production such as Enterprise Resource Planning (ERP) softwares have become not enough to constantly monitor, control and improve manufacturing systems. The competitiveness of a company strongly depends on its ability to transform into economic value the core process. As stated in [1], the economic efficiency of modern value creation, and therefore the decisive potential of companies, has to be found in the process capability, rather than in the production capability. Therefore, the ability of timely deliver the required quantity with the required quality, keeping the usage of resources at the minimum level, requires an in-depth knowledge of the operating manufacturing system, which can be achieved by constantly gathering information and understanding the behavior in order to apply the most effective control strategies [2].

In recent years, Manufacturing Execution Systems (MES) has gathered attention as key software platform to implement advanced control strategies, especially dealing with real-time control [3]. Moreover, the tight coupling between digital and physical world that has become a promising research and industrial topic has enhanced the relevance of understanding the system architecture needed to implement such solutions [4, 5, 6].

Especially when it comes to production quality, information at different levels of the factory should be available in order to develop integrated control solutions. Therefore, MES acquired relevance as central software module for the application of advanced Zero-Defect Manufacturing (ZDM) solutions, going beyond traditional data mining approaches [7], but they still require a standardized approach for it.

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In the following, a brief explanation of the main aspects characterizing the ZDM paradigm is provided; the proposed reference architecture for ZDM strategies is described in details together with the included software modules; then, a EU-funded project is presented as reference case study to show the applicability of such architecture dedicated to ZDM solutions; finally, the main contributions of this work and future research are summarized in the conclusive Section.

1.1. Zero-Defect Manufacturing (ZDM) paradigm

The implementation of MES has enhanced the control of manufacturing systems for production quality. However, MES allows even more advanced ZDM solutions than the traditional quality-oriented approaches. The main limitations that can be overcome by the ZDM paradigm are the following ones.

- Traditional production and quality control tools mainly rely on statistical analysis of historical quality data based on product dimensional features. They are not suitable for small lot productions and complex patterns monitoring and control as they do not consider additional information on machine states and process variables along production stages and among product types for a more responsive quality control system.
- New sensor technologies have enabled large variety of data to be gathered real-time in production lines, during the process execution at extremely high acquisition rate. The challenge of synthetizing such heterogeneous, multi-source signals for proactive process control purposes calls for suitable data gathering and integration solutions.
- Traditional methods mainly provide quality monitoring functionalities, with few potential for proactive parameters' adjustment and control. Solutions to proactively avoid the generation of defect require a multi-level integrated software architecture.
- Knowledge-based approaches to support humans in the understanding of complex root-cause dynamics are not developed and the error budgeting process is still mainly driven by human experience, especially because the information gathering process is difficult due to spread data storage modules.
- Current practices do not provide solutions for repairing defective items on-line by proper corrections at downstream processes, but scrap and off-line rework are still the only adopted practices once the defect has been generated.
- Currently adopted quality control strategies are mainly single stage strategies, i.e. they do not consider the impact of quality monitoring actions on the economic, logistics and quality performance of the multi-stage systems in which they are applied. This makes the dynamic adjustment of multi-stage systems production targets, and the consequent re-organization of the quality control system, not applicable in the current scenario.

All these major points clearly show that a suitable control architecture integrating the correct software modules allows the integration of information coming from different sources at different levels of the factory and therefore enhancing both feedback and feedforward control strategies for zero-defect manufacturing.

2. Overview of the reference architecture

In the previous Section, the reasons why MES have become central in the operations and control of manufacturing systems have been explained. In addition, the ZDM paradigm has been presented with respect to the requirements for integrated software solutions at factory level.

In the following, the proposed reference architecture is presented in details. The reference architecture is shown in Figure 1. The reference architecture has been modeled within the deployment formalization mode used in systems architecture. The colored flat boxes indicate many competence areas existing in a manufacturing company. The solid yellow boxes, namely '*device*', within the areas represent the different softwares that the company uses in order to run its business. The solid blue boxes, namely '*execution environment*', indicate the software modules that are proposed in the reference architecture in order to address the required functionalities. Dashed arrows represent information flows among areas or softwares, while the straight line represents execution and control actuating capabilities. The violet-colored areas indicates the main management softwares that companies usually have: Product Lifecycle Management (PLM), where nominal information about the product such as CAD files, Bill of Materials (BOM), Production Cycles (CAM) are contained; Enterprise Resource Planning (ERP), where information about incoming materials from suppliers and outgoing products to customers are usually managed; Manufacturing Execution System (MES), where operations at shop-floor level are actually managed. Within the shop-floor area, the three main sources of data and information are represented, i.e. process machines, inspection machines and operators. These icons represent the placeholder for physical shop-floor machines with connectivity to field level sensors and actuators. The light-pink area named Data Intelligence shows the proposed architecture, to be integrated with the existing architecture, aiming at developing and implementing ZDM strategies.

2.1. The role of the MES

The central role of the MES is highlighted by the fact that the only way to actually control the manufacturing system is through the MES. In fact, the real-time data gathered through the multi-source multi-sensor network are analysed and used to build process-level and system-level models to design ZDM strategies that are returned to the MES as control

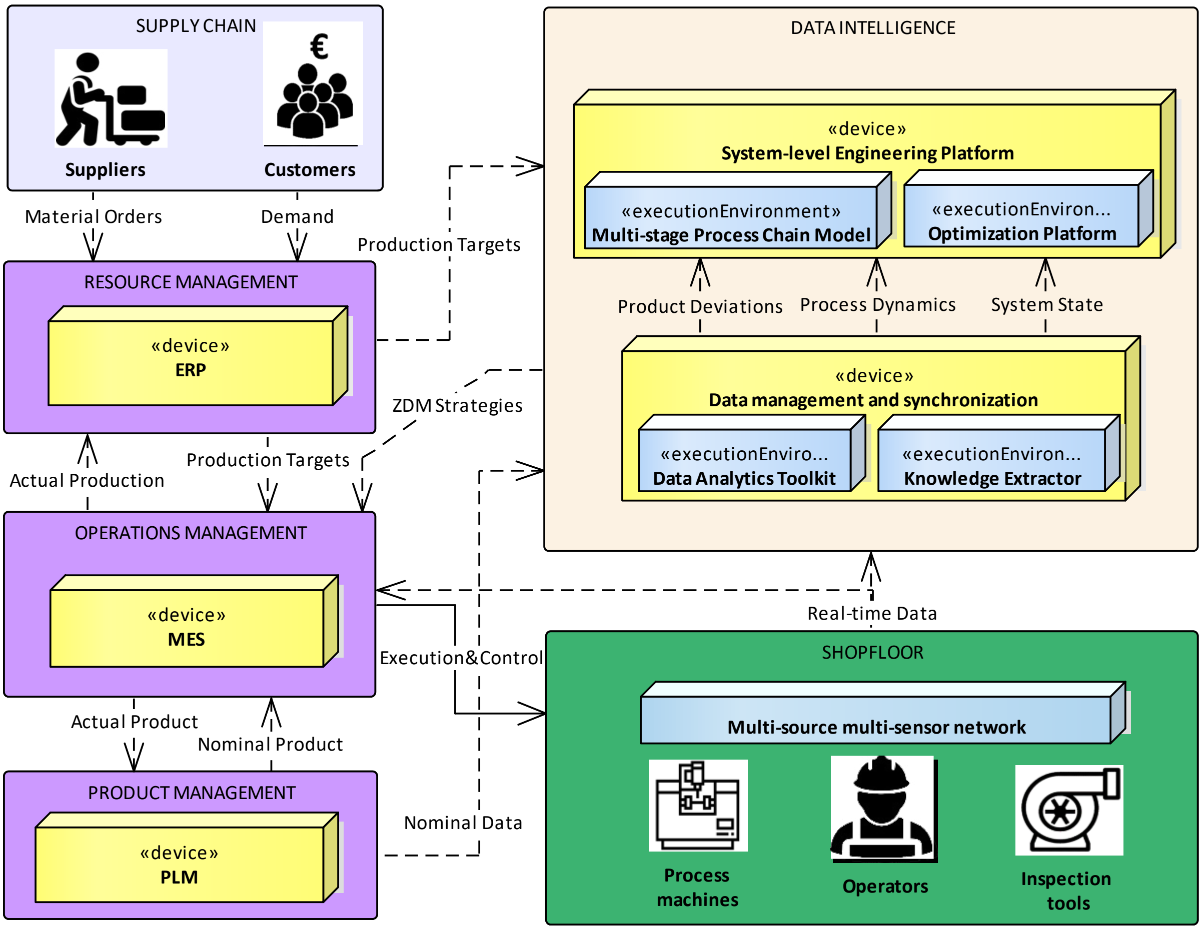

Fig. 1. Reference architecture and software modules for ZDM strategies, with information flows (dashed arrows) and actuating controls (straight arrows).

strategies to be actuated at plant level. Moreover, the MES is usually the software that takes as input the nominal production plan from the ERP system and the nominal CAD/CAM files in order to execute the production. Then, through the MES feedbacks are gathered and returned to the other softwares: the actual production, and eventual backlog quantity is returned to the ERP; possible feedbacks about the production cycle and the product quality are gathered on the shop-floor to be provided to the PLM and to the R&D department in general.

Therefore, a proper implementation and application of a MES software allows a company to better manage the information flow from and to the shopfloor, and hence to improve the productivity. However, at the same time, advanced tools are needed to develop and implement advanced quality-oriented strategies. In fact, existing systems dedicated to quality rarely consider system-level quality, especially because of the lack of information integration from different sources and proper supporting modelling tools. This means that current implemented architectures lack the Data Intelligence module shown in Fig. 1, as well as clear information flows between PLM and MES, and ERP and MES, which guarantee the integration of nominal and actual data related to products, materials, and processes.

The goal of the following Sections is to propose a reference architecture capable to be integrated within the existing systems, in particular the MES, which has the aim of allowing the implementation of advanced ZDM strategies, answering to the open gaps explained previously in Section 1.

2.2. Requirements

Even though the presented architecture is meant to introduce advanced software solutions for digitalization of companies, some requirements are needed to be explicitly considered when dealing with the design and implementation. In fact, in order to be able to integrate information coming from different sources at different levels and using it, a manufacturing company should have reached already a certain degree of digitalization which includes the following main points:

- Part tracking system: the part tracking system monitors the status of the parts on the shop-floor, i.e. what has been the last operation a part has gone through, if it had been reworked or inspected, together with other information about the production order, such as the customer, the due-date, the lot.
- Machine state monitoring: machine states can be usually defined at least as operational, failed, waiting. The machine states are traditionally used to define the main production KPIs with respect to the machine availability.

2.3. First layer: Multi-source multi-sensor network

The first architecture layer is used to gather data from the shop-floor. The main hardware solution for this layer is a multi-source multi-sensor network. In fact, data may come from different sources and different types of sensors might be needed for the data gathering. Especially, the main source of production data are:

- Process machines
- Inspection machines
- Operators

Process machines provide information about the machine states, i.e. if the machine is working, with which cycle time, and in case it is failed, which failure mode has occurred. This set of data is particularly relevant when process models are going to be implemented or if any critical process variable has been identified as meaningful to be monitored.

Inspection machines provide information about the part status. In particular, inspection machines represent the main source of information about quality, since they provide product measurements for given stages.

Operators detain the actual knowledge about the shop-floor, therefore feedbacks provided by them represent key information. The challenge in this case consists of how to gather feedbacks from the operators. Therefore, an in-depth analysis of the mechanisms occurring at shop-floor level is needed. For instance, operators might be able to change instructions in the process machines. Hence, if this process change is not captured, analysis about the process might be completely wrong.

2.4. Second layer: Data management and synchronization

The platform allows to collect, synchronize, monitor and store data gathered from the distributed heterogeneous, multi-resolution and multi-scale data sources from the first layer. The different data sources can be connected by developing appropriate interfaces (wrappers), using OPC-UA and XMPP protocols. Afterwards, the heterogeneous data acquired can be contextualized by gathering raw materials and product flow information from existing end users' PLM and ERP platforms. A set of rules and a common abstract information structure on infrastructure level can be defined for ensuring a smooth acquisition and integration of different information flows into the platform.

This data management system includes at least two different software toolkit:

- The Data Analytics Toolkit includes methods for significant correlation identification, root cause analysis and for product variation propagation modeling throughout the stages of the system.
- The Knowledge Extractor integrates the data analysis in order to model the system dynamics at process level, so that models can be built. These models take in input the specific incoming critical product characteristics, the process conditions, and provide in output estimates of the critical product characteristics obtained by the modelled process. Moreover, at product level defect and workpiece quality propagation and accumulation mechanisms can be identified and applied to modelling of the application domains. The Knowledge Extractor provides a systematic approach to identify similarities among products and processes, so that small lots of similar products can be managed by the same – or adapted – strategies.

2.5. Third layer: System-level Engineering Platform

The objective of this layer is the design, development, implementation and testing of a system engineering platform to optimize the joint quality and production logistics control policies to be implemented at shop floor level that integrates quality, production efficiency and economical aspects into a unique framework and analyzes the global coherence and economic feasibility of the decisions taken at local level. The platform is based on a process-chain modeling and analysis tool that jointly considers the dynamics of the material flow in the system as well as the product variation propagation throughout the process stages, also integrating the relevant correlations between process variables, machine states and product quality characteristics identified in the previous layer. The main modules included in this software are:

- Multi-stage Process Chain Model: this module aims at developing an integrated model of the whole system by state composition techniques through a modular approach, able to capture the dynamics of the workpiece flow in the multi-stage process chain. Moreover, a performance analysis tool, based on analytical methods and simulation, should be included to predict the integrated quality, logistics and economics performance measures of the system.
- Optimization Platform: this optimization engine is integrated with the Multi-stage Process Chain Model in order to use it as a kernel to be iteratively called so to optimize defect-avoidance policies and other ZDM strategies, as they will be explained in details later. The Optimization Platform is based on multi-objective optimization methods in order to address alternative KPIs existing in the company, such logistics (lead time, delivery date, etc.), economics (cost, etc.) and quality (yield, good throughput, scraps, etc.).

3. Multi-level control strategies for ZDM

In this Section, multi-level control strategies for Zero-Defect Manufacturing are explained, by using as reference an ongoing European project, ForZDM. The goal of the ForZDM project is the development, implementation and demonstration of next generation ZDM strategies capable of dynamically achieving production control solutions for multi-stage manufacturing systems [8]. The ForZDM project, funded by the European Union as part of the Horizon

2020 cluster, deals with use-cases coming from high-value complex-part production, i.e. jet engines shafts, medical micro-catheters, and railway axles. Within the international project, a generic architecture is to be developed that covers the entire spectrum of a global zero-defect manufacturing system, from sensor development, via centralized data acquisition, data analysis using statistical methods and artificial intelligence, to proactive control interventions in the actual manufacturing process.

In the past, the focus was on the optimization of individual and separate processes using static process control systems. However, even after the optimization of a single production process, there is still the possibility of defect generation in the form of deviations propagating and superimposing over several process steps. Therefore, it is of key importance the modeling and optimization at system-level of defect-avoidance policies which can be translated to short-term real-time control strategies. In fact, on the one hand the long-term performance and competitiveness of the company should be kept, on the other hand, monitoring and control strategies for the day by day operations should be effectively aligned to the long-term strategy.

Figure 2 shows the architecture that has been being implemented within the ForZDM project. The characteristic multi-layer structure can be noticed, starting from the shopfloor where the multi-source multi-sensor network gathers information, up to the data management platform and to the system-level engineering and optimization platform. Arrows highlight the information and data flow coming from different sources such as the ERP.

In the following, the implemented ZDM strategies are explained. These ZDM strategies aim at having an impact on multiple levels.

3.1. Low-level control loop

This level includes a CPS to implement defect generation prevention strategies to adjust the process parameters before the process to prevent the occurrence of defects, on an item-to-item basis. Firstly, an advanced process monitoring tool has been developed for critical process stages to identify process and machine degradation patterns by cross-correlating process and resource related variables with product quality measurements at the same stage [9]. Secondly, in order to adapt current process conditions to the specific quality characteristics of the product under treatment and to the specific condition of the process, a new CPS has been designed. Taking in input the workpiece related information collected at the upstream correlated stages and available in the ForZDM database and the conditions of the critical process, this model-based CPS will estimate and predict the risk of generating a defect in the downstream process and, in case of high risk, a process adaptation policy will be implemented [10]. The system investigates stable process parameter and fixture conditions using the meta-models developed and adjusts process settings to prevent the risk of defects. With this smart system, the current process will be tailored and adapted to the part under treatment, thus proactively avoiding the generation of the defect.

3.2. Medium-level control loop

At medium level, the control strategies focus on evaluating a set of technically feasible defect compensation policies which can be applied after the occurrence of defects, which involve corrective actions undertaken (i) within the same process or (ii) in one/many downstream correlated stages. In-line rework strategies (i), are explored and evaluated considering the KPIs and the propagation models

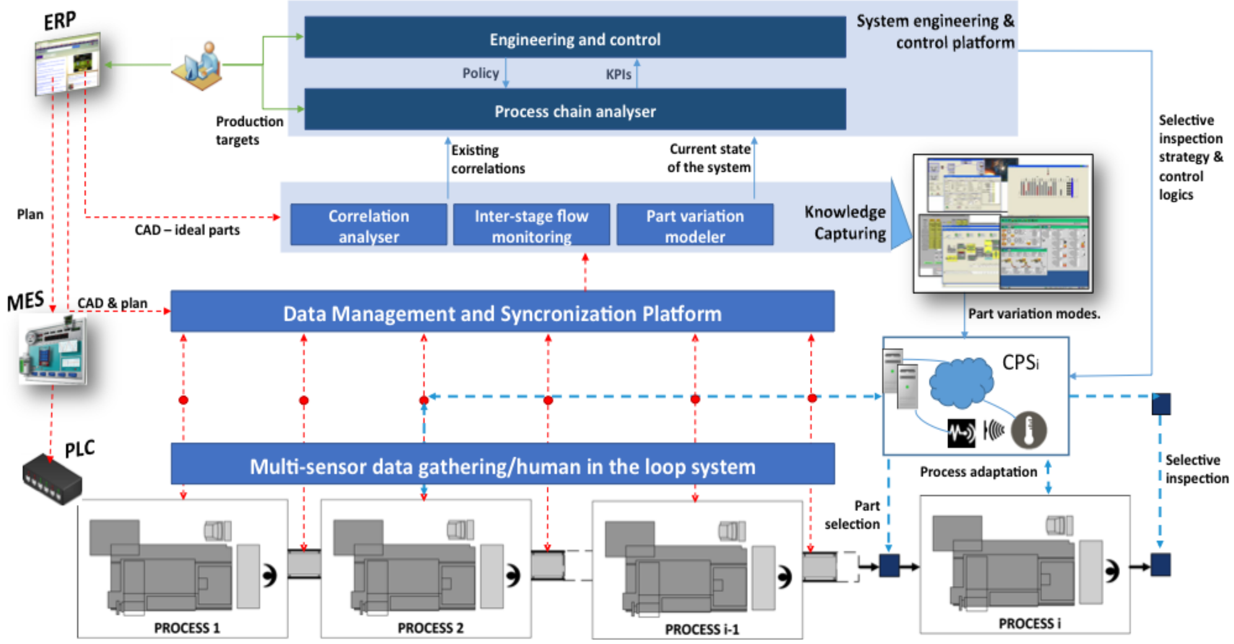

Fig. 2. Architecture for ZDM strategies in the ForZDM project.

developed within the Data Management and Synchronization platform [11], which will provide the means for evaluating and optimizing rework procedures. The expected output is the selection of a set of technically feasible rework solutions at different stages and the preliminary design of the rework procedure complying with the technical requirements. The final selection among available technically feasible rework strategies will be done within the system-level engineering platform by verifying the joint quality and logistics performance at system level. Moreover, feasible CPSs for defect compensation at downstream correlated stages (ii) are identified based on the Data Analytics Tool and evaluated in terms of applicability and impact (KPI) on the project use cases [12]. For the selected candidate strategies, specific algorithms and control policies to enable the defect compensation are designed, and the expected benefits of these solutions are evaluated by simulation. The best candidate compensation solution(s) are implemented in a dedicated software tool.

3.3. High-level control loop

The developed System-level Engineering Platform considers in input the processing times of each stage, the complex stage correlations identified at medium level, the state-based stage models, the inspection time and frequency, the size of the inter-stage buffers/kanbans in the system, the system configuration, the main operational costs of the system, and will calculate in output the distributions of the effective throughput of conforming parts, the system yield, the average inventory, and the lead time as well as the service level of conforming products, once fixed a specific lot size and due date. This digital performance prediction platform is used as a kernel throughout ForZDM to check the quality/logistics feasibility and the economic benefits of the zero defect propagation solutions formulated at medium level. Together with the Optimization Engine, for each defect type, the impact of different defect management policies on the system's effective production rate is evaluated, deriving the optimal combination of defect management policies defined at medium level at different stages. For instance, the selective inspection policy at each inspection point will be optimized at system level to find the best trade-off between inspection time and effective production rate, to reduce system's inspection effort.

4. Conclusion

This work has introduced a reference architecture for implementing ZDM strategies in digitalized companies that use already the MES as core software for the operations management. The presented architecture is shown in terms of software modules and integration with other company management systems. The reference architecture has been implemented in a European project, where the ZDM strategies are explained and highlighted, showing the benefits of applying such approach even in complex manufacturing environments dealing with high value-added parts.

However, the proposed research is only a first step towards the industrial implementation of ZDM-oriented architecture. In fact, the presented architecture represents a major change for companies. One of the main challenge remains still the ramp-up period in which the actions are implemented. The rapidity and the right sequence of actions with which companies can reach a steady use and fast adaptation of the ZDM strategies to the always changing context represent a major challenge for future researchers.

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