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Comparison between product and process oriented Zero-Defect Manufacturing (ZDM) approaches

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Abstract. Contemporary manufacturing companies pay a lot of attention to product quality as this aspect affects directly their competitiveness, productivity and the reputation of the company. Traditional quality improvement methods such as Six Sigma, Lean etc. seems unable to cope with the market's quality standards. Contemporary technological advancements allowed the successful implementation of Zero Defect Manufacturing (ZDM) which is replacing traditional quality improvement methods. According to a recent review article ZDM can be implemented in two ways the product oriented and the process oriented approach, but there is no clear understanding of the advantages and disadvantages of each approach. The current research proposes a methodology for quantifying the performance of each approach. To accomplish that a set of ZDM parameters is defined to describe the problem and the proposed methodology is applied on a specific industrial use case in order to enumerate the ZDM parameters. The results from the application of the proposed methodology will assist manufacturers and researchers to select the most suitable approach to their specific case in order to achieve sustainable manufacturing. The results showed that the performance of either product or process oriented approach is heavily depending on the input parameters and use case.

Keywords: Zero Defect Manufacturing, ZDM, Product oriented, Process oriented, Quality management

1 Introduction & State of the Art

Contemporary manufacturing companies pay a lot of attention to product quality as this aspect affects directly their competitiveness, productivity and the reputation of the company [1]. Low quality products may have numerous negative implications for a manufacturing company such as direct economic losses or increasing of the negative environmental impact of the production system. At the same time there can be also indirect economic losses due to customer dissatisfaction, which can have severe impact to the profitability of a manufacturing company [2][3]. Therefore, manufacturers must implement at least one Continuous Improvement (CI) method, such as Lean manufacturing, Six Sigma etc. in order to ensure that the produced products are of high quality and the performance of the production at acceptable levels [4]. Traditional CI methods are

widely used in the manufacturing domain but because of their design are struggling to cope with the current needs of the market [5]. In a recent literature review paper the characteristics of the traditional quality improvement methods were analyzed and their enabling factors and barriers were identified ending to the conclusion that there is a need for new quality improvement methods that can reach higher levels of sustainability [6].

Contemporary technological advancements allowed the successful implementation of an approach called Zero Defect Manufacturing (ZDM) [7][8]. The implementation of ZDM can offer to manufacturers possibilities that previous CI methods were unable to provide[8] and at the same time improve the performance of a system. ZDM is implemented using four individual strategies named “detect”, “predict”, “repair” and “prevent” as described by Psarommatis et al [8]. Those strategies and their connections between them can be seen in Fig. 1. A key feature of ZDM is the fact that for every quality oriented event whether it is detection or prediction a mitigation action must be performed. Doing that it can be assured that at the end of the production there are only acceptable parts and no defected products will end to the customers.

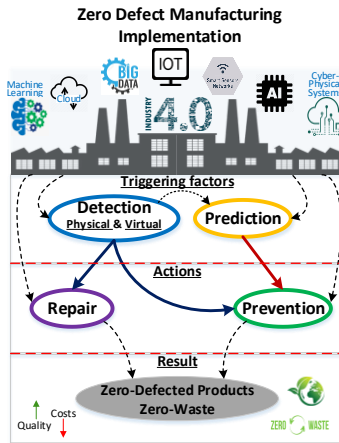


Fig. 1. ZDM implementation strategies [8]

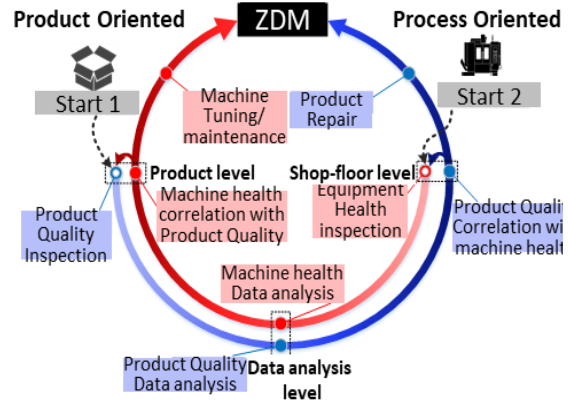


Fig. 2. ZDM product and process approaches [8]

ZDM utilizes many of the tools and methods that traditional quality improvement methods are using, but the biggest difference is the addition of the “prediction” approach and therefore it is able to offer more efficient prevention actions, serving the objective “do things right the first time”. Because of the uncertainty that manufacturing systems have defects are an unavoidable phenomenon, ZDM utilizes the predictive techniques to aim for the best solution but it also utilizes corrective and preventive techniques to act in case of a defect. Using all three techniques corrective, preventive and predictive can significantly increase the level of efficiency and sustainability, something that manufacturing companies are keen to achieve [9].

ZDM approach can be implemented on both the product and process level, something that is not the case for traditional quality improvement methods which are imple-

mented only on the process level [6][10]. Fig. 2 illustrates the product and process approach that ZDM can implement [8]. The difference is the starting point of the implementation of the ZDM. On the one hand product ZDM starts from the investigation and analysis of the quality of the product and in case of abnormalities are identified, then the process/ machine is investigated. On the other hand, the process ZDM starts from the investigation and analysis of the health of a machine and, by extend, the process and, again, if abnormalities are observed the quality of the produced product is investigated. In both approaches the same steps are followed but in different order. The result from both approaches is the same, which is achieving ZDM. What is important is that for the successful implementation of ZDM data from both the product and process levels must be taken [11] regardless the ZDM approach. Early studies in ZDM presented high quality solutions utilizing data from both the product and process level without differentiating them [12]. In fact many studies have been performed using one of the two ZDM approaches with significant results [13][14], but without maximizing their results from selecting the most effective ZDM approach for their use case.

Contemporary manufacturing companies are mainly focusing on the number of products they produce, acquiring new customers, increasing distribution networks, and preparing for next season without considering the severity of the cost of poor product quality [15]. This cost includes both internal and external costs, from the direct costs arising from a defective product to the disruption of the consumer relationships and company's reputation [16]. Poor quality costs can be classified to the following categories: rework costs, freight costs, chargebacks, product returns and loss of sales [17][18]. According to the American Society for Quality (ASQ) companies lacking effective quality management often have a cost of poor quality equal to 20 percent of sales or more [19].

To the authors' best knowledge all the studies implementing ZDM are selecting an approach without evidence of its superiority than the other ZDM approach. In literature there is no study that identifies the key parameters that defines the two ZDM approaches and study their performance. This has as a result researchers and manufacturers to select either approach according to their experience. Furthermore, the identification and the definition of the two ZDM approaches was introduced in 2020 by Psarommatis et al. [8][6], therefore it is logical that there are no studies on this topic. The last decade many studies have been performed towards a product oriented approaches [20][21][22][23]. Therefore, the current paper aims to provide a methodology for comparing of the two ZDM approaches and define the parameters that should drive the decision for selecting either product or process oriented ZDM implementation.

2 Proposed methodology

In the current chapter the proposed methodology for the generic quantification of the performance of product and process oriented ZDM will be presented. The goal was to create a lean method easy to use to support manufacturers and researchers on selecting the proper approach depending on their specific case for harvesting as much as possible

from ZDM implementation. The first step for establishing the proposed method was to define the two approaches and identify the key parameters that are involved.

Table 1 presents the key parameters identified for the formalization of the two ZDM approaches. Manufacturers implementing quality improvement methods because their systems are characterized by a certain defect rate (DR) which must be reduced. The defect rate has direct link with the losses that are arising due to poor quality (PQLR). The PQLR is also linked with the corresponding profit margin that manufacturers set to their products. In the product oriented (PRD) ZDM all the products are inspected therefore the cost of inspection is a key factor on this approach. Furthermore, if defects are detected then they must be repaired to meet the specification. The inspection process has a specific accuracy, meaning that some defects might pass undetected according to that accuracy. When defects are detected the process data are analyzed to identify the cause of the defect and correct it. The analysis of the process data has a cost which needs to be included (MDAC).

Table 1. Defined problem parameters

Parameter Name	Notation	Parameter Description
Defect Rate	DR	-Is a percentage that shows how many defects are estimated that will occur
Profit	PRF	-Is a percentage illustrating the profit margin that a manufacturer sets compared to the products production cost
Poor Quality Ratio	PQLR	-It is a percentage showing the potential losses due to poor quality compared to the total sales. In this factor the following aspects are included: freight costs, chargebacks, product returns and loss of sales.
Inspection Cost	PIC	-It is a percentage showing how much it costs the inspection per unit of product compared to the unit cost
Machine Data Analysis Cost	MDA C	-It is a percentage showing how much it costs the data analysis per unit of product compared to the unit cost
Machine Data Correlation Accuracy	MDA	-It is a percentage showing the probability of the accuracy of the system that correlates machine data with product defects.
Inspection Accuracy	IA	-It is a percentage showing the probability of being accurate the inspection equipment and accurately detect a product defect.
Rework Cost	RC	-It is a percentage showing the cost that is required for reworking a part compared to the unit cost.

On the other hand, the processes oriented (PRS) ZDM as stated by Fig. 2 analyses all the process data for all the products being produced, which implies a Machine Data Analytics Cost, MDAC. If abnormalities are detected to the process data, inspection is performed to the related parts. If the inspection results to a detection of a defect, this defect must be repaired. As in the product-oriented approach the PQLR is also present on the process oriented approach.

To make the proposed method as generic as possible and independent of use case all the defined parameters presented in Table 1 are in percentages and the cost-oriented values are related to the unit cost, which is set to be 1. Equations 1-8 are used to calculate the performance of each approach. More specifically, the performance of each approach is given by equation 8, which contains only the terms that are different in both cases and all the terms that are included to both cases, such as maintenance are not studied. The outcome of equation 8 is measured in money units and represents the cost that each approach is adding to the total production cost. Therefore, the best performed approach is the one with the lowest adding cost.

$$Salles = unitCost * lifeVolume * (1 + PRF) \quad (1)$$

$$TheoreticalDefects(ThD) = DR * lifeVolume \quad (2)$$

$$UndetectedDefects(UnD) = \begin{cases} ThD - lifeVolume * DR * IA & , PRD \\ ThD - ThD * MDA * IA & , PRS \end{cases} \quad (3)$$

$$PoorQualityLosses(PQL) = \frac{UnD * PQLR * Salles}{ThD} \quad (4)$$

$$ICtotal = \begin{cases} ThD * IA * PIC & , PRD \\ ThD * MDA * IA * PIC & , PRS \end{cases} \quad (5)$$

$$MDACtotal = \begin{cases} ThD * IA * MDAC & , PRD \\ ThD * MDA * MDAC & , PRS \end{cases} \quad (6)$$

$$RCtotal = \begin{cases} ThD * IA * RC & , PRD \\ ThD * MDA * IA * RC & , PRS \end{cases} \quad (7)$$

$$Perf = ICtotal + MDACtotal + PQL \quad (8)$$

3 Visualization of PRD and PRS ZDM approaches

Using the methodology presented in section 2 and using specific enumerated values of the parameters defined in Table 1 the performance of PRD and PRS are visualized for a specific industrial use case in the semi-conductor domain. Initial trials showed that the parameters named PIC and MDAC (Table 1) have the highest influence to the final result. Therefore, those values were selected to take multiple values keeping the rest constant. More specifically parameters DR, PRF, PQLR, MDA, IA, and RC have taken the actual value that it is been used in the real industrial use case while the values for the PIC and MDAC were taken a value from a range using as limits some extreme values. To visualize and compare the two approaches the relative difference between PRD and PRS approaches were used, slightly modified (Equation 9). The modification is that in the numerator the difference between the $Perf_{PRD}$ and $Perf_{PRS}$ is calculated without converting it to the absolute value. This means that when the relative difference is positive the PRD approach is better and when it is negative the PRS is better.

$$relDif = 100\% * \frac{Perf_{PRD} - Perf_{PRS}}{\frac{Perf_{PRD} + Perf_{PRS}}{2}} \quad (9)$$

Fig. 3 illustrates the visualization of the quantification of the performance of PRD and PRS approaches. On the x-axis is the parameter PIC which takes values between [0.01,0.36] and each plot has six lines representing MDAC. The results show that for low PIC and high MDAC values the PRD approach is better where as for the opposite situation high PIC and low MDAC the PRS is better. The two top plots of Fig. 3 have PQLR 0.05 which is low compared to the literature and the two bottom plots have PQLR 0.3. Those values were selected as extreme values in order to visualize the effect of PQLR parameter. The effect that PQLR has to the solution is that the higher it is the plots are moving upwards and at the same time the slope of the curves is decreased. The life volume does not have any influence on the final result. Furthermore, the rest of the parameters PRF, MDA, IA and RC have less effect but always at the same direction. Depending on their values they intensify or lessen the performance of each approach.

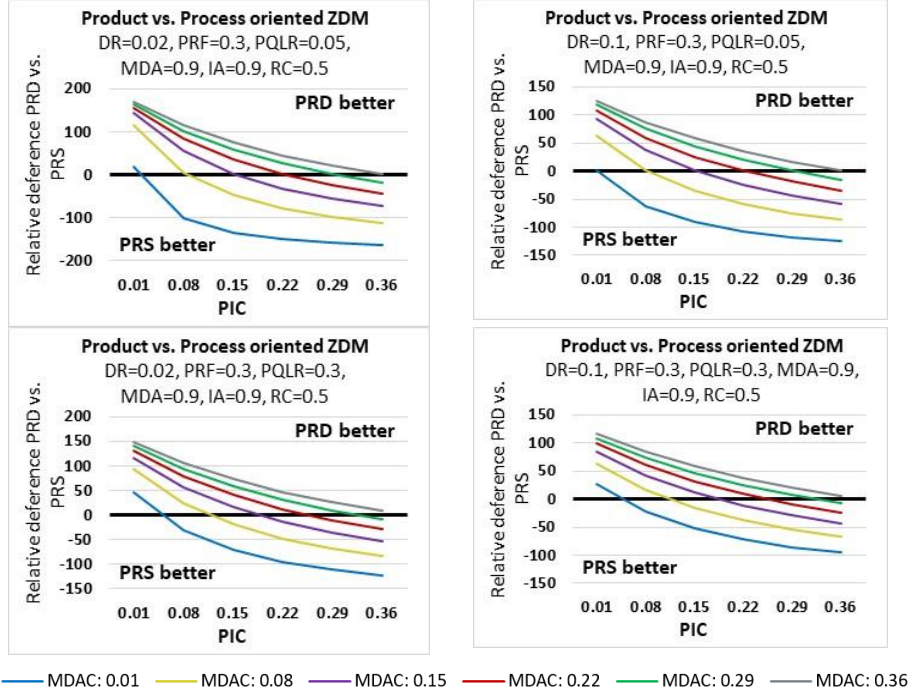


Fig. 3. Product and Process oriented ZDM comparison for the current use case

4 Conclusions and future work

This paper proposed a method for quantifying the selection of product and process oriented ZDM approaches. The proposed method was based on identifying the differences between the two approaches and quantify only those. To this extend eight parameters were defined based on which the quantification of the performance of each ZDM approach was performed. From those eight parameters the inspection cost (PIC) and the

machine data analysis cost (MDAC) were the parameters that affect the selection the most. The results from the performed analysis revealed that the selection of product or process oriented ZDM approach is heavily depending on the application and the selections that manufacturers will perform in term of equipment. Therefore, as conclusion from the analysis someone can keep that both approaches can be efficient but depending on the selections one of them will produce better results than the other one. Therefore, the practicality of the proposed approach is that researchers and manufactures could use the proposed methodology to compare both ZDM prior to the implementation of a ZDM application in order to select the most efficient and sustainable way to implement ZDM. The selection of the proper ZDM approach will ensure that no resources are wasted and at the same time increase the sustainability of the system which is crucial step to accomplish. Future research will focus on the enhancement of the proposed approach for identifying in more details the parameters that are involved in the problem.

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