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ScienceDirect

Procedia CIRP 104 (2021) 1351–1354

www.elsevier.com/locate/procedia

54th CIRP Conference on Manufacturing Systems

Digitally Enhanced Quality Management for Zero Defect Manufacturing

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Abstract

Though the idea of Zero Defect Manufacturing is not new, it remains a disruptive concept that is able to entirely reshape the manufacturing ideology. Existing literature suggests that Zero Defect Manufacturing can be implemented in two different approaches – namely product- (defective parts) and / or process-oriented (defective equipment) approaches. The recent onset of Industry 4.0 presents organizations with a plethora of technologies that promise to further enhance the quality of both products and processes, but also adds a third dimension to Zero Defect Manufacturing - people. Therefore, in this paper, we add the people-oriented approach as a third dimension to Zero Defect Manufacturing and draw on practical insights to present a framework for digitally enhanced quality management.

Keywords: Zero Defect Manufacturing, Quality Management, Predictive Maintenance, Industry 4.0, Digitalization

1. Introduction

Quality management has been an important element of manufacturing systems for decades. In the 1940s, W. Edwards Deming convinced Japanese industrial leaders that quality was the key to market domination [1]. This message resonated well with one company in particular, Toyota, which was already at that time experimenting with "built-in-quality" concepts such as *Jidoka* (automation with a human touch) and the *Andon* system of stop-and-call at every defect. Later, in the 1960s, the concept of Zero Defect Manufacturing first began to emerge as a quality and reliability program in the U.S. [2,3]. This was quickly followed by the development of the Taguchi methods in the 1970s, and Six Sigma (at Motorola) in the 1980s. In the 1990s and 2000s, Lean Manufacturing and Total Quality Management (TQM) were high on the agenda of most executives and top managers. [4] presents a detailed overview of the alternative philosophies to quality management, including lean, six sigma, and lean six sigma. The authors also suggest that ZDM is becoming more and more enabled thanks to technological improvements (p. 13).

For example, with the onset of sensor technology and the Industrial Internet of Things (IIoT), in the 2010s came the potential for a new wave of digitally enhanced quality management and the concept of ZDM again gained traction on the quality management agenda. Emerging key enabling technologies, such as in-line data gathering solutions, data storage and communication standards, data analytics tools and digital manufacturing technologies offer new opportunities for ZDM [5], such that organizations are now able to move closer to achieving their vision of Zero Defects.

In this paper, we present practical insights on various approaches to ZDM. In the literature, there is a clear distinction between product-based (defects on the actual parts) and process-based (defects of the manufacturing equipment) approaches [6]. However, the role of people – the most important aspect of a manufacturing system – is often largely neglected, under-researched and should be explored further [7]. Manufacturing quality is significantly influenced

10.1016/j.procir.2021.11.227

by people. Therefore, we introduce a third, people-based approach. We suggest that although effective countermeasures can be introduced for the *compensation* of product defects and the *correction* of process defects, organizations must simultaneously prioritize the *cultivation* of its human resources – continuously improving quality through the development of human capital. For example, [8] suggests that the continuous training of operators will improve the efficiency of production processes and the ability of operators to act quickly to solve quality problems.

2. Theoretical background

In this section we present a short overview of relevant themes in Zero Defect Manufacturing (ZDM) from the scientific literature, covering the fields of lean production, quality management, and digitalization. [9] suggests that ZDM consists of four strategies*: detection, repair, prediction,* and *prevention*.

Not surprisingly, similar key areas appear in the Digital Lean Manufacturing (DLM) domain, where [10] presents DLM as an approach that "builds on new data acquisition, data integration, data processing and data visualization capabilities to create different descriptive, predictive, and prescriptive analytics applications to *detect, fix [repair], predict* and *prevent* unstable process parameters and/or avoid quality issues […] that may lead to waste within the cyber- and physical worlds".

These four strategies should not be considered as completely discrete and as such, must be interconnected to successfully implement ZDM. The following sections provide overall descriptions of each strategy.

2.1. Detection

Jidoka (automation with a human touch) is a specific system in a machine that can automatically stop the machine by deploying a simple mechanism upon the detection of an abnormality. It was first pioneered in Sakichi Toyoda's Type-G Automatic Loom in the 1920s. [11] suggests that the emergence of Industry 4.0 technologies (e.g. IIoT, CPS, etc.) has given rise to the concept of *Jidoka 4.0*, characterizing shopfloors with software and hardware components such as sensors, actuators, controllers and advanced analytics solutions which provide the capabilities to detect and diagnose quality problems, often before they occur.

Visual inspection by humans or indeed complex vision systems can be also be used to identify defects in raw materials pre-process, as well as for monitoring in-process work pieces and post-process finished goods [8]. Virtual metrology has also been identified as a detection mechanism [12].

2.2. Repair

In hindsight, to identify *repair* as a ZDM strategy is somewhat bizarre, as producing defects and carrying out rework is waste (or *muda* in the lean jargon). In a literature review of ZDM, [7] discovers that few industries are in fact utilizing a repair strategy for ZDM – as many defects may in fact be non-repairable (i.e. expensive beyond repair). However, it does appear that technological advances may enable a certain amount of compensation for defective products through intelligent feed-forward mechanisms in the process chain – contributing toward an overall ZDM strategy.

2.3. Prediction

The concept of prediction is a much more modern phenomenon than detection. However, [7] reports that the prediction strategy is currently underutilized, because defining accurate prediction models is a very difficult and complex task that requires a vast amount of accurate data However, data mining approaches can be used for the prediction or virtual detection of quality defects in ZDM [13].

2.4. Prevention

The prevention strategy is a complex process and requires multiple inputs from different sources in order to be effective [7]. Technological approaches based on the selection, installation and integration of sensors, deep learning, AI, and control system algorithms aim at providing a reliable solution for defect prevention in ZDM, including failure pattern recognition, prediction of manufacturing trends and optimization of machine parameters.

2.5. Theoretical Summary

To summarize, [7] suggests that *detection* is currently the hottest topic within ZDM. However, when implemented effectively, *prediction* and *prevention* strategies can enable manufacturers to avoid the production of defective parts before the occurrence, rather than having to face repairing products upon detection of the defect. As such, prediction and prevention are expected to increase in popularity in the coming years – given advances in machine learning and artificial intelligence (AI).

3. Digitally enhanced quality management

The teachings of Deming placed great emphasis on his system of profound knowledge, composed of four, integral parts [14]:

1. Appreciation for a system
2. Knowledge of variation
3. Theory of knowledge
4. Psychology

Though recent advancements in ZDM theory build on previous quality management approaches such as TQM and indeed Six Sigma (with its core focus on eliminating variation in processes), as well as a strong grasp of a theory of knowledge around quality control, an overall appreciation for the system is in general lacking, and a specific understanding of psychology and people development seems to be absent. For example, many ZDM applications focus only on individual production processes within otherwise vast multi-stage production systems [5], and there is an inherent lack of focus on people – the most important element in a manufacturing system.

Thus, in addition to the correction of defective processes and the eventual downstream compensation for defective products, we present cultivation of human resources as a third important policy of ZDM. Furthermore, we suggest that correction, compensation, and cultivation are essential for understanding the ZDM strategy, and present them as the three Cs of ZDM. In the following sections, we illustrate each of these policies using practical insights from retrospective industrial use cases.

3.1. Correction

[6] presents a framework called intelligent fault diagnosis and prognosis systems (IFDAPS) for manufacturing systems, which gathers sensor data from the equipment and uses signal processing for fault diagnosis and failure prognosis, plant optimization and feedback control. The principal functions performed by IFDAPS are as follows:

- Continuous collection of data from different sensors, including status of equipment, processes, and products.
- Continuous processing of the data collected to evaluate the condition of the equipment and processes.
- According to previous data collection, the condition or the fault can be identified.
- According to the condition of the component or machine, the remaining useful life or possible faults can be predicted.
- According to the results of diagnosis and prognosis, operation and plan can be optimized by intelligent optimization algorithm.
- The performance indicators and results can be used for self-adjustment of the control system to correct the causes of faults, enabling near zero defect level of manufacturing.

3.2. Compensation

ZDM strategies for multi-stage production systems require the knowledge of existing complex correlations from different parameters. [15] introduces a Knowledge Capturing Platform (KCP) that aims at realizing ZDM and faces the rising challenges in multi-stage production systems for achieving an efficient fabrication of high-quality products. Using the KCP, the authors suggest that the causes of defects and their propagation paths can be identified, hence downstream compensation measures can be executed.

By identifying complex relations between measurement series independent of their scale and location, it is possible to make use of pre-determined inter-stage correlations for downstream compensation strategies. As such, advanced monitoring systems can be used to detect critical process conditions and deploy countermeasures before defects on the part or damage to the machine can occur.

3.3. Cultivation

Augmented reality promises to enhance the learning of operators in smart factories. For example, [16] presents AR as a tool for realizing pick-by-vision in an order picking process, where zero defects is an important goal, and [17] suggests that AR is a superior method for training assembly operators. However, human-centered automation is defined as automation designed to work cooperatively with human operators in pursuit of stated objectives [18]. This suggests that AR solutions would need to be integrated with AI solutions in smart factories and ZDM strategies.

Regarding modern ZDM solutions, such automation must be capable of facilitating the mutual learning of humans and machines. For example, [19] presents a system which combines the augmented worker (wearing an augmented reality (AR) connected headset) with shopfloor AI to better support the goals of ZDM. The intention of such a system is to improve the level of predictive and prescriptive decision support in the smart manufacturing system. The authors describe the major goals of the system as supporting operators with decision making and supporting operators with taking action (e.g., maintenance, machine setups, etc.). Importantly, the authors include actions in which the operator and the system collaborate *cyber-physically*.

3.4. Framework for digitally enhanced quality management

For effective implementation of ZDM, we suggest that the ZDM strategies for prediction and prevention should be prioritized over strategies for detection and repair, as illustrated in our framework for digitally enhanced quality management (Fig. 1). Identifying triggering factors and action areas for defect prevention and continuous improvement are essential for eliminating defects and repair / rework as a waste within the lean manufacturing philosophy [4]. Our framework does however illustrate the important links between detection (and repair), prediction, and prevention in ZDM, with correction, compensation, and cultivation policies at the core. For example, any repair actions should consist of correction of the product and / or process parameters, compensation of the subsequent process parameters to account for any defective parts in the process, and ultimately cultivation actions which emerge as learning opportunities for operators and engineers to prevent future occurrences of this failure mode.

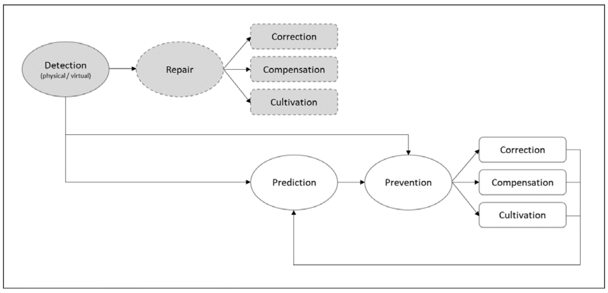

Fig. 1. Framework for digitally enhanced quality management (adapted from [7]).

As such, data and knowledge / insights from the failure modes encountered in the detect and repair phases should be stored and referenced for the prediction and prevention strategy subset of ZDM. Through data mining and semantic coding, defect propagation can be predicted early on, triggering correction, compensation, and cultivation actions to permanently prevent known defects from occurring.

4. Conclusion and Further Work

The goal of ZDM is to eliminate defects and therefore achieve higher efficiency, greater eco-friendliness and lower production costs [9]. Through an analysis of the current literature on ZDM, we identified four core strategies (Detection, Repair, Prediction, and Prevention) and three policies (Correction, Compensation, and Cultivation) for moving manufacturing companies nearer to a vision of zero defects in the digital era. We also provide valuable practical insights into such ZDM strategies and policies.

We suggest that to advance to field of ZDM, further work should adopt a greater focus on the role of the human in smart factories. [20] indicates that to realize the effects of industry 4.0, for example better quality, lower cost and shorter lead times, digital technology capabilities must be combined with human capabilities. As such, gaining a better grasp of the manufacturing system as a system rather than a collection of discrete processes is essential, as well as gaining a deeper understanding of the how key enabling technologies can be used to support and develop human capital. Afterall, "*Incorporating human learning gives automation its human touch*" [11].

Acknowledgements

The authors acknowledge the support of the EU projects *DAT4.Zero* (GA 958393) and *Qu4lity* (GA 825030).

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