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A practical guide for implementing Zero Defect Manufacturing in new or existing manufacturing systems

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Abstract

The approach to achieving zero defects by using Industry 4.0 technologies is what constitutes Zero Defect Manufacturing (ZDM). However, its implementation is not a simple task since it requires careful design and new methods. The current literature on zero defect manufacturing lacks methods, tools, and guidelines for a successful shift toward ZDM implementation in manufacturing facilities aligned with the recent advancements in enabling technologies as well as data-driven approaches and models. In this paper, we propose a step-by-step practical implementation guide for achieving zero defects in modern manufacturing facilities. While considering the links with various ZDM strategies, this guide can be applied to both new and existing production systems. The proposed method has been tested with an industrial example that concerns the manufacturing of an electronics board in the case of a European semiconductors manufacturer. We demonstrated, using this industrial example, that the multi-criteria approach that has been proposed may effectively evaluate the potential risk of defects for each stage of manufacturing and the extent to which ZDM adoption is required.

Keywords: Design; Manufacturing system Design; Sustainability; Zero Defect Manufacturing; ZDM; Quality assurance; Implementation guide.

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1. Introduction

The implementation of ZDM is not a simple task as it requires careful design and more importantly new methods [1]. Zero Defect Manufacturing (ZDM) is composed of four main strategies: “Detect” and “Predict” that are the triggering ZDM strategies, and the “Repair” and “Prevent” that are the action ZDM strategies [2]. The three ZDM pair strategies are “Detect-Repair”, “Detect-Prevent” and “Predict-Prevent” [2]. The main difference of ZDM with the traditional quality assurance methodologies is the fact that ZDM ensures 100% of the products are inspected via any method, either detection or prediction [3, 4]. It is impossible to achieve ZDM if not all the products are inspected. In traditional quality improvement methods such as Six Sigma, Lean manufacturing, Lean Six Sigma, Theory of Constraints, and Total Quality Management, the analysis starts after the production has started and defects or quality issues start occurring [5]. The design for ZDM approach that is proposed in the current paper is going one step further and considers critical design factors from the beginning for achieving ZDM and not while the production is running.

Implementing ZDM is a challenging task since it necessitates careful planning and innovative techniques. The current literature and practice lack a practical guide for successfully incorporating ZDM in manufacturing facilities that are in line with recent developments in enabling technology as well as data-driven approaches and models. In the current paper, the authors propose a practical guide with the steps to be followed for implementing ZDM into manufacturing systems. Those steps can be implemented in both existing and new production systems. In the proposed implementation guide, there are two sets of parameters: product analysis parameters, and ZDM strategies key control parameters.

The questions answered with the information and method provided in this study are as follows:

- How can ZDM implementation be integrated into a new manufacturing system?
- How can ZDM implementation be integrated into an existing manufacturing system?
- What are the steps to follow for ZDM implementation?
- What are the restrictions for ZDM implementation?
- What are the restrictions for ZDM implementation?

The remainder of the paper is structured as follows. Section 2 provides the state-of-the-art on the topic, and Section 3 presents the proposed implementation guide. Next, Section 4 provides an industrial example to test the validity of the proposed approach. Finally, Section 5 ends the paper by discussing the implications, limitations, and further research.

2. State of the art

Several scholars have approached the issue of ZDM implementation by providing generic frameworks and architecture for applications in different industrial settings. These frameworks and architectures are generic in nature often applicable to both existing and new manufacturing systems, considers on-line or offline detection of defects combined with other associated ZDM strategies predict, prevent, and repair [2]. Majority of the pertinent literature on ZDM implementation falls into this category. In this context, chronologically, May and Kiritsis (2019) in [6] design a holistic framework and introduce ad-hoc strategies applicable to both new and existing manufacturing lines to achieve zero-defects in manufacturing through a platform that integrates inspection tools, enabling technologies, and AI models that fosters competitiveness and sustainability of manufacturing plants. Later, Magnanini et al. (2020) in [7] illustrate a reference architecture and relevant software packages to facilitate industrial implementation of ZDM strategies. Powell et al. (2021) in [8] provide a framework for digitally enhanced quality management for achieving ZDM by adding human centricity as a third approach beyond the traditional focus on products and processes. Mathiyazhagan & Bhatia (2021) in [9] investigate capability enhancement methods to for successfully implementing ZDM through improvement of existing systems. Azamfiriei et al. (2021) design and develop a multi-stage and multi-layer system framework for quality inspection in industry 4.0 enabled production facilities [10]. Sousa et al. (2022) focus on the technical aspects and demonstrates how a generic interface and framework can lead to ZDM by facilitating effective use of metrology data to reduce product and process defects [11].

Another group of scholars have considered the data aspects to improve existing and design new manufacturing facilities for achieving zero-defects. In that vein, Mourtzis et al. (2021) focus on optimizing the design of machinery for achieving ZDM based on data-driven approaches and AI models and validates their methods in a real-life use case scenario [12]. Caccamo et al. (2021) provide a hybrid architecture for achieving ZDM in modern manufacturing facilities through data-based approaches and management systems in several contexts with low level of digitalization for minimizing the complexity of implementation in existing and/or new manufacturing systems [13]. Dreyfus et al. (2022) discuss in detail the issues of virtual metrology as an approach for estimating product quality in Industry 4.0 and provides an integrative conceptual framework to support implementation concerning ZDM [14].

Besides, several researchers have investigated the ZDM phenomenon in terms of its effect to the entire manufacturing system by analyzing trade-offs with other productivity issues such as scheduling, machine's health, etc. On that regard, Psarommatis, May, and Kiritsis (2021) investigate key control parameters of predictive maintenance for achieving successful implementation of ZDM systems, and also analyzed tradeoffs between parameters of production scheduling, predictive maintenance, and ZDM [15]. Lindstrom et al. (2020a) propose a cost based ZDM model for multi objective optimization and design of manufacturing systems by considering different performance target measures in trade-off such as productivity, safety [16], and quality Lindstrom et al. (2020b) analyze the necessities for change and desired effects of ZDM implementation through case studies of manufacturing companies including several processes [17].

As outlined above, to date, ZDM literature mostly focused on different components of the implementation independently or proposed generic architectures and/or frameworks. Although there have been previous attempts such as Eleftheriadis & Myklebust (2016) that creates step-by-step quality management guidelines for achieving ZDM [18] or Gaikwad et al. (2020) that implements ZDM in a very specific scenario, there is still lack of a practical guide for ZDM implementation in manufacturing facilities aligned with the recent advancements in enabling technologies and data-driven approaches and models [19]. Therefore, in this study we address the aforementioned gap and hence propose a step-by-step practical implementation guide for achieving zero-defects in modern manufacturing facilities for both greenfield and brownfield scenarios also considering the links with different ZDM strategies.

3. ZDM implementation guide

The purpose of the proposed guide is to define the steps required for the ZDM implementation and not to develop a specific technology for a specific quality problem. Figure 1 illustrates the steps that are proposed for the implementation of ZDM. There is a differentiation between the design of a new system and the implementation of ZDM in an existing manufacturing system. The difference lies in the fact that when the system pre-exists and produces the product there are more available data and therefore the design for ZDM can be more accurate and straightforward. More specifically, when the manufacturing system pre-exists, data such as the defect rate at each manufacturing stage and specific KPIs are available that can assist in the design for ZDM process. However, when a manufacturing system is designed from the beginning, the only available data are historical data from other or similar processes that can be used to assist in the design of the quality assurance implementation. The first information that is required is to identify the most optimum ZDM approach: product-oriented, process-oriented or hybrid [20]. The ZDM approach determines from which point the ZDM process starts: from the product or the process.

Regardless of the ZDM approach, the product analysis is the same, the bill of materials (BoM) and bill of processes (BoP). Each task of the BoP is analyzed and combined with aspects of BoM and sustainability and the BoP tasks are ranked based on the impact that a defect will cause at this manufacturing stage and therefore the ranking reveals the need of each for ZDM implementation. More information regarding the product analysis process will be given in Section 3.1.

After the ranking of the tasks and starting from the task with the highest impact if defected, the three ZDM pair strategies are investigated to calculate the performance of each ZDM pair strategy to each product task. Based on the produced ZDM performance maps, the proper ZDM technology will be developed or selected and will be deployed. More information regarding the generation of the ZDM performance maps will be provided in Section 3.2.

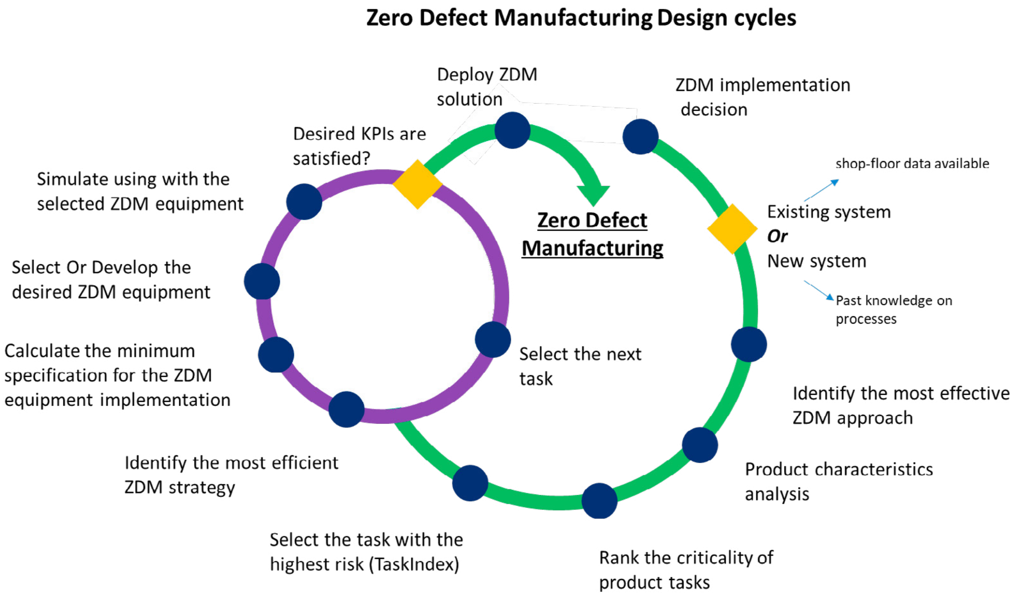

Fig. 1. Design for ZDM framework

Table 1. Product analysis parameters (MFG: manufacturing stage)

No.	Parameter Name	Abbreviation	Description
1	Cost of materials for current MFG	CM	The cost of materials required for performing the current task.
2	Cumulative Cost of materials up to this MFG	CCM	The cumulative cost up to this task that the product caries from previous manufacturing stages
3	Weight of materials for current MFG	WM	The weight of materials required for performing the current task.
4	Cumulative Weight of materials up to this MFG	CWM	The cumulative weight of materials up to this task
5	Manufacturing time for current MFG	MT	The nominal processing time that is required to perform the current task. This cost contains the actual machine cost, setup cost, energy cost and machine depreciation.
6	Cumulative Manufacturing time up to this MFG	CMT	The cumulative processing time that was spent for manufacturing all the tasks prior to the current one.
7	Human operation time for current MFG	HT	The time that human operators spent for performing the current task.
8	Cumulative Human operation time up to this MFG	CHT	The total time that has put to the product up to this point by human operators.
9	Machine operation cost	MOC	The cost for operating a specific machine
10	Cumulative machine operation cost	CMOC	The cumulative machine operational cost up to a specific task
11	Human operation cost	LOP	The labor cost for performing a specific task
12	Cumulative Human operational cost	CLOP	The cumulative labor cost required up to a specific task
13	Energy consumption for current MFG	EC	The energy that is consumed for the processing of a specific task
14	Cumulative Energy consumption up to this MFG	CEC	The total energy that is consumed prior to a specific task
15	Is the part at this MFG repairable	REP	Can the part be repaired if defected at the current manufacturing stage. This is an estimated percentage showing how many parts out of the total can be

			repaired. 100% means that all the parts can be repaired, 0% means that none of the parts can be repaired.
16	Labor Time required for recycling preparation	LRT	The time required from human operators to recycle a defected product this time contains the cost for disassembly, and recycling.
17	Cost of recycling if defected	CRCY	The total cost that required to recycle a defected product, this cost contains the cost for disassembly, and recycling

3.1. Product analysis

The product analysis is a critical step for the sustainable design of a manufacturing system. Performing detailed analysis for each manufacturing stage might be very time consuming and costly. Also, implementing ZDM to all the manufacturing processes of a product can be extremely costly and significantly reduce the performance of the system. Therefore, ZDM should be implemented with priority to the highly risky tasks, and partial ZDM is applied to some other tasks to assure Zero-defects. Partial ZDM refers to the implementation of single ZDM strategies and not as a pair. More specifically, the ZDM strategies that can be implemented alone are the “Detection” and “Prediction”. Implementing those strategies alone in low-risk tasks will ensure 100% of accepted product at the end of the manufacturing process.

Table 1 presents the generic parameters that are being used for the ranking of the tasks. These parameters are the same for either a new production system or an existing one. Those parameters are covering some generic parameters that are addressing all the aspects of sustainability. More specifically, the defined parameters are covering economic, environmental, and social aspects. All the values in Table 1 represent average values.

To calculate the value that will contain all the values of the defined parameters presented in Table 1, a weighted formula function will be used (equation 1) [21, 22]. In equation 1 PNVal$_i$ is the normalized value of the parameter “i”. The normalization is performed using equations 2 and 3, all parameters have cost behavior, meaning that the lower the better, except the REP which has the exact opposite behaviour. NW$_i$ is the normalized weight value that corresponds to the importance for each parameter. The sum of all weights for each parameter must be equal to 1. The initial weight values can take values between [0-10] with 10 being very important and 0 means not important. Once a value between [0-10] is given for each weight, equation 4 is used to normalize the weights and convert them to the proper form to be used in equation 1 [23]. Furthermore, N is the total number of parameters in the current case 17.

$$TaskIndex = 1 - \sum_{i=1}^{N} nw_i * PNVal_i \qquad (1)$$

$$PNVal_i = \frac{Pval_{max} - Pval}{Pval_{max} - Pval_{min}} \qquad (2)$$

$$PNVal_i = \frac{Pval - Pval_{min}}{Pval_{max} - Pval_{min}} \qquad (3)$$

$$nw = \frac{w}{\sum_{i=1}^{N} w_i} \qquad (4)$$

3.2. ZDM strategies selection

Identifying the most efficient and well suited ZDM strategy for each task is not a simple task. Once all the tasks have been ranked using the methodology presented in Section 3.1, it is then needed to start with the task with the highest *TaskIndex* and perform simulations with different parameters for each ZDM strategy. Those simulations help on quantifying the desired KPIs based on which the different ZDM strategies are compared. Psarommatis 2021 has proposed a methodology called “design for ZDM” and describes in detail how to perform those simulations and select the most suited ZDM strategy for each task [1]. The simulations were performed using a ZDM oriented dynamic scheduling tool [23–27], and the results from the simulations were used for developing a Digital Twin. This step was necessary to avoid time consuming simulations. The digital twin was emulating the scheduling tool and therefore a high number of alternative combinations of ZDM control parameters were tested to derive the ZDM performance maps. The ZDM performance maps illustrates the performance of each ZDM pair strategy for different control parameters. Table 2 presents the key ZDM control parameters that characterize each individual ZDM strategy and are required to quantify before a ZDM implementation. Those parameters were first introduced by Psarommatis (2021) in [1].

Table 2. ZDM strategies key control parameters

Parameter Name	ZDM strategy	Parameter Description
Inspection Cost	Detect	Is the cost/piece that the inspection equipment or operator require for inspecting the part
Inspection Time	Detect	Is the time/piece that the inspection equipment or operator require for inspecting the part
Detection Accuracy	Detect	Is percentage that shows the average accuracy of the inspection equipment or operator
Detection Repeatability	Detect	Is percentage that shows the average repeatability of the inspection equipment or operator
Repairing Cost	Repair	Is the average cost for repairing a defected part. The repairing cost takes into consideration the extra raw materials needed for the repair and the labor and machine operational cost for performing the repair.
Repairing Time	Repair	The time that is required in to perform the repair
Reparability %	Repair	Is a percentage illustrating the probability of a defected part be reparable.
Prevention Cost	Prevent	The cost that is required for spare parts, consumables and the operator time to implement the prevention actions.
Prevention Time	Prevent	The time required to implement the prevention actions.
Prevention success Rate %	Prevent	It is a percentage that shows the probability that a prevention action was successful or not, if the prevention actions are successful or there was a miss-diagnose.
Prediction Horizon	Predict	Is the timeframe that the prediction algorithm looks ahead in time to predict quality issues to try to prevent them.
Prediction Accuracy %	Predict	Is the probability of successfully predicting a defect in the given prediction horizon
Prevention Reaction Time	Predict	Is the time that is required for implementing the prevention actions.

4. Industrial example

In the current section, an example of the use of our proposed product analysis method will be presented. The example concerns the manufacturing of an electronics board coming from a European semiconductors manufacturer, Figure 2 illustrates the simplified version of the Bill of Processes (BoP). In total there are 8 simplified/grouped tasks for demonstration purposes, whereas in the analytical BoP there are 62 individual tasks. The goal of the current industrial example is to calculate the TaskIndex. The TaskIndex is a measure quantifying the potential risk if the product is defected at the corresponding manufacturing stage. TaskIndex takes values from 0 to 1, the higher the TaskIndex the higher the risk of a potential defect. Therefore, the analysis of ZDM implementation should start from the tasks with the highest TaskIndex.

As someone would expect the task with the highest TaskIndex is the TSK-1-1, which contains all the costs, time, and energy from the previous manufacturing steps. Accordingly, someone would expect that TSK-1-2 and TSK-1-6 should have the immediate larger TaskIndex. Table 3 presents the values for each of the defined parameters (section 3.1), as well as the final TaskIndex that was calculated using the corresponding equations. At this point, it is mentioned that all the cost values are the nominal cost of the corresponding materials, machine operational cost, and labor cost. Furthermore, all the times are referring to the average times over a period of 6 months. TSK-1-4 has the second higher TaskIndex value followed by TSK-1-2, followed by TSK-1-7. Therefore, the proposed multi-criteria approach can successfully quantify the potential risk of defects for each manufacturing stage and by extent the need for ZDM implementation. This result means that the implementation of ZDM should start from the tasks with the highest TaskIndex.

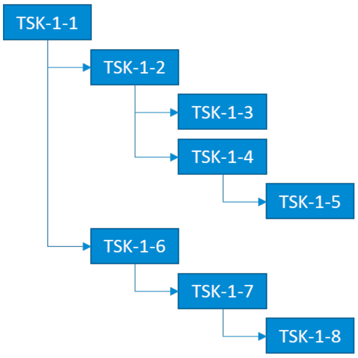

Fig. 2. Simplified Bill of Processes

Table 3. Product analysis parameters

Tasks	**TSK-1-1**	**TSK-1-2**	**TSK-1-3**	**TSK-1-4**	**TSK-1-5**	**TSK-1-6**	**TSK-1-7**	**TSK-1-8**
CM (€)	4.50	2.35	1.50	15.05	7.80	10.50	7.80	15.74
CCM (€)	88.10	51.71	0.00	7.80	0.00	23.54	15.74	0.00
WM (kg)	0.21	0.43	1.54	1.40	1.84	0.48	0.85	2.44
CWM (kg)	8.98	4.78	0.00	1.84	0.00	3.29	2.44	0.00
MT (mins)	15.40	5.30	4.80	21.20	7.40	2.50	5.50	2.70
CMT (mins)	49.40	33.40	0.00	7.40	0.00	8.20	2.70	0.00
MOC (€)	77.77	47.08	46.72	56.89	36.75	28.17	73.24	31.28
CMOC (€)	320.13	140.36	0.00	36.75	0.00	104.52	31.28	0.00
HT (mins)	35.40	2.50	5.40	7.50	1.20	2.80	4.50	2.10
CHT (mins)	26.00	14.10	0.00	1.20	0.00	6.60	2.10	0.00
LOP (€)	10.62	0.75	1.62	2.25	0.36	0.84	1.35	0.63
CLOP (€)	7.80	4.23	0.00	0.36	0.00	1.98	0.63	0.00
EC (Kwh)	1.88	0.97	0.61	3.57	0.39	0.29	0.68	0.53
CEC (Kwh)	7.05	4.57	0.00	0.39	0.00	1.21	0.53	0.00
REP (1:Yes, 0:No)	0	1	0	0	1	0	0	1
LRT (mins)	52.40	32.20	5.40	35.78	2.40	4.40	3.50	1.50
CRCY (€)	15.72	9.66	1.62	13.40	0.72	1.32	1.05	0.45
TaskIndex	0.8382	0.3592	0.1522	0.4534	0.0815	0.1973	0.2200	0.0910

5. Discussion and Concluding Remarks

This research contributed to both the literature and practice by providing a practical guide with steps for ZDM implementation in smart factories of industry 4.0 considering both brownfield and greenfield application scenarios. Moreover, the managerial contribution is that the research paves the way for further discussions and ideas toward designing eco factories of the future with zero-defects. The current research suggested a method for structurally evaluate and rank the different tasks in a BoP based on the need of ZDM implementation at this manufacturing stage. Using a real industrial example, we performed a first validation of our approach with a simple use case from the semiconductor domain. The results of the validation example revealed that the ranking of tasks based on the risk if defected is a multi-criteria and complex procedure, and the results are not obvious, which is the reason behind the current research paper. The proposed method can be used either at new manufacturing systems and existing ones. The key differences is that existing manufacturing systems have already inspection, data collection and analysis equipment, which sometimes this might be limiting and increasing the cost of ZDM implementation. When a new manufacturing system is designed for a specific product then the most efficient equipment for the specific case can be acquired and achieve higher levels of performance. Furthermore, the proposed methodology can be used of any type of discrete manufacturing systems. The higher the quality requirements the higher the need of ZDM and the higher the benefits from the proposed approach.

The application of the proposed method is generalizable and open to enrichments in different contexts.The limitation of this research is related to the complexity and difficulty of testing the proposed method and practical implementation guide in real industrial scenarios since it is challenging to engage industrial companies for collecting the required data for achieving results.

Future research should focus on applying the proposed method to several cases in redesigning existing and/or designing new manufacturing systems for achieving zero-defects. Another area of investigation could be to improve this method for multi-objective optimization of various performance target measures beyond quality.

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