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Procedia Computer Science 253 (2025) 805–814

Procedia Computer Science

www.elsevier.com/locate/procedia

6th International Conference on Industry 4.0 and Smart Manufacturing

Zero-Defect Manufacturing Maturity Model

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Abstract

This research paper focuses on Zero-Defect Manufacturing (ZDM) with the goal of proposing a ZDM Maturity Model including the critical factors that contribute to ZDM success. Using a design science approach, a new ZDM Maturity Model was developed. An extensive literature review was conducted to extract the main critical factors for successful ZDM implementation. These key factors were then organized into six socio-technical dimensions-i.e., Product, Process, Platform, People, Partnership, and Performance-and described across five maturity levels-i.e., Initial, Managed, Defined, Integrated, and Exploited. In doing so, this paper advances ZDM research and provides industrial stakeholders with a practical tool to assess companies' maturity and progress toward achieving zero defects.

Keywords: Zero-defect; Quality 4.0; Maturity; Readiness.

1. Introduction

Zero-Defect Manufacturing (ZDM) embodies the principle of "getting it right the first time" in production. In today's industrial landscape, ZDM is increasingly relevant as it aims to eliminate defects in production processes [1, 2], enhance product quality, and significantly reduce waste and resource consumption [3], all while maintaining customer satisfaction. By focusing on defect prevention rather than detection, ZDM is a strategic approach that aims to eliminate defects, thereby achieving operational excellence and sustaining competitive advantage [4].

However, transitioning to ZDM is complex and requires a thorough understanding of the current manufacturing processes, technologies, and organizational practices. In this respect, assessing a company's maturity for ZDM is recognized as a critical step to drive strategic improvements and to identify areas that need development or optimization [4]. Nevertheless, despite the growing research interest, there are few studies focusing specifically on ZDM maturity assessment.

Consequently, this paper aims to contribute to bridge this gap by developing a ZDM Maturity Model (MM). This model identifies key elements contributing to quality excellence and outlines the progressive stages of maturity in

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10.1016/j.procs.2025.01.142

achieving zero defects. By integrating insights from various sources into a structured framework, this work highlights the transformative potential of a systematic approach to ZDM implementation and provides manufacturing stakeholders with a tool to evaluate their maturity and progress towards ZDM.

According to its objective, the remainder of the paper is structured in the following way: Section 2 provides an overview of the theoretical foundations and historical context of ZDM and MMs; Section 3 outlines the research methods adopted in order to develop the ZDM MM; Section 4 presents the results from the literature review as well as the final structure and content of the proposed ZDM MM; finally, Section 5 outlines the contributions of the work done, its limitations and directions for future research.

2. Related Work

2.1. Zero-Defect Manufacturing

The shift in the quality paradigm, referred to as Quality 4.0, primarily involves two strategic elements: first, the integration of traditional quality tools with modern technologies like connectivity, artificial intelligence, and automation to improve performance and enable data-driven decision-making at all operational stages; and second, the adoption of comprehensive strategies for value creation that include personalization, perfection, partnership, prediction, and delivery.

In the expanding realm of Quality 4.0 research, one of the most innovative approaches is ZDM. ZDM marks a strategic shift in manufacturing, evolving from practices that merely respond to defects, to those that prevent them. ZDM aims to ensure both process and product quality by minimizing defects using corrective, preventive, and predictive methods, primarily thanks to the support of data-driven technologies [5]. While the strategies of detecting and repairing, or detecting and preventing defects are not new, advancements in data-driven technologies have made their implementation more efficient [1]. On the other hand, the strategy of predicting and preventing defects represents a relatively new approach to foresee and mitigate defects before they occur, embodying the principle of *"doing things right the first time."*

ZDM presents a transformative potential for the manufacturing industry, fostering greater quality, operational efficiency and sustainability [6]. However, the successful implementation of ZDM is not straightforward. In this respect, assessing company's maturity for ZDM is recognized as a strategic step [2, 5] that allows for targeted and effective improvements, minimizes risks, and sets the stage for a successful transformation roadmap towards achieving and sustaining high levels of quality. In this respect, recent studies have started researching on ZDM maturity, to identify critical success factors, implementation challenges and best practices, and develop assessment frameworks and MMs to support manufacturers.

2.2. Digital Maturity Models

Maturity typically signifies progress in the development of a system towards achieving a target state [7]. MMs offer a structured path for assessing capabilities and maturity levels within an organization, particularly focusing on specific areas like processes, people, and technology. These models have been extensively applied to various domains [7], including assessment of companies' digital maturity to assess and guide them through their digital transformation.

Digital MMs are used to evaluate the extent to which a manufacturing company has adopted and integrated digital technologies into its operations, thereby enhancing its overall competitiveness. These models typically categorize digital maturity into several stages, ranging from initial digitization efforts to the creation of fully digitalized, integrated, and optimized systems. Each stage is defined by specific characteristics in terms of technology adoption, workflow integration, data utilization, workforce capabilities, etc. (for a review refer to [8]).

Digital MMs are not only diagnostic tools but can also serve a prescriptive purpose [9]. They help identify gaps in digital capabilities and provide targeted recommendations for technology investments, training, and process improvements. A pivotal aspect of these models is their ability to support the definition of a roadmap for digital transformation by identifying the current level of digital maturity and outlining the steps necessary to reach higher levels of maturity.

In summary, MMs provide a valuable framework for assessing and enhancing digital maturity in manufacturing companies. They offer a clear, structured way to understand the current state of digitalization, make informed decisions about future investments, and systematically advance toward higher levels of digital integration and optimization.

3. Research Methodology

To develop the ZDM MM, the design science approach proposed in [10] was adopted. Accordingly, the research process was organized in three main steps that were carried out within the EU project “FLASH-COMP”. First, a literature review was conducted following the recommendations of the PRISMA 2020 statement. Articles were collected from the Scopus database using the following search string: *TITLE-ABS-KEY (ZDM OR "zero defect" OR zero-defect OR "zero waste" OR "Quality 4.0" OR "Quality 5.0" OR "TQM 4.0" OR "Total Quality Management 4.0") AND TITLE-ABS-KEY (readiness OR maturity OR performance OR KPI OR "success factor" OR CSF OR "enabling factor" OR enabler OR roadmap OR human) AND TITLE-ABS-KEY (manufacturing OR digital* OR "industry 4.0" OR "industry 5.0")*. The search returned 468 documents. Only papers published in journals and conference proceedings written in English between 2014 and 2024 were included. Documents in not relevant subject areas, such as nursing and arts, were filtered out. Then, a two-step screening process was implemented. First, titles and abstracts were screened; second, the remaining full papers were carefully analysed to include only those documents with relevant data and insights on ZDM and/or Quality4.0, particularly emphasizing on maturity factors and levels. After this selection process, 69 papers remained in the final sample. Bibliometric data of the selected articles were retrieved from Scopus and analyzed following the recommendations of [11] to map the contributions of research constituents (e.g., authors, institutions, journals). Subsequently, papers’ content was analyzed using the 6Ps framework (i.e., Product, Process, Platform, Performance, People, Partners) proposed by [12] to dissect and categorize the main maturity dimensions and factors as well as maturity levels presented in each paper. Afterwards, the results of the literature analysis were used to define the first structure and content of the ZDM MM. The findings of the literature review were extended by including additional factors and items that were not well addressed in the identified ZDM and Quality 4.0-related studies. Besides, the definition of the five maturity levels was outlines leveraging the findings of the literature review. Finally, the proposed ZDM MM was reviewed by two experts from the EU project “FLASH-COMP” and the collected feedback were used to refine the model. The final ZDM MM is described in the followings.

4. Results

4.1. Findings from the literature review

4.1.1. Descriptive Analysis

The first and foremost observation on the literature analysis is about observing the emergence of the research on ZDM concepts and methodology. This preliminary observation showcases the increasing significance and attention, with particular emphasis on the recent time 2014-2024 as shown in Fig. 1.

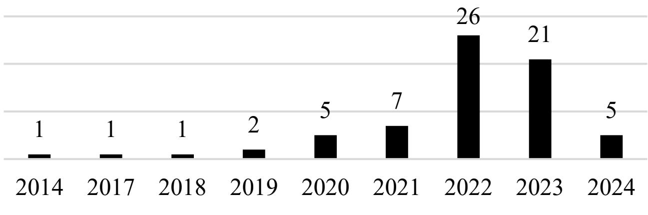

Fig. 1. Timeline of Selected Articles (January 2024)

Furthermore, among the sample of papers considered in the analysis, the literature review revealed two major clusters of authors majorly invested in the ZDM research. The set of Authors in Cluster #1 has actively contributed to the research area of ZDM concentrating on the human-factors, technological advancements, and readiness level assessment, while the Authors in Cluster #2 are oriented towards Quality 4.0 centring on empirical studies of organizational readiness and critical success factors in implementing Quality 4.0.

Table 1. Main clusters of Authors

Cluster #1			Cluster #2		
Author	University	Articles	Author	University	Articles
F. Psarommatis	University of Oslo	7	J. Antony	Khalifa University of Science and Technology	6
G. May	University of North Florida	3	M. Sony	University of the Witwatersrand	6
V. Azamfirei	Malardalen University	3	O. McDermott	University of Galway	6
D. Kiritsis	École Polytechnique Fédérale de Lausanne	3	R. Jayaraman	Khalifa University of Science and Technology	3
M. C. Magnanini	Politecnico di Milano	2	V. Swarnakar	Khalifa University of Science and Technology	3
D. Powell	SINTEF Manufacturing	2			

4.1.2. Content Analysis

The collected literature was then examined for excerpts and/or inclusions of readiness / maturity factors scattered along various axes directed at Quality 4.0 and ZDM initiatives. A brief mapping of these factors found along the 6P dimensions (Product, Process, Platform, People, Partners, Performance) proposed in [12] is presented in the Fig. 2. Among the analysed dimensions, the People, Process, and Platform are the most addressed ones since they are recognized as pivotal for successful ZDM implementation. While processes, technologies, organizational and human capital-related aspects are frequently discussed in relation to ZDM progress, the Product, Partnership and Performance dimension have received less attention so far.

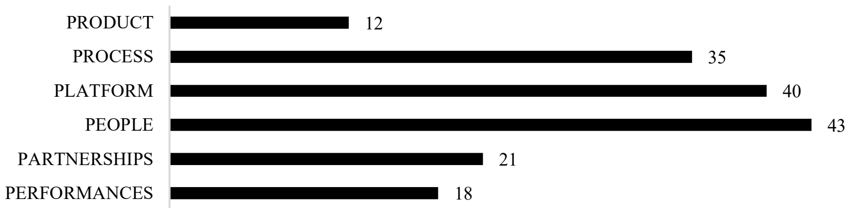

Fig. 2 Number of papers addressing each 6P dimension

In addition, the literature analysis revealed that few articles discussed the readiness/maturity levels. Collectively, these articles postulated assessment levels typically consisting of 5 levels ranging from low readiness/maturity level to very high readiness/maturity level. Evidently, these articles further defined these maturity levels on various pretexts such as maturity of technology employed [13], progression towards quality objectives [14], etc. Furthermore, these assessments are carried out either internally by the company personnel (e.g., sponsors or champions) or externally by third-parties or industry experts (e.g., consultants) to classify the readiness/maturity level.

4.2. The ZDM Maturity Model

The ZDM MM was developed by leveraging the findings of the literature review and enriching them with additional insights from the EU project “FLASH-COMP”. The structure and the content of the ZDM MM is presented in the following paragraphs. First, the five Maturity Levels are outlined. Second, the six dimensions of the ZDM MM inspired by [2] – i.e., Product, Process, Platform, People, Partnership and Performance - and the factors included in each of them are detailed.

4.2.1. Maturity Levels

Defining of the Maturity Levels is crucial as they should clearly indicate the capability gap [15] of the situation observed in the organization from shopfloor to technological infrastructure to the workers skillset. The five Maturity Levels of the proposed ZDM MM were inspired from the finding of the literature review (e.g., [2][13-17, 19, 28]) and are based on the Capability Maturity Model Integration best practice. Within existing MMs a common design principle is to represent maturity as several cumulative stages where higher stages build on the requirements of lower stages with 1 representing low maturity and 5 high maturity. Accordingly, in the developed ZDM MM, level 1 is the lowest level and represents an initial state, while level 5 is the highest level and represents full maturity in ZDM.

4.2.2. Maturity Dimensions and Factors

The Product dimension centres around the product characteristics related to quality, sustainability and the aspects of digital enhancement expected from the market such as traceability, connectivity, and diagnostic ability of the product. These factors are captured in the product with the use of cutting-edge technology. As shown in Table 2, 7 factors are considered: Customisation level offered by the company [19]; Integration of Sensors and Actuators to understand if the product is equipped with the ability to be integrated with external devices; Communication and Connectivity to analyse how the product communicates with external environment; Storage and Exchange of Information to measure if the product can facilitate data exchange; Monitoring to assess if the product exhibits self-monitoring capabilities; Smart Traceability to assess if the product is enabled to capture traceability information [20]; Smart Servicing to measures if the organisation offers services related to products [21].

Table 2. Product dimension

PRODUCT DIMENSION	LEVEL 1 INITIAL	LEVEL 2 MANAGED	LEVEL 3 DEFINED	LEVEL 4 INTEGRATED	LEVEL 5 EXPLOITED
CUSTOMISATION	No Customisation	Reactive	Standardised Procedures	Systemic Approach	Strategic
INTEGRATION OF SENSORS/ ACTUATORS	No use of Sensors/ Actuators	External sensors / actuators integrated	Sensor readiness processed by product	Sensors and other sources are analysed inside the product	Procut able to respond autonomously to the ambient
COMMUNICATION/ CONNECTIVITY	No Communication/ Connectivity	Low	Medium	High	Complete Communication / Connectivity
DATA STORAGE AND INFORMATION EXCHANGE	No functionalities	Individual ID	Product has passive data source	Product with data storage for autonomous information exchange	Data and information exchange are integral part
MONITORING	No Monitoring	Low	Medium	High	Full Monitoring
SMART TRACEABILITY	No Traceability	Low	Medium	High	Completely traceable
SMART SERVICING	No Services	Low	Medium	High	“Automated” services in place

The Process dimension has the main objective of assessing the level of maturity in the most relevant manufacturing processes in the ZDM context. Several aspects of quality management system and ZDM strategies are covered, from establishing a quality control system, to indication on levels of inspection [3] taking place at the company, defining procedures to manage quality issues, data analysis [22–24] on quality checks to assess the capturing and utilisation of available quality data collectively creating a process-driven culture that is critical for building a ZDM practice. Moreover, this dimension reports about the other important factors such as Risk Analysis to evaluate if there are control plans are in place to identify factors that affect the product quality; Standardised tools or methods [25] to assess the intervention actions in place to follow up with the quality issues that may arise during the quality inspection and/or during the processes; ZDM Strategies represents the different strategies that can be undertaken to attain zero-defect from the most reactive to the most proactive ones [3].

Table 3. Process dimension

PROCESS DIMENSION	LEVEL 1 INITIAL	LEVEL 2 MANAGED	LEVEL 3 DEFINED	LEVEL 4 INTEGRATED	LEVEL 5 EXPLOITED
PROCESS MANAGEMENT	Ad-hoc processes	Most important processes are well-defined	Processes are well-defined and documented	Processes are managed as a system	Processes are managed proactively

QMS - QUALITY CONTROLS	QC at final tests	QC are executed at final tests and during the process	QC at final tests, during the process and acceptance stage	QC and reliability tests are executed	QC with active feedback system
QMS – LEVEL OF INSPECTION	Sample inspection	Sample inspection	100% inspection	100% inspection	100% inspection
QMS - PROCEDURES	No procedures	Reactive problem-solving procedures	Reactive problem-solving procedures	Proactive problem-solving procedures	Proactive problem-solving procedures
QMS - DATA ANALYSIS OF QUALITY CHECKS	No Data analysis	Irregularly managed	Periodically	Regularly and frequently	Real-time
RISK MANAGEMENT SYSTEM	No risk analysis	Product-oriented	Product and Process	Standard Methods (FMEA)	Standard Methods (FMEA)
STANDARDISED TOOL OR METHODS OF INTERVENTION	No Root-cause analysis	Based on experience	Standard Methods	Standard Methods and interventions	KAIZEN
ZDM STRATEGIES	Detection	Detection – Offline repair	Detection – Online repair	Prediction	Prediction - Prevention

The Platform Matrix brings out the digital advancements the company could pursue in terms of building both the infrastructure and technological integration. The Platform dimension holds together 10 factors: 1) Inspection Instruments and Sensors employed in detecting the defects; 2) Asset Administration Shell (AAS) to assess the level of integration with AAS; 3-4) Vertical and Horizontal Interoperability to understand the extent to which the existing/planned architecture can contribute to establish a seamless data flow in the system; 5-6) Digital Twin and Data Analytics to assess the level of adoption of Digital twin and Data analytics in capturing real time data, which would be effective in devising and re-defining the strategies backed by the data; 7) Industrial Data Platform to assess the presence and functionality of the Industrial data platform, to assess how well-linked these platforms are with other systems [23, 26–28]; 8) Human-Machine Interface to assess the level of easiness in accessing the digital systems; 9) Tracking System to measure the capacity of the company in terms of tracking, localization and monitoring capabilities along the value chain; 10) Data Space to understand the footing of the company in terms of data spaces adoption, to facilitate in both, sharing and accessing data from multiple sources.

Table 4. Platform dimension

PLATFORM DIMENSION	LEVEL 1 INITIAL	LEVEL 2 MANAGED	LEVEL 3 DEFINED	LEVEL 4 INTEGRATED	LEVEL 5 EXPLOITED
INSPECTION INSTRUMENTS AND SENSORS	No Inspection instruments	Semi-Automated	Automated systems	Automated systems	Virtual Metrology
ASSET ADMINISATRATION SHELL (AAS)	No AAS	Basic AAS	Passive AAS	Reactive AAS	Proactive AAS
VERTICAL INTEROPERABILITY	No Vertical Interoperability	Low	Medium	High	Full Vertical Interoperability
INDUSTRIAL DATA PLATFORM	No Data Platform	Data Platform as basic repository	Well-defined Platform	Platform with Robust interoperability	Data Platform on well-defined policies, standards and procedures
DIGITAL TWIN (DT)	No DT	Introducing DT	DTs in Place	Future-oriented DTs	Advanced DTs

DATA ANALYTICS	No Data Analytics	Basic Analytics	Analytics in Place	Future-oriented Analytics	Advanced Analytics
HUMAN MACHINE INTERFACE	Paper based information	Static HMI	Fixed and/or mobile HMI	Advanced fixed and/or mobile HMI	Adaptive HMI
TRACKING SYSTEM	No Tracking System	Real-time tracking	Tracking of products	Tracking, localisation and monitoring	Tracking and monitoring in upstream and downstream
HORIZONTAL INTEROPERABILITY	No Horizontal Interoperability	Low	Medium	High	Full Horizontal Interoperability
DATA SPACE	No Data Space	Basic	Intermediate	Advanced	Data Space in place

The People dimension emerged as the most critical influence on the successful implementation of ZDM. The identified factors range from inculcating ZDM centred initiatives in the business strategy to adapting organizational culture inclusive of ZDM mindset. Additionally, this dimension includes alignment of People Management practices with ZDM: (i) Skills and training for effective ZDM performance [28] [16]; (ii) Ergonomics and Working conditions, (iii) Employee engagement, and (iv) Reward mechanism. All these factors collectively report on the organisations' effort in improving the working environment, creating channels to foster employee participation and recognise employee contributions towards implementing ZDM strategies.

Table 5. People dimension

PEOPLE DIMENSION	LEVEL 1 INITIAL	LEVEL 2 MANAGED	LEVEL 3 DEFINED	LEVEL 4 INTEGRATED	LEVEL 5 EXPLOITED
ZDM BUSINESS STRATEGY	No ZDM	Some Initiatives	Strategy under development	Strategy is formalized	ZDM strategy in place
ZDM CULTURE	No ZDM Culture	Interests from top management	Some organisational orientation	Organisational commitment to ZDM	ZDM is the core of company's culture
ORGANISATION	No ZDM organisation	Some interactions	Ad-hoc Cross-functional teams	Collaborative efforts to resolve quality issues	Collaborative efforts towards ZDM
SKILLS AND TRAINING	No practices	Some practices in place	Defined programmes	Training in place	Well-defined training
HF & WORKING CONDITIONS	No practices	Some practices in place	Sporadic initiatives	Implementing real programmes	Well-rounded programs in place
EMPLOYEE ENGAGEMENT	No practices	Some programmes	Initiation of consultation	Employees involved in improvement	Employees are co-creators
REWARD MECHANISM	No practices	Some initiatives in place	Initiation of appraisal	Coherent practices in recognising ZDM	Reward mechanisms related to ZDM

The Partnership dimension relates to the identification of the partners needed for transition towards ZDM and for achieving the desired business goals. It describes the workflows whose purpose is to support the transition towards more collaborative relationships with key stakeholders, to create strong and collaborative partnerships that are crucial for a successful ZDM implementation. Accordingly, partners included in the dimensions are: Research and Innovation; Training and Education; IT Solution Providers. The other prominent factors are Supplier centeredness and Customer centeredness [22, 29–31], which refer to the accomplishments brought about by aggregating supplier/consumer inputs, in developing, and/or producing new products and services; Industrial Data Sharing Ecosystems [6, 16] to facilitate more collaboration in terms of data sharing schemes towards developing an industrial data space to foster ZDM.

Table 6. Partnership dimension

PARTNERSHIP DIMENSION	LEVEL 1 INITIAL	LEVEL 2 MANAGED	LEVEL 3 DEFINED	LEVEL 4 INTEGRATED	LEVEL 5 EXPLOITED
RESEARCH AND INNOVATION	No relationships	Limited Participation	Active involvement in joint projects	Collaboration in R&I projects	Systemic participation
TRAINING AND EDUCATION	No training	Occasional training programmes	Regularised training programmes	Planned learning programmes on ZDM	Widespread learning programmes and training on ZDM
IT SOLUTION PROVIDERS	No relationships	Basic digitalisation services	Collaborative in developing solutions	Reliable partnerships	Strategic partnership with game changing value
SUPPLIERS	No relationships	Transactional	Collaborative	Partnership	Strategic partnership
CUSTOMERS	No relationships	Transactional	Collaborative	Partnership	Strategic partnership
INDUSTRIAL DATA SHARING	No relationships	Only informal communication	Initial activities fostering data-sharing schemes	Bi- or multi-lateral contractual frameworks	Formal industry agreements in place

The Performance dimension investigates the definition, monitoring, and interpretation of KPIs. It is divided into 8 areas: Operational/Technical [5] to monitor the performances of machines and production activities; Economic [32, 33] focused on economic and financial results such as Total Cost of Quality, Cost of Poor Quality, etc; Environmental and Social [34, 35] to measure all the aspects of the triple bottom line; Customer Satisfaction that refers to the systems/tools adopted in monitoring customer satisfaction; Product-Service Lifecycle to assess to which extent and according to which criteria product's impacts are assessed along the lifecycle; Supply Chain to assess the modalities through which industries can measure the overall performances of their supply chain.

Table 7. Performance dimension

PERFORMANCE DIMENSION	LEVEL 1 INITIAL	LEVEL 2 MANAGED	LEVEL 3 DEFINED	LEVEL 4 INTEGRATED	LEVEL 5 EXPLOITED
OPERATIONAL	Not measured	Descriptive	Diagnostic	Predictive	Prescriptive
ECONOMIC	Not measured	Descriptive	Diagnostic	Predictive	Prescriptive
ENVIROMENTAL	Not measured	Descriptive	Diagnostic	Predictive	Prescriptive
SOCIAL	Not measured	Descriptive	Diagnostic	Predictive	Prescriptive
CUSTOMER SATISFACTION	Not monitored	Occasional monitoring	Periodical monitoring with traditional tools	Regular monitoring	Constant monitoring through established and novel channels
P-S LIFECYCLE	No Product LC management	Few LC aspects included	Life-cycle Costing (LCC)	LCC and Environmental LCA	LCC, Environmental LCA and Social LCA
SUPPLY CHAIN	Performance not measured	Important attributes are monitored	Physical and Economical performance are monitored	Physical, Economical and Sustainability aspects	Initiatives to enable continuous improvement of all the aspects
DATA PERFORMANCE	Data quality not understood	Evaluation against generic standards	Establishing detailed measurement	Proactive monitoring of Data quality	Evidence-based monitoring of Data quality

5. Discussion and Conclusions

ZDM is an emerging research area, and this study is one of the first attempts to develop a comprehensive ZDM MM. By harmonizing maturity factors for ZDM into the 6P dimensions, the ZDM MM goes beyond the state of the art and contributes to enhance current understanding of the multiple facets that characterized ZDM and must be considered for its successful implementation in manufacturing. In doing so, it provides an initial response to the call of numerous researchers who have highlighted the lack of appropriate frameworks and tools to support companies in their transition towards ZDM (e.g., [36]). Furthermore, the proposed ZDM MM serves as a practical tool for businesses to assess their maturity and progress toward achieving zero defects. Practically, the ZDM MM can serve as a tool for tracking and monitoring the progress of ZDM initiatives within the organization, identifying underperforming areas, enabling targeted improvements for each specific factor over time, and offering insights into the organization's advancement towards zero defects.

Despite the contributions of the ZDM MM developed in this study, some limitations must be acknowledged. First, its creation was primarily based on a literature review, and the initial evaluation involved only two experts. Additionally, the method for measuring maturity and the development of the assessment instrument is still pending. Finally, the model has not yet been validated in real industrial settings. To address these limitations, future research will focus on elaborating the maturity measurement method and developing the corresponding assessment instrument. A pilot study will then be conducted to gather additional insights from industrial practitioners. Finally, comprehensive case studies in manufacturing settings will be conducted to validate the assessment instrument and evaluate the ZDM MM's applicability in industrial companies.

In conclusion, the ZDM MM provides an assessment framework for organizations aiming to enhance their manufacturing excellence by eliminating defects and waste. This model delivers valuable insights and practical guidance through a structured approach based on organization's readiness and progress in adopting ZDM. By systematically assessing various process, technological, and social aspects, the ZDM MM helps identify current strengths and areas for improvement, driving operational excellence, competitiveness, and long-term sustainability.

Acknowledgements

This study has been partially funded by the Horizon Europe project FLASH-COMP – GA number: 101058458, and the HumanTech Project, which is financed by the Italian Ministry of University and Research (MUR) for the 2023-2027 period as part of the ministerial initiative "Departments of Excellence" (L. 232/2016).

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