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Advancing zero defect manufacturing: A state-of-the-art perspective and future research directions

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ABSTRACT

Zero Defect Manufacturing is a disruptive concept that has the potential to entirely reshape the manufacturing ideology. Building on the same quality management philosophy that underpins both lean production and Six Sigma, the Zero Defect Manufacturing paradigm has in recent years developed significantly, given the onset of Industry 4.0 and the increasing maturity of its digital technologies. In this paper, we review contemporary advances in Zero Defect Manufacturing using structured literature review. We explore emergent themes and present important directions for future development in this continuously emerging field of research and practice. We highlight two specific Zero Defect Manufacturing strategy types: defect prevention, and defect compensation; as well as identify two important themes for future ZDM research, namely advancing ZDM research (particularly with a view to progressing from zero-defect processes to zero-waste value chain strategies) and overcoming the global application challenges of ZDM (with emphasis on cyber-security and the extension of defect prevention and compensation strategies to less explored manufacturing processes).

Contents

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1. Introduction

An increasing emphasis on sustainable production requires that manufacturing companies continuously deliver higher quality products of increasing complexity at lower cost, while simultaneously limiting the use (and particularly waste) of resources within entire industrial ecosystems (Colledani et al., 2014a). Deming (1982) suggested that a focus on quality first is a key to market domination – where improved quality leads to reduced costs (due to less rework, fewer mistakes, and fewer delays), as well as better use of machines and materials. As such, Zero Defect Manufacturing (ZDM) has emerged as a means of moving closer to achieving an organization's "first-time-right" quality strategy (Raabe et al., 2017). Though the idea of zero defects is not new, it remains in this sense a disruptive concept that is able to entirely reshape the manufacturing ideology – by simultaneously considering production planning, quality management, and maintenance management factors (Psarommatis et al., 2020).

Zero Defects first emerged as a strategy in the US the 1960 s (Halpin, 1966). Much of the development of the zero defect mindset is credited to Philip B. Crosby, who was at that time a quality control department manager on the Pershing Missile program at the Martin Company (Harwood, 1993). In his *Absolutes of Quality Management*, Crosby (1985) suggested that the performance standard must be zero defects, such that managers and workers should not accept any level of non-conformance, and that "*zero defects should be their personal standard*". At around the same time in 1960 s Japan, highly influenced by the teachings of Dr. W. Edwards Deming, Toyota Motor Company launched its Zero Defects Campaign, which became a major stimulus to quality control activities across the organization. *Zero Defects* was further adopted in Toyota's 1968 corporate policy and continued thereafter as a company initiative. In more general terms, these events were quickly followed by the emergence of the Taguchi methods in the 1970 s, and subsequently Six Sigma (particularly at Motorola) in the 1980 s. In the 1990 s and 2000 s, Lean Production and Total Quality Management (TQM) were high on the agenda of most large firms as a means of moving towards a zero defect vision.

ZDM is an emerging paradigm that goes beyond traditional quality approaches such as Lean Production and Six Sigma. It aims for the complete elimination of defects, not simply through detection and correction of defective products and process parameters, but also through defect prediction and prevention. As a technology-intensive concept, ZDM began gaining greater traction on the quality management agenda with the onset of digitalization and Industry 4.0 in the 2010 s, presenting the potential for a whole new wave of digitally enhanced quality management. The term Industry 4.0 was coined in 2011 by a German government initiative to prepare the German manufacturing industry for the digital era (Sinha et al., 2020). Since then, a plethora of emerging key enabling technologies, such as in-line data gathering solutions, data storage and communication standards, data analytics tools and digital manufacturing technologies have begun to offer new opportunities for ZDM (Eger et al., 2018), enabling organizations to move even closer to achieving the vision of zero defects.

The aim of this paper is to provide a state of the art perspective of ZDM by presenting a thorough and critical (systematic) review of the extant literature. We bring out pertinent factors and useful insights into the contemporary advances in ZDM and identify several interesting research gaps which serve as avenues for future research within this important and emerging field of research.

2. Research design

To investigate the state-of-the-art perspectives of ZDM, we adopted systematic literature review (SLR) as our research method. An SLR is "*a systematic, explicit, comprehensive, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners*" (Fink, 2010).

The SLR process begins with a *planning* phase, where the reviewers clearly identify the purpose and intended goals of the literature review. A review protocol was also developed by the reviewers, which allowed the detailed procedure (documented in the following sections) to be followed. Next is the *selection* phase, where the literature search and screening processes are carried out to select the core literature. Then comes the *extraction* phase, where articles are excluded based on specific quality criteria before the remaining articles are studied to extract the useful data and applicable information. Finally, in the *execution* phase, the data extracted from the literature is synthesised and analysed – before the results can be documented and presented.

An initial search using search terms "Zero Defect" and ""Manufacturing" was performed in the Scopus database. The Scopus database was selected as it covers a satisfactory share of relevant, extant literature and produces less noise, compared to other databases (Bjørnbet et al., 2021). Our initial search returned 477 articles during the period 1965–2021, with a significant share of results stemming from the period from 2017 onwards (as shown in Fig. 1).

The 477 articles were then sorted based on the following criteria (see Table 1.):

1. Research articles should demonstrate *rigour* – hence only peer-reviewed journal articles and conference proceedings were included.

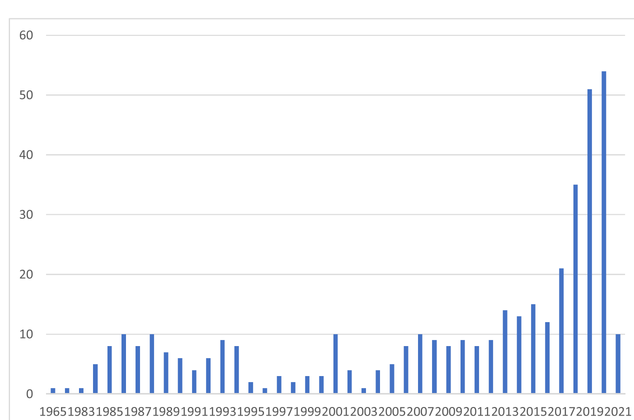

Fig. 1. Zero Defect Manufacturing - Publications per year (Scopus).

Table 1
Overview of sorting and exclusion process.

Articles included	Articles excluded	Criteria
477	–	Title – abstract – keywords: "Zero Defects" and "Manufacturing"
407	70	RIGOUROUS • Journal articles • Peer-reviewed conf. proceedings
381	26	RELEVANT • Engineering • Computer science • Materials science • Business Management • Decision science
216	165	RECENT • Timespan 2011–2021

2. Research articles should be *relevant* – hence only relevant specific subject areas were included (For example, papers from the arts and humanities, astronomy, and medicine fields were rejected at this stage).
3. Research articles should be *recent* – hence only articles post-Industry 4.0 (2011 +) were included.

The distribution of the articles (publications per year) included in the review is shown in Fig. 2.

Such a distribution makes this work both timely and significant. For example, the previous state-of-the art review of ZDM presented in Psarommatis et al. (2020) only considers publications in the period 1987–2018, thus approx. 50% of the articles included in this current study of advances in ZDM are new. As such, Psarommatis et al. (2020) provides a suitable underpinning and point of departure for further analysis of more than 100 additional journal articles and peer-reviewed conference publications.

Fig. 3 (above) illustrates the distribution of publication type, where 65% are articles from conference proceedings and 35% are from international journals. Fig. 4 (below) shows the distribution of articles based on country of origin, with nearly 50% of the articles originating from Italy, Germany, and India. Interestingly, the majority of ZDM research originates from continental Europe (Both Manufuture-EU and the European Factories of the Future Research Association (EFFRA) have placed ZDM high on the research agenda since 2011, see MANUFUTURE-EU, 2013 and EFFRA, 2020).

Following the systematic sorting and exclusion process, the remaining 216 articles were then closely examined using a process of interpretive synthesis to identify prominent, recurrent themes and potential variability across the literature. Based on these emergent

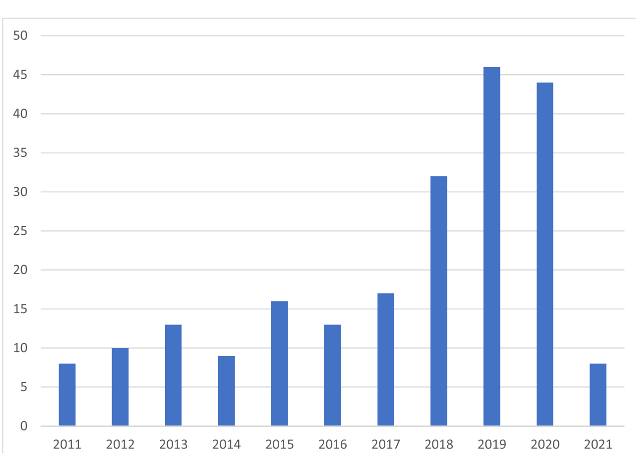

Fig. 2. Distribution of the reviewed literature.

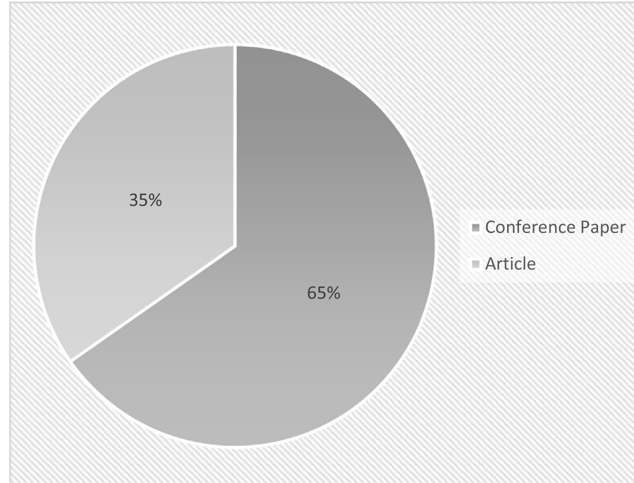

Fig. 3. Publication type.

themes and variables, we were able to forge a frame for which to further classify the extant literature on ZDM:

1. Scope: Is the research based on single-stage, multi-stage, or Supply Chain (system) level ZDM?
2. Focus: Is the research based on process-centric, product-centric, or people-centric ZDM?
3. Type: Is the research purely theoretical or is it applied (with practical examples)?
4. Hierarchical level: Does the research present ZDM at a strategic, tactical, or operational level?
5. Technology: Which key enabling technologies (KETs) does the research discuss? (e.g., monitoring systems, Digital Twins, Artificial Intelligence, etc.).

Each of these five classification criteria were applied to all papers. It should be noted that several of the papers fell into multiple categories within each classification (E.g., articles considering both process- and product-centric ZDM approaches). This was especially the case regarding KETs, where multiple technologies are often presented together, in individual works. In this respect, we assigned multiple tags to these articles such that we did not risk missing contributions both within and across the various classification schemas. We present the results of this subsequent classification of the rigorous, relevant, and recent extant literature in the following section.

3. Analysis of the state-of-the-art

In this section we present and discuss the results of classifying the rigorous, relevant, and recent ZDM literature to provide a comprehensive overview of the current state-of-the-art.

3.1. Single-stage, multi-stage, or supply chain?

Much of the ZDM literature focuses on the optimization of individual and discrete (single-stage) production processes. However, even after the optimization of a single process, there is still a possibility of defect generation in the form of deviations that propagate in subsequent process steps (Magnanini et al., 2019). Therefore, more recent research has adopted a focus on so-called multi-stage manufacturing systems (Eger et al., 2018), which encompass entire production lines – sometimes consisting of many discrete processes. Beyond multi-stage manufacturing systems, one might also expect to find ZDM strategies for supply chains or digital supply networks.

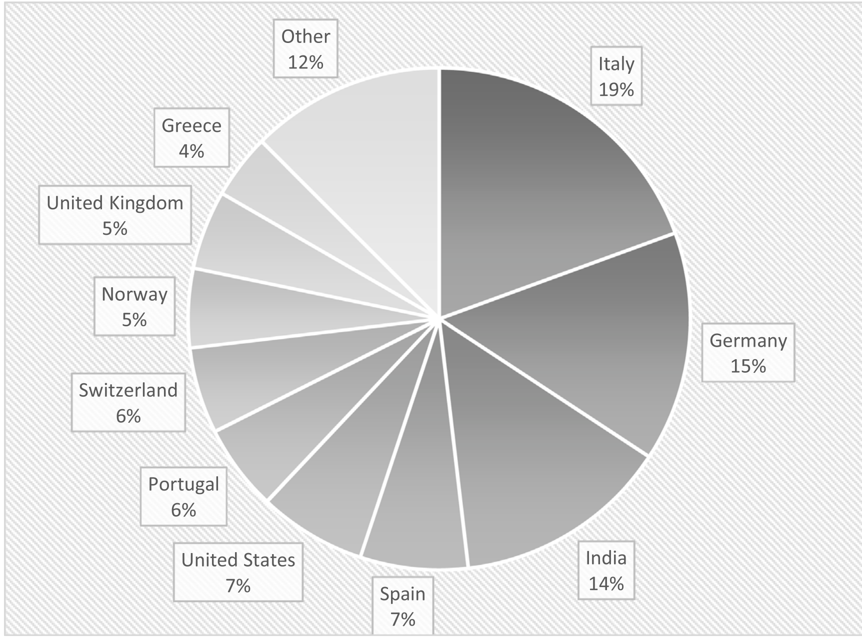

Fig. 4. Country of Origin.

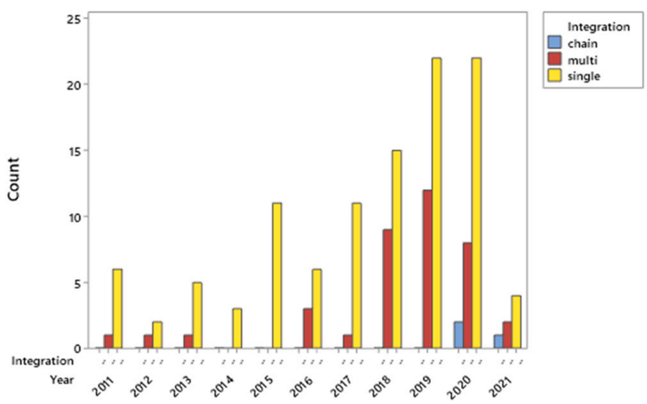

Fig. 5. Single-, multi-stage, or supply chain perspective.

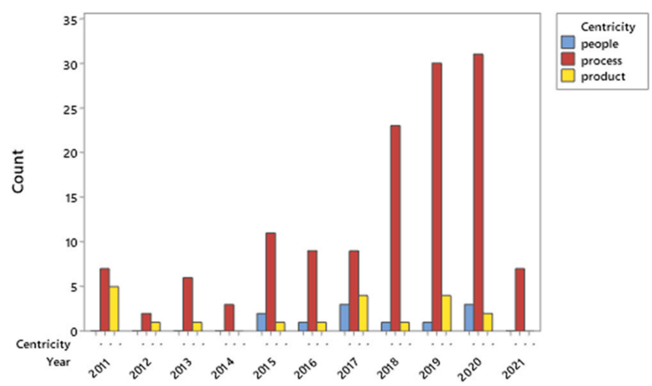

Fig. 6. Process-, product-, or people-centricity.

In this section we explore the literature considering these dimensions (see Fig. 5).

Firstly, there is a clear trend of developing from single-stage to multi-stage and supply chain level ZDM research. However, the majority of both early and contemporary ZDM research has tended to focus on single-stage processes (e.g., Chiou et al., 2011; Arsuaga Berrueta et al., 2012; Myklebust, 2013; Weng and Saeger, 2013; Caggiano et al., 2015; Linares et al., 2015; Kiraci et al., 2017; Montinaro et al., 2018; Eldessouky et al., 2019; Beckert et al., 2020). Around 2018 there was a marked shift toward multi-stage processes in ZDM research (e.g., Colledani et al., 2018; Kang et al., 2019; Lindström et al., 2019; Shiokawa and Ishii, 2019; Tosello et al., 2019; Psarommatis et al., 2020). More recently, one or two instances of supply chain level ZDM research have emerged (e.g., Bosi et al., 2020), though these are few and far between.

3.2. Process, product, or people-centric?

Our next classification of the ZDM literature concerns the dimensions of *process-*, *product-*, and *people-centricity* (see Fig. 6). For example, Powell et al. (2021) suggest that although much of the existing ZDM literature presents the concept as either a product-centric (defective parts) or process-centric (defective equipment) approach, the recent intensification of research on the roles of humans (e.g., machine operators and assembly workers) in Industry 4.0 raises an important third approach, namely a *people-centric* view.

Again, there appears to be an abundance of ZDM research that focusses on manufacturing processes (e.g., process monitoring, process control, process parameters, etc.). This has been a common theme in the ZDM literature throughout the previous decade (e.g., Chen and Lyu, 2011; Weng and Saeger, 2013; Zoesch et al., 2015; Ngo and Schmitt, 2016; Snel et al., 2017; Montinaro et al., 2018; Magnanini et al., 2019; Papacharalampopoulos et al., 2020). It can be explained as ZDM paradigm builds on SPC concepts, where the process is central with respect to other system components and resources. There also seems to be a trend towards more product-centricity in ZDM research (e.g., Krammer et al., 2017; Alfaro-Isac et al., 2019; Aal et al., 2020). Though the people-centric component of ZDM has begun to appear in the extant research, most of the examples seem to be rather coincidental, often coming secondary to a focus on the process dimension (e.g., Mahmud et al., 2015; Siew et al., 2016; Kang et al., 2019; Steringer et al., 2019; Wang et al., 2019). The role of humans in ZDM has otherwise until now been vastly overlooked, and the few examples of research that include the human element are simply anecdotal (as was also concluded by Psarommatis et al., 2020)).

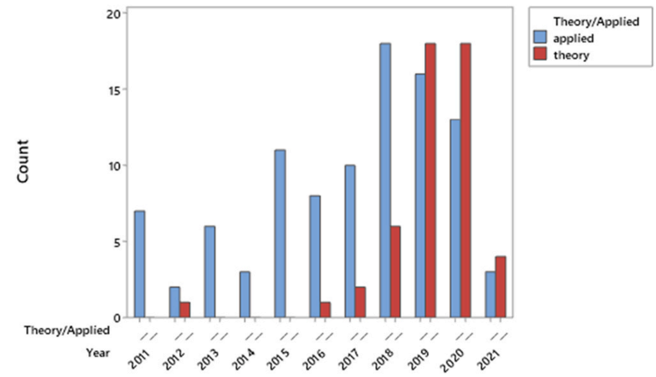

Fig. 7. Theoretical or applied research.

3.3. Theoretical, or applied?

In this classification, works have been analysed with respect to the theoretical or applied content. *Theoretical* papers have been selected as those in which results are either preliminary (with respect to anticipated further testing in real applications) or are based on restrictive assumptions only. *Applied* papers have been selected as those in which the research is based on real industrial cases and solves specific applied problems.

Much of the extant ZDM literature is based on applied research and presents practical examples of ZDM concepts. An interesting trend can be noticed in Fig. 7. Despite the rising of ZDM paradigm grounded on applied problems, recent research has begun focusing on more general results and theoretical proofs of concept. Data availability which started with Industry 4.0 ten years ago allowed the automated implementation of advanced monitoring solutions, with the aim of process improvement (e.g., Vu et al., 2011), and more accurate measurement solutions for responsive identification of defective products (Chen and Lyu, 2011; Arsuaga Berrueta et al., 2012). Then, researchers focussed on the data elaboration and usage, as well as on the development of model-based methodologies for quality improvement. The main factors which seem to limit the applicability of developed theoretical solutions include the validation of solutions in real contexts (e.g., Bengoechea-Cuadrado et al., 2019; Yeh and Chen, 2019, 2020; Brito et al., 2020), challenging integration requirements for multi-source sensors and data fusion (Shiokawa and Ishii, 2019; Bosi et al., 2020), and ZDM frameworks with high-level specifications (Mourtzis et al., 2021; Nazarenko et al., 2021; Psarommatis, 2021).

3.4. Strategic, tactical, or operational?

Works have been furtherly classified according to the company level of involvement related to the type of solution/concept presented. A *strategic* level means that the proposed solutions/concepts have a long-term effect on company strategy and concern high-level decisions, such as system configuration/reconfiguration (Mourtzis et al., 2021), including inspection allocation (Shiokawa and Ishii, 2019), supply-chain design (Bosi et al., 2020), multi-level software integration for data management (Schmid and Hanitzsch, 2011), and sensor allocation (Beckert et al., 2020).

A *tactical* level means that the proposed solutions/concepts have a medium-term effect on company policy and concern production decisions which have to be taken regularly, to ensure an effective system behaviour with respect to the identified production goals. Examples include production planning, inspection strategies, and / or maintenance policies (Myklebust, 2013; M Colledani et al., 2014a, 2014b), but also data mining and analysis methodologies for knowledge extraction and formalization (e.g., Vafeiadis et al., 2017).

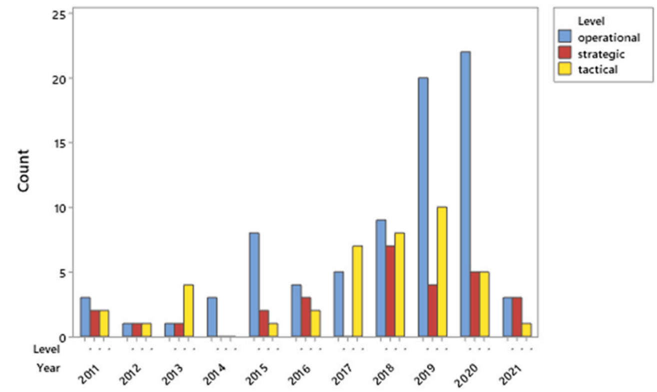

Fig. 8. Strategic, tactical or operational ZDM.

Finally, an *operational* level implies that the proposed solutions/concepts involve continuous decisions having a short-term, or even real-time, effect on the system behaviour. This might include rework decisions with respect to product deviations (Schimanski et al., 2016), scheduling (Psarommatis et al., 2020), and monitoring solutions (D'Addona et al., 2015).

In fact, most of the research has focussed on ZDM as an operational endeavour (see Fig. 8). In particular, the sudden spread of methodologies supporting the operational effectiveness of manufacturing systems by integrating data-based and model-based strategies (e.g., Digital Twins and Cyber-Physical Systems) enhanced the research on operational-level results in the last few years. By also considering the analysis with respect to the applicability of solutions, it is interesting to note that recent results on operational strategies also partially belong to theoretical works. This might mean that research is pushing for quite advanced solutions which are encountering implementation challenges in real contexts, as mentioned above.

3.5. Key enabling technologies (KET)

Industry 4.0 presents a plethora of technologies (e.g., Zheng et al., 2021), which we consider to be the key enabling technologies of ZDM. As such, we select the following technologies to further classify the analysed works:

- Artificial Intelligence (AI): data-driven techniques for automated data analysis and decision making
- Architecture and Standards: integration and communication protocols of industrial software
- Big Data analytics: elaboration, analysis, and visualization of massive amount of industrial data
- Cyber-Physical Systems (CPS): control strategies combining physical and digital resources
- Internet of Things (IoT): multi-source distributed data gathering solutions
- Inspection and monitoring: solutions for the measurement and monitoring of product and process resources
- Simulation and modelling: solutions for the implementation of digital counterparts of product/process/systems (as Digital Twins, etc.)
- Extended Reality (XR): solutions for the integration of virtual and physical representations.

For sake of classification, in works where more than one KET was included, the primary technology has been selected (e.g., when AI is used in a monitoring system, if the focus of the paper is on the development of a data-driven methodology to replace an existing monitoring system, the identified classification is AI. On the other

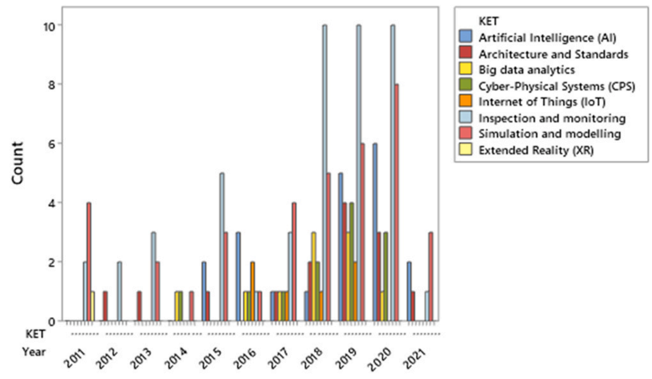

Fig. 9. Key Enabling Technologies.

hand, if AI is used to design a new inspection/monitoring system, the identified classification is inspection and monitoring).

Fig. 9 illustrates the spread of various KETs discussed in the extant ZDM literature. We discovered several articles that presented AI (Zurita et al., 2016; Chiariotti et al., 2018; O'Brien and Humphries, 2019; Escobar et al., 2020) and digital twin (Papacharalampopoulos, Stavropoulos and Petrides, 2020; Pombo et al., 2020; Psarommatis, 2021) approaches to ZDM, though there was an abundance of literature that discusses more the architecture and monitoring systems perspectives of ZDM. For example, both Angione et al. (2019) and Magnanini et al. (2020) present seminal work with regard to reference architectures for ZDM, while Ferretti et al. (2013); Caggiano et al., (2015, 2016, 2020); and Dimla (2018) each present examples of various monitoring systems for ZDM.

4. Overview of ZDM strategies

During our analysis and categorization of the ZDM literature, we discovered several complementary *strategies* for ZDM. In this Section, we discuss these ZDM strategies. A ZDM strategy can be defined as the set of tools, resources, and control rules with the aim of avoiding defects in complex manufacturing systems.

In traditional quality strategies, feedback control loops are usually implemented at single-process levels to detect and repair defects, even when the production system is complex and includes more than one stage or machines, as depicted in Fig. 10:

Traditional quality strategies keep separate the analysis of product data, which come from inspection processes, and process data, which comes from in-situ monitoring solutions. In this way, quality control loops are triggered only by inspection stages, which may come significantly later than the process in which the defect could have originated. Thus, quality strategies are usually implemented as feedback loops, leading to issues such as delay in the defect identification, difficult root-cause analysis for quality problems, defect detection and repair / rework as a main correction strategy, and lack of concurrent analysis of product and process data.

On the other hand, ZDM strategies aim at proactively identifying defects or potential defects and attempt to find methods that (1) prevent defects in the first instance and (2) avoid rework by compensating for defects and deviations downstream in the process chain, by means of feedforward control loops. A schematical representation of such ZDM strategies is depicted in Fig. 11. As shown, the ZDM paradigm grounds on the integration of product and process data coming from multi-source process chains.

In the following sections, we describe these two ZDM strategy types in more detail.

4.1. Defect prevention

Defect prevention can be achieved when the process is known in depth and a machine state analysis is done so that process conditions leading to defects or possible deviations of the product from expected outcome are proactively identified. According to the extant literature, some of the main situations where this strategy could be successfully applied are (i) production systems based on chemical and thermal processes, and (ii) multi-stage machining systems.

In case (i), the type of chemical and thermal reaction occurring in pharmaceutical production or semiconductor fabrication, depends strongly on machine condition. Moreover, in this type of production, defect compensation or mitigation is quite difficult, due to the continuous nature of the process. Hence, to reach a zero-defect condition, quality strategies should focus on defect avoidance. Some examples are presented in (Huang et al., 2018) with respect to the semiconductor fabrication, and in (Dengler et al., 2021) in relation to pharmaceutical production.

In case (ii), multi-stage machining systems are characterized by propagation of dimensional deviations, which may not be identified as defects at single-stage level, but that together accumulate and present a defect at the end of the production line. Hence, the prediction of defects according to process conditions avoid the propagation of deviations along the process chain (Du, Ho and Kaminski, 2021).

4.2. Defect mitigation or compensation

Defect compensation strategies are typical of those production systems where product quality strongly depends on dimensional and geometrical features. Defect compensation can be widely used as ZDM strategy to replace rework activities, which wastes time and resources and does not add value with respect to the core product process chain. Some of the main applications of ZDM compensation strategies can be found in (i) multi-stage machining systems, (ii) assembly systems.

In multi-stage machining systems, well-known methodologies such as stream-of-variation can be used to adapt the downstream process (usually by acting on fixture positioning) to avoid the propagation of dimensional and geometrical deviations of the measured part (Magnanini et al., 2019). If a model-based solution is not available, due to the line complexity, specific downstream

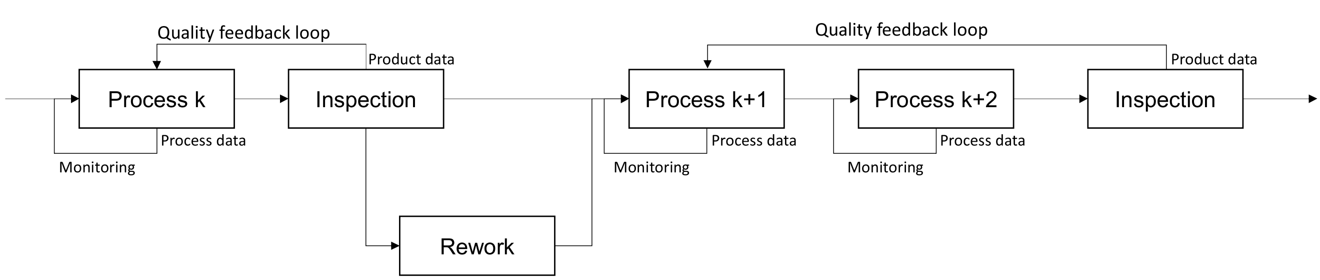

Fig. 10. Schematical representation of traditional quality strategies.

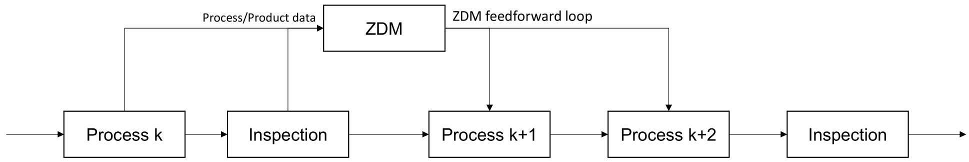

Fig. 11. Schematical representation of ZDM strategies.

compensation actions can be defined, without the need of off-line rework (e.g., Eldessouky et al., 2019; Eger et al., 2020).

In assembly systems, components which are individually within tolerance may result in a defective assembled product due to the intrinsic parts variability. Hence, compensation strategies such as selected assembly, where components are matched in order to minimize the expected assembled product deviation, could support in avoiding rework or even end-of-line inspection resulting in scrap products (M. Colledani et al., 2014a, 2014b).

5. Gap analysis and future research paths

In this section we provide a narrative of ZDM research gaps as identified by Psarommatis et al. (2020) and build on this seminal work by offering further directions for future research.

5.1. Research gaps

Table 1. presents the ZDM research gaps and narrative as offered by Psarommatis et al. (2020).

Research Direction (Psarommatis et al., 2020)	
Shift from local to global solutions	*An effective zero defect manufacturing system can only be achieved by adopting a holistic approach - not only to achieve zero defects but also to maximise quality and performance via integration of four ZDM strategies (detection, repair, prediction, and prevention). Though there are currently many collaborative projects (both at national and international scale) aiming at achieving such ZDM systems, high impact scholarly papers on the subject are yet to be published.*
Investigate pros and cons	*One of the most significant advantages of zero defect manufacturing is cost reduction due to waste elimination. Nonetheless, having the goal of manufacturing with zero defects may result in negative impact on other performances in trade-off such as time and resources required to achieve such an objective. However, many of the previous studies investigating the pros and cons of zero defect manufacturing specifically are quite few, and a more thorough analysis on the subject should be considered for further research in the field.*
Role of people and human activities in manufacturing	*The most important aspect of manufacturing is sometimes largely neglected: people. The manufacturing system is often viewed simply as a collection of processes and / or process chains only. However, manufacturing quality is often significantly impacted by the human-in-the-loop. The role of people in ZDM should be investigated further. This is significantly under-researched and is certainly a topic to be explored further.*
New business models for ZDM	*Financial analyses from the business point of view are also missing from much of the extant ZDM literature. Therefore, future research must provide economic information regarding the performance of particular ZDM use cases, and provide further insight into business aspects and benefits concerning the implementation of the specific ZDM methods.*

We suggest that although these research directions are both relevant and timely based on earlier extant literature, through our analysis we can be more specific in terms of future research opportunities. As such, these are described in the following section.

5.2. Future research opportunities

Based on the aforementioned research gaps, we identify the following five areas for future ZDM research. These areas are further grouped in two specific streams – advancing ZDM research and overcoming the global application challenges of ZDM.

Advancing ZDM.

1. Beyond ZDM: Zero-waste value-chain strategies
2. Fast transfer of ZDM solutions for First-Time-Right and quality ramp-up minimization
3. Human-in-the-loop

Overcoming the global application challenges of ZDM

4. Information & communication technology (ICT) solutions for the secure horizontal and vertical data integration
5. Extension of defect prevention and compensation ZDM strategies to less explored manufacturing processes

We present an overview of the future research themes as well as a Research Framework for Advancing ZDM (Fig. 12) in the following sections:

As the analysis of the state of the art has shown so far, research on ZDM strategies and solutions have reached already a good level of maturity. Hence, the available research should push towards the technological transfer of the ZDM solutions to the global industry, while going forward in the theoretical research. Grounded on this view, the following paragraphs focus on the characterization of research guidelines and directions, to boost ZDM research and applications in practice.

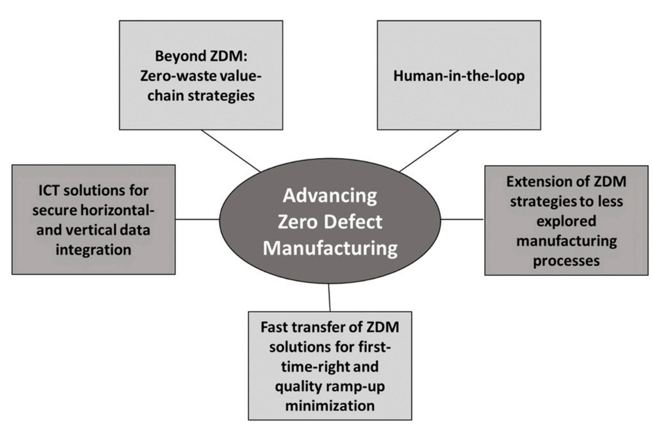

Fig. 12. A Research Framework for Advancing Zero Defect Manufacturing.

5.3. Research directions to advance ZDM

5.3.1. Beyond ZDM: Zero-waste strategies at value-chain

In its core, ZDM aims to achieve zero defects in a production system: scrap reduction, lower production costs, shorter production times, higher productivity, and a higher resource and energy efficiency. In the last decade, the strong focus on digitalizing the manufacturing environment has pushed the ZDM frontier to apply several Industry 4.0 technologies even closer to zero defects. However, the increasing emphasis on sustainable production requires that manufacturing companies continuously deliver higher quality products of increasing complexity at lower cost, while limiting the use of resources within entire industrial ecosystems. One of the four distinctive strategies in ZDM is to repair and increase parts and product lifetime. The ZDM can be basis to transform the traditional manufacturing chain from linear to circular by finding ways to repair and re-use materials, parts, and products to last more than only one product lifecycle.

To move towards zero waste, ZDM must integrate circular economy initiatives and sustainability aspects. To this aim, following progresses beyond current state-of-the-art should be attained: (i) Non-destructive inspection methods and quality monitoring solutions to detect defects without consuming or wasting material; (ii) Diagnostics and defect avoidance methods should be developed to prevent and predict defects and waste; (iii) Circular value-capture solutions aiming at the re-use, re-cycle, re-manufacture of products or defective products to minimize the effect on the environment.

5.3.2. Fast transfer of ZDM solutions for First-Time-Right and quality ramp-up minimization

In a continuously evolving context, manufacturing companies must adapt quickly and react fast to changes. Manufacturing systems have reached a mature level of reconfiguration capabilities thanks to technological and software innovations. However, companies still struggle to adapt production strategies, as ZDM solutions, to new or changed manufacturing systems. Firstly, this occur because often ZDM strategies have been optimized for the specific use-case. Secondly, the effort in data gathering, modelling, and optimization takes much time with respect to the actual system reconfiguration or product changeover. This is even more evident in manufacturing contexts characterized by one-of-a-kind production, where general first-time right solutions are extremely challenging, and where data availability is very limited, e.g., manufacturing of large parts for energy applications. Moreover, these sectors are usually characterized by strict quality requirements and high precision. Hence, companies find themselves in continuous ramp-up phase with respect to the production. To tackle this issue and achieve the first-time right, solutions dedicated to the knowledge transfer of ZDM strategies from one product to another (as well as fast model generation and parameter tuning) should be studied. At the same time, more integrated approaches for the product design and engineering could be explored, for companies to gather and distribute knowledge about production not only at shop-floor level but also in departments which are usually treated separately with respect to production.

The goal of this research direction is therefore to study integrated solutions for the design, engineering, and manufacturing of scalable ZDM solutions, which could formalize and make available the distributed and unstructured knowledge of a company.

5.3.3. Human-in-the-loop

Until recently, ZDM has neglected manual-intensive manufacturing processes, having focused on more automated processes. However, given the available technological solutions for operator assistance, as well as the spread of human-robot collaboration systems, the human factor cannot be neglected anymore. When the human factor is kept in the loop, capabilities become extremely flexible. Moreover, the empowerment and training of workforce allow for clear improvements. Important aspects are represented also by the existing knowledge in people-centric processes, as product and process design, as well as manual or partially manual processes, e.g., assembly or human-robot collaborations.

In this context, knowledge capturing, transferring and distribution between workforce as well as production phases becomes both challenging and promising. For instance, in assembly operations, tasks to ease the assembly and allow a better knowledge of the process for instructions and quality verification represent a possible direction of research. At the same time, the relation between human processes and quality has been rarely investigated, for clear data privacy issues and modelling challenges. Nevertheless, research should allow for solutions where the human knowledge and capabilities are enhanced, and where digitalization supports the workforce, who represents the real innovation source in manufacturing and have the real resilience capabilities in unexpected contexts.

5.4. Research directions to overcome application challenges of ZDM in global industry

5.4.1. Information technology solutions for the secure horizontal and vertical data integration

When ZDM solutions are to be implemented in industries, issues like data security and data safety to gather, integrate and re-elaborate data from different sources and software will need to be solved. As it has been noticed within the state of the art analysis, most of the applied research focus on the implementation of specific solutions within the manufacturing company borders, and especially at shop-floor level. However, more advanced ZDM solutions which have been proposed within the years by researchers lack application also because of implementation complexity with respect to available software solutions for the secure horizontal and vertical data integration. In this context, horizontal data integration should aim at the development of Key Enabling Technologies (KET) to integrate and fuse data from different sources, as ERP, MES and PLM, while vertical data integration should focus on the data sharing among companies to follow the product life-cycle.

Challenges for this objective include the generalization of data models for scalable solutions, the development of secure and standardized communication protocols, as well as advanced data mining solutions to store and use available data. It should also be mentioned that the success of this research direction is the key for the widest applicability of ZDM solutions not only to Large Enterprises, but also to Small and Medium Enterprises (SMEs), which usually suffer of the so-called digital divide. Hence, results of the proposed research direction would enhance the competitiveness of SMEs, which represent most European companies.

5.4.2. Extension of defect prevention and compensation strategies to less explored manufacturing processes

The analysis performed in the previous Sections has shown that the wide number of ZDM solutions introduced by researchers has on the other hand been applied to a restricted number of manufacturing technologies and processes. To overcome this issue, challenges for the extension of defect prevention and compensation strategies to less treated manufacturing processes should be understood.

For instance, ZDM solutions for continuous processes are yet to be explored. Indeed, continuous manufacturing processes are complex, often they rely on thermal transformation which makes difficult the characterization of defect compensation. To this aim, inspection solutions and advanced monitoring become extremely relevant when dealing with continuous processes. Indeed, in this case defect prevention solutions should represent the objective of the research. Defect prevention implies high knowledge of the underlying process, which is often translated into advanced model-based Digital Twins of the process for the proactive identification of deviating process condition leading to defective output. Hence, one of the objectives for this research direction would be to focus on continuous production, characterized by complex multi-stage dynamics and evolving product material properties. Examples are steel extrusion, pharmaceutical production, food production and semiconductor fabrication, where the synchronization between production stages must be extremely accurate in order to avoid the excess of product permanence in specific stages which would be resulting in defective output, e.g. ovens, or where process parameters must adapt to the product characteristics obtained by means of chemical or thermal transformation acting on the material properties, e.g. extrusion of steel bars.

6. Conclusion

Through adopting SLR as our research method, the aim of this paper was to present a thorough and critical review of literature with the objective of bringing out pertinent factors and useful insights into developments and advances in Zero Defect Manufacturing (ZDM). The academic literature available on ZDM was critically reviewed and classified into the most prominent subject areas, which were (i) scope (single-, multiple-, or system-level); (ii) focus (product-, process-, or people-centricity); (iii) type (theoretical or applied); (iv) hierarchical level (strategic, tactical, or operational); and (v) technology (KETs). By analysing each of these areas, some specific directions for further research have been identified, and were used to develop the research framework for advancing ZDM (shown in Fig. 12).

Although this literature review may not be exhaustive, it serves as a scientifically grounded and comprehensive base for understanding the application, implications, and further developments of ZDM. As such, the work makes a significant theoretical contribution in that we have mapped specific requirements for the future research of academics and scholars aiming to study and advance the field of ZDM. We also contribute to practice by providing factors and insights for practitioners to consider when designing and implementing ZDM solutions, in practice, beyond discrete, single process applications. As Psarommatis et al. (2020) points out, there is a particular synergy to be realised through well-structured collaboration between industry and academia. Therefore, we suggest that these goals are best achieved through action-oriented research, in practice.

We also discovered that much of the research focussed on detecting and fixing defects, rather than predicting and preventing them. Though much can be learned from defect detection and repair, we suggest that these should not be considered zero defect strategies – where *"right-first-time"* is the recognized standard. We therefore identified two core ZDM strategies – *defect prevention* and *defect compensation* – both of which present important areas for further research in ZDM.

Additionally, future ZDM research must stretch beyond individual processes and factory shopfloors to involve other critical functions. For example, we also discovered a lack of the adoption of a systems perspective in current ZDM research. Though an operational perspective is critical to succeeding with ZDM, the key to eliminating defects is to understand the company as a system. Thus, future ZDM research should also include product development and market perspectives to close the loop and foster continuous improvement and organization-wide learning (early Zero-Defect research considered design and engineering functions, though recent efforts consider only digitalization of the shop floor). For example, current ZDM research focusses on producing zero-defect products. However, the manufacturing phase can often still be too late to avoid or compensate for defects. Hence, future research should focus on the re-design of products to further avoid defects which have been detected during the manufacturing or use phase. This implies that information about the manufacturing and use should become accessible to product designers. This research direction will also put the human factor at the centre of ZDM, since design and engineering is still very much a people-centric activity. Research in this field should focus on the integration of multi-source data from product life-cycles, and knowledge extraction and formalization that can be re-applied in the design phase.

Future ZDM research should also consider sustainability and green economy initiatives. For example, ZDM for Zero Waste is currently an important focus area on the European research agenda (Horizon Europe, 2021) that should combine ZDM efforts with Circular Economy approaches. As such, from the perspective of control actions, sustainability should also be emphasized, to have not only zero-defect products and processes, but also zero-waste production systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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