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Design and management of manufacturing systems for production quality

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ABSTRACT

Manufacturing companies are continuously facing the challenge of operating their manufacturing processes and systems in order to deliver the required production rates of high quality products, while minimizing the use of resources. *Production quality* is proposed in this paper as a new paradigm aiming at going beyond traditional six-sigma approaches. This new paradigm is extremely relevant in technology intensive and emerging strategic manufacturing sectors, such as aeronautics, automotive, energy, medical technology, micro-manufacturing, electronics and mechatronics. Traditional six-sigma techniques show strong limitations in highly changeable production contexts, characterized by small batch productions, customized, or even one-of-a-kind products, and in-line product inspections. Innovative and integrated quality, production logistics and maintenance design, management and control methods as well as advanced technological enablers have a key role to achieve the overall *production quality* goal. This paper revises problems, methods and tools to support this paradigm and highlights the main challenges and opportunities for manufacturing industries in this context.

1. Introduction, motivation and objectives

Product quality and delivery reliability are key factors for success in the manufacturing industry. Moreover, the increasing emphasis on sustainable production requires maintaining the resource efficiency and effectiveness along the product, process and production system life cycle [274]. Quality, production planning and maintenance are fundamental functions for achieving these goals. They have been widely analysed in the literature over the past several decades. The production planning field has developed methods for reducing work in progress (WIP), while meeting desired production rate levels. The Statistical Quality Control (SQC) field has introduced optimized tools for monitoring the behaviour of processes to achieve the desired product quality. The Maintenance Management field has derived policies for preserving the efficiency of degrading resources over time by offering pro-active and predictive capabilities [112]. Traditionally, all these fields have been treated by scientists and industrialists almost in isolation. Yet it is clear that equipment availability, product quality and system productivity are strongly interrelated. As a matter of fact, quality, maintenance and production planning strongly interact and jointly determine those aspects of a company's success that are related to *production quality*, i.e. the company's ability to timely deliver the desired quantities of products that are conforming to the customer expectations, while keeping resource utilization to a minimum level.

For example, low WIP improves the ability of identifying quality problems in the system at an earlier stage but at the same time makes maintenance actions more critical to the system. More inspections make it possible to better assess the degradation state of the resources yet also increase the system lead-time. Frequent maintenance of resources tends to improve part quality, but reduces the operational time of the machines in the system, which affects the overall production.

It is clear, then, that the mutual relations among quality, production planning and maintenance control should not be underestimated while configuring and managing the manufacturing system as a whole. Important practical questions, such as "Which is the expected system effective production rate if the time to preventive maintenance of one machine is reduced?" and "Which is the effect of increasing the inspection frequency of one product feature on the overall production yield of the system?" remain unsolved. This lack of understanding results in sub-performing unbalanced systemic solutions that tend to privilege one of the aspects while penalizing the overall manufacturing system efficiency.

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The key questions that this paper addresses can be formulated as follows: "Which are the main industrial problems related to the achievement of *production quality* targets?" "Which tools can support the joint consideration of quality, production logistics and resource maintenance in manufacturing system design and operation?" and "Which are the main technical achievements and insights brought by the use of these tools in industry?"

Recently, several production paradigms have been proposed that are strongly related to and have an impact on *production quality*. These paradigms have considerably reshaped the boundaries within which the three aspects interact. Reconfigurability [134], flexibility [278], changeability [309] and co-evolution [280] stress the importance of aiming at a strong coordination between the dynamics of the system life cycle and the dynamics of the product and process life cycles. Takata et al. [274] introduce the notion of "life cycle maintenance" to be in phase with such requirements. Yet, if a system evolves with faster and faster dynamics, new challenges arise for *production quality*. In particular, the long-term performance of the system becomes less important, while *production quality* performance during system ramp-up assumes fundamental relevance [86]. Moreover, small-lot production becomes more frequent than mass production. Therefore, a new *production quality* paradigm is needed for mass customization [60] and mass personalization [282], for open architecture products [135] and for high product variety manufacturing [79]. Available concepts and programmes, such as Six-Sigma, Just In Time, Continuous Improvement, Total Quality Management, Toyota Production System and World Class Manufacturing, are not designed for such dynamically changing contexts. A new integrated concept of *production quality* needs to be developed to meet this aim.

Another industrial trend that has been recently investigated and framed [81] is the increase of the *complexity* of manufacturing systems, in terms of hardware, software and management rules. Complexity strongly undermines the achievement of the desired *production quality* performance. Complex systems are typically characterized by alternative process plans [208], multiple parallel resources, part type dependent routings, and late variant differentiation [102]. The resulting challenge lies in the additional burden placed on diagnosis, root-cause analysis, and error budgeting.

In response to these innovative aspects of manufacturing systems, multiple in-line technologies for data gathering and performance monitoring have emerged. A considerable amount of data is typically made available on modern shop floors by multi-sensor technologies [304]. However, most of the time this information is treated only locally and is not spread among different company functions nor among partners within a production network. For example, it is not infrequent for a quality management department to ignore the reliability statistics of the machines on the shop floor [152]. This behaviour makes it hard to correlate disruptive phenomena taking place at shop floor level with the product quality and to gather insights in the behaviour of the system as a whole. It would be necessary to move from isolated engineering practices to more integrated ones such as advocated by System Engineering initiative [105]. Therefore, these data are not fully exploited and translated into a business competitive advantage for the company.

The impact of complexity on *production quality* is even more significant when considering the production network level. For example, except for the period of the deep economic crisis 2009–2010, the number of recalls has been constantly increasing also due the lack of inter-organizational quality systems [61]. Product recalls indicate that manufacturing companies are particularly vulnerable to ensure quality when they source via a global supply chain with poor visibility [164]. Global automotive warranties are estimated at USD 40 billion per year, i.e. a 3–5% loss in sales [89]. Low priced production often leads to quality problems, and outsourcing leads to a shift in knowledge concerning techniques and processes. Thus, technical failures are more likely to occur due to communication failures among the different parties engaged in the supply chain and to missing definitions for technical interfaces. Since most of the flaws that eventually cause failures are introduced in the production phase, early failure analysis can avert high recall costs and loss of image.

Legislation that limits industrial waste production, increases target product recyclability rates and places the manufacturer at the centre of the end-of-life treatment process through the Extended Product Responsibility (EPR) principle is an additional driver that strongly influences the *production quality* paradigm by penalizing the generation of defects and waste in manufacturing. Moreover, sustainability issues related to energy efficient production [76] have to be taken into account while designing and operating the system as a whole for a desired output *production quality*-related performance target.

To promote intense and coordinated research activities aimed at developing innovative technological and methodological solutions to the aforementioned challenges, industrial organization and funding bodies have recently launched several actions. For example, at European level, the Factories of the Future (FoF) Public Private Partnership has included the topic "Zero Defect Manufacturing" as a priority in its FoF 2020 Roadmap. Moreover, under the FP7 call on "Zero Defect Manufacturing" four projects have been funded boosting cross-sectorial research and aiming at achieving the largest possible target impact for the developed technologies. These activities share the objective of supporting the development of a knowledge-based manufacturing and quality control culture within the EU. Similar activities have also been promoted in the USA within the Advanced Manufacturing Partnership (AMP).

This paper provides an overview and a framework of the industrial practices, scientific methodologies, and enabling technologies to profitably manage the *production quality* targets in advanced manufacturing industries. It also identifies key open research and practical issues that need to be addressed by the research community. The paper is structured as follows: the next paragraph presents a set of real cases that demonstrate the industrial motivation to the problem. Section 2 proposes a new system dynamics model for highlighting the relevant quality, maintenance and production logistics interactions. Sections 3 and 4 discuss, respectively, the state-of-the art methods and tools and the enabling technologies supporting the *production quality* paradigm. Finally, Section 5 describes the most promising future research topics in this area.

1.1. Industrial motivation

In order to highlight the main practical implications related to the interactions among quality, production logistics and maintenance and to point out how these challenges are currently tackled by companies, a comprehensive set of real industrial examples have been collected. These case studies have been gathered by analysing existing publications, running industrial projects, both publically and privately funded, and by gathering authors expertise. They include both traditional production sectors such as the automotive and electronics sector and emerging sectors of certain interest for the worldwide manufacturing context, including the production of medical devices as well as the green energy production industry. Moreover, they include a reasonably wide spectrum of manufacturing processes, such as machining, assembly and forming, at both macro and micro scales, and on both metallic and non-metallic workpieces.

The industrial cases support the following considerations:

- The interaction among quality, production logistics and maintenance aspects is a complex issue to be managed.
- This problem involves different companies and different departments within each company. The coordination and cooperation among them in achieving a right balance between these conflicting goals is seen as a key issue for success.
- Depending on the specific product and market context, companies tend to prioritize one of the aspects. Finding the right balance boosts the long-term company profitability.