CEN WS ZDMbasics

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Zero Defects Manufacturing – Basic Principles and Requirements

Fabrication zéro défaut – Principes de base et exigences

ICS: 03.120.10

CCMC will prepare and attach the official title page.

Contents

Foreword

This CEN Workshop Agreement (CWA 18230:2025) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid way to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by the Workshop ZDM Basic Principles and Requirements, the secretariat of which is held by DIN consisting of representatives of interested parties on 2023-09-08, the constitution of which was supported by CEN following the public call for participation made on 2023-07-18. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

Manufacturing Companies use a variety of quality management methods to improve their operational performance to attain high-quality production standards. The application of Industry 4.0 technological advances along the production process chain has led to a fundamental change in manufacturing quality management systems. These advances make it possible to achieve unprecedented levels of manufacturing quality and to produce high-quality products most efficiently, i.e., to realize the paradigm of zero-defect production.

Zero Defects Manufacturing (ZDM) is the latest and most advanced approach to quality assurance, combining data-driven strategies and modern technologies to ensure defect-free production. It is built upon four foundational strategies: “Detect” and “Predict” as the triggering strategies, and “Repair” and “Prevent” are the action strategies. These are applied in pairs to form three core combinations: “Detect-Repair”, “Detect-Prevent” and “Predict-Prevent”. The fourth pair “predict-repair” is not possible because repair is happening when a defect has happened, the concept of prediction is to predict when something will happen in the near future and since it has not yet occurred to prevent it. The main difference between 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. 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. Modern technological advancements provided capabilities that were not possible in the past. These technological advancements initiated the emergence of another QMS method named Zero Defect Manufacturing (ZDM).

A key differentiator of ZDM is its reliance on both historical and real-time data, enabling the prevention of defects before they occur. This integration of data streams transforms manufacturing processes by incorporating quality control applications across production lines, machinery, automation systems, and supply chains. Such capabilities are made possible through the development of IT systems and the principles of Industry 4.0, creating a seamless flow of information and actionable insights. A key differentiator of ZDM is its reliance on both historical and real-time data, enabling the prevention of defects before they occur. This integration of data streams transforms manufacturing processes by incorporating quality control applications across production lines, machinery, automation systems, and supply chains. Such capabilities are made possible through the development of IT systems and the principles of Industry 4.0, creating a seamless flow of information and actionable insights.

Short version of ZDM definition

ZDM is a holistic approach for ensuring both process and product quality by reducing defects (CWA 17918)

Detailed ZDM definition

ZDM is a holistic approach for ensuring both process and product quality by reducing defects through corrective, preventive, and predictive techniques, using mainly data-driven technologies and guaranteeing that no defective products leave the production site and reach the customer, aiming at higher manufacturing sustainability

1 Scope

The workshop will create a CEN-CENELEC Workshop Agreement (CWA) with the proposed titles: "Zero Defects Manufacturing – Basic Principles & Requirements ". The WS will define the basic principles and requirements for Zero Defects Manufacturing and set the basis for ZDM conformity assessment. It provides a structured framework to guide organizations in achieving operational excellence through defect prevention, predictive analytics, and continuous quality improvement, leveraging the latest advancements in Industry 4.0 technologies.

- Define Basic Principles of ZDM: Establish the foundational concepts and methodologies for implementing and sustaining ZDM practices across manufacturing environments. Clarify the roles of detection, prediction, repair, and prevention strategies in achieving defect-free production.
- Set Requirements for ZDM: Specify minimum technical, organizational, and process requirements for adopting ZDM methodologies effectively. Address integrating ZDM principles with existing quality management systems and operational processes.
- Develop ZDM Conformity Assessment: Propose a comprehensive evaluation system to assess and certify manufacturers based on their adherence to ZDM principles and their level of operational maturity.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/

— IEC Electropedia: available at http://www.electropedia.org/

3.1
Zero Defect Manufacturing (ZDM) Ready

"ZDM Ready" refers to the preparedness level of a manufacturing system to adopt and implement Zero Defect Manufacturing strategies effectively. It assesses whether the necessary organizational, technological, and procedural foundations are in place before ZDM can be systematically deployed.

Key Components:

- Personnel (PE)

- Procedures (PR)

- Infrastructure (INF)

- Company Culture (CC)

3.2
Zero Defect Manufacturing (ZDM) Achieved

"ZDM Achieved" denotes the operational stage in which an organization has successfully implemented ZDM strategies to ensure real-time defect detection, prediction, and prevention. Production systems consistently deliver defect-free outputs.

Key Characteristics:

- Real-time monitoring and AI insights

- Closed-loop feedback

- Achievement of KPIs

- Integration of sustainability and predictive maintenance

3.3
Capability Maturity Model Integration (CMMI)

CMMI is a globally recognized framework for assessing and improving an organization's process maturity. It provides structured levels to evaluate how well an organization's processes enable quality outcomes and continuous improvement.

3.4
ZDM Maturity Levels (based on CMMI)

3.4.1
Opportunistic Excellence

Processes are ad hoc and reactive. There is no formal documentation or repeatability. ZDM cannot be implemented.

3.4.2
Process-Governed Excellence

Processes are documented and tracked at the project level. Some ZDM components, like detection, may begin to appear.

3.4.3
Systematic Excellence

Processes are standardized across departments. Preventive strategies and basic predictive tools begin to be deployed.

3.4.4
Performance Excellence

Data and KPIs are actively used. Predictive analytics and semi-autonomous systems support real-time decision-making.

3.4.5
Evolutionary Excellence

AI-driven systems drive continuous improvement. Processes are autonomous and proactively prevent defects.

3.5
Pre-Production Phase Stages in ZDM Implementation

3.5.1
Readiness Assessment

Evaluate ZDM readiness across Personnel, Procedures, Infrastructure, and Company Culture pillars.

3.5.2
Product/Process Analysis

Identify if ZDM approach will be product-oriented, process-oriented, or hybrid.

3.5.3
BoM & BoP Analysis

Analyze the Bill of Materials and Bill of Processes to determine critical stages for ZDM intervention.

3.5.4
Task Ranking

Rank each manufacturing task based on defect impact to prioritize intervention.

3.5.5
Strategy Pairing

Apply appropriate ZDM strategies: Detect–Repair, Detect–Prevent, or Predict–Prevent.

3.5.6
Technology Deployment

Select and implement detection, prediction, and prevention technologies based on the design cycle.

4 ZDM basic principles and requirements

The evaluation and certification of a manufacturing system should be performed in two steps. The first step is during the pre-production phase, which means before the production of a product starts, and during the production phase, the efficiency of the designed and applied ZDM methods and tools is measured (Figure 1).

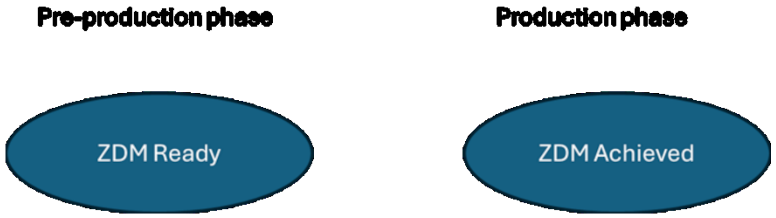

Figure 1: ZDM stage

In the context of ZDM, the Capability Maturity Model Integration (CMMI) is instrumental in helping manufacturers evaluate their current capabilities, identify areas for improvement, and systematically progress toward achieving ZDM goals. The CMMI provides a structured approach for assessing and improving an organization's process maturity.

4.1 Evaluation procedures Capability Maturity Model Integration (CMMI)

Capability Maturity Model Integration (CMMI) is a model for evaluating an organization's processes, which was developed by Carnegie-Mellon University (USA) in 1986 for software implementation processes[1]. This Model provides a structured approach for assessing and improving an organization's process maturity. In the context of Zero Defect Manufacturing (ZDM), CMMI is instrumental in helping manufacturers evaluate their current capabilities, identify areas for improvement, and systematically progress toward achieving ZDM goals. By aligning ZDM implementation with CMMI's five maturity levels (Figure 2), organizations can adopt a clear roadmap for enhancing processes, technology integration, and workforce capabilities.

- **At Level 1 (Initial)**, processes are reactive, ad hoc, and poorly controlled. There is minimal emphasis on defect prevention, and efforts are typically focused on addressing issues after they occur. ZDM readiness is absent at this stage, as foundational infrastructure such as data collection systems and predictive analytics is not in place.
- **Progressing to Level 2 (Managed)** involves establishing repeatable processes, implementing basic defect detection mechanisms, and introducing systematic tracking of production metrics. These steps lay the groundwork for ZDM readiness by fostering consistency and enabling organizations to start monitoring and managing quality.
- **Reaching Level 3 (Defined)** marks a significant milestone where processes are standardized and integrated across departments. Organizations establish formalized defect prevention strategies, clear data structures, and systematic inspection methods. At this stage, predictive capabilities begin to emerge, supported by robust data collection and analytics frameworks. This level aligns closely with ZDM readiness, demonstrating a manufacturer's ability to control variability, track defects effectively, and create a stable foundation for advanced ZDM practices such as real-time monitoring, dynamic scheduling, and AI-driven quality management.
- **Advancing to Level 4 (Quantitatively Managed)** introduces a data-driven approach to quality management. At this level, organizations use quantitative performance metrics to monitor and control processes effectively. Predictive analytics and advanced monitoring tools are integrated into production systems, allowing real-time detection and prevention of defects. Key performance indicators (KPIs) such as First Pass Yield (FPY) and Cost of Poor Quality (CoPQ) are systematically tracked and analyzed to drive continuous improvement. Decision-making becomes semi-autonomous, leveraging predictive models and real-time data to enhance process stability and align with ZDM objectives.
- **Achieving Level 5 (Optimizing)** represents the pinnacle of maturity, where processes are fully autonomous and continuously improved through advanced technologies. At this level, organizations leverage artificial intelligence (AI), machine learning, and digital twins to optimize quality management dynamically. Real-time data insights enable systems to predict, prevent, and adapt to potential issues autonomously, ensuring defect-free production. This level fosters a culture of continuous innovation and flexibility, allowing manufacturers to respond seamlessly to changing demands, disruptions, or new requirements. Sustainability becomes a core focus, with ZDM supporting waste reduction, resource efficiency, and environmental goals.

[1] Mateo-Casalí, M.Á., Fraile, F., Boza, A., Poler, R. (2023). A Maturity Model for Industry 4.0 Manufacturing Execution Systems. Industry 4.0: The Power of Data. Lecture Notes in Management and Industrial Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-29382-5_22

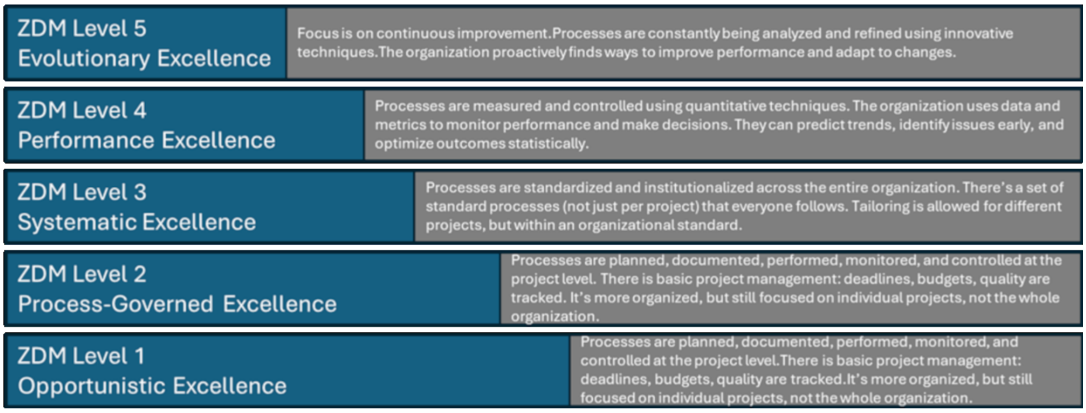

Figure 2: CMMI Levels

4.2 Pre-production phase

The adoption level of ZDM is influenced by multiple variables from all the different levels in a manufacturing system. A manufacturing system is encompassed by its operational and information technologies and the organization's behaviour, i.e., people, procedures, and information flow. Four pillars define ZDM readiness: “Personnel” (PE), “Procedures” (PR), “Infrastructure” (INF) and “Company culture” (CC)[2]. If a company performs well in these four pillars, then the level of readiness is high for adopting ZDM (Figure 3).

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[2] Psarommatis, F., May, G., Azamfirei, V., Magnanini, M.C. and Powell, D., 2023, June. A readiness level assessment framework for Zero Defect Manufacturing (ZDM). In International Conference on Flexible Automation and Intelligent Manufacturing (pp. 451-459). Cham: Springer Nature Switzerland.

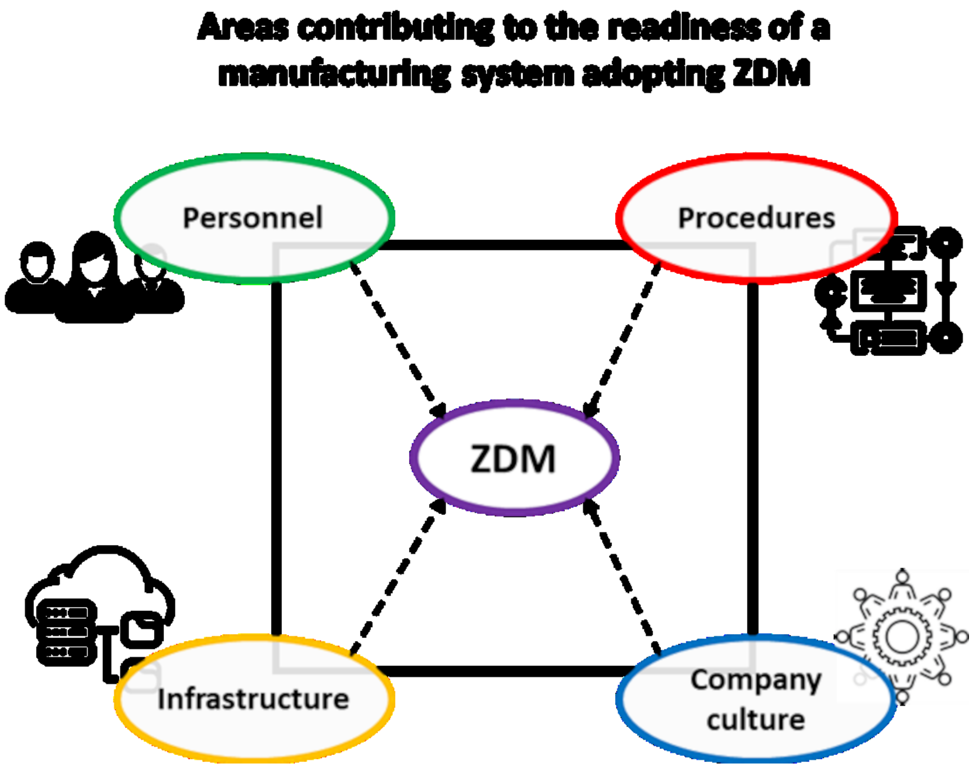

Figure 3: Key pillars for ZDM readiness[3]

4.2.1 Procedures

Figure 4 presents the four individual strategies that comprise ZDM, namely Detect, Predict, Repair, and Prevent, alongside the corresponding connections. The four ZDM strategies are divided into two categories: triggering factors and actions. The triggering strategies are Detect and Predict, which are responsible for identifying a quality issue. Notably, the triggering ZDM strategies must be applied for every product. Detect can be divided into physical and virtual detection of a defect that has already occurred. In contrast, Predict is responsible for predicting when a defect will occur soon. Those two triggering strategies alone cannot increase the quality of the production. For that reason, there are the other two ZDM strategies, Repair and Prevent, which are the actions that can be taken in the event of input from the triggering ZDM strategies. This means that ZDM strategies must always be used in pairs, using one triggering strategy and one action strategy. By doing so, the following ZDM strategy pairs are formed:

- Detect–Repair
- Detect–Prevent
- Predict–Prevent

[3] Psarommatis, F., May, G., Dreyfus, P.A. and Kiritsis, D., 2020. Zero defect manufacturing: state-of-the-art review, shortcomings and future directions in research. International journal of production research, 58(1), pp.1-17.

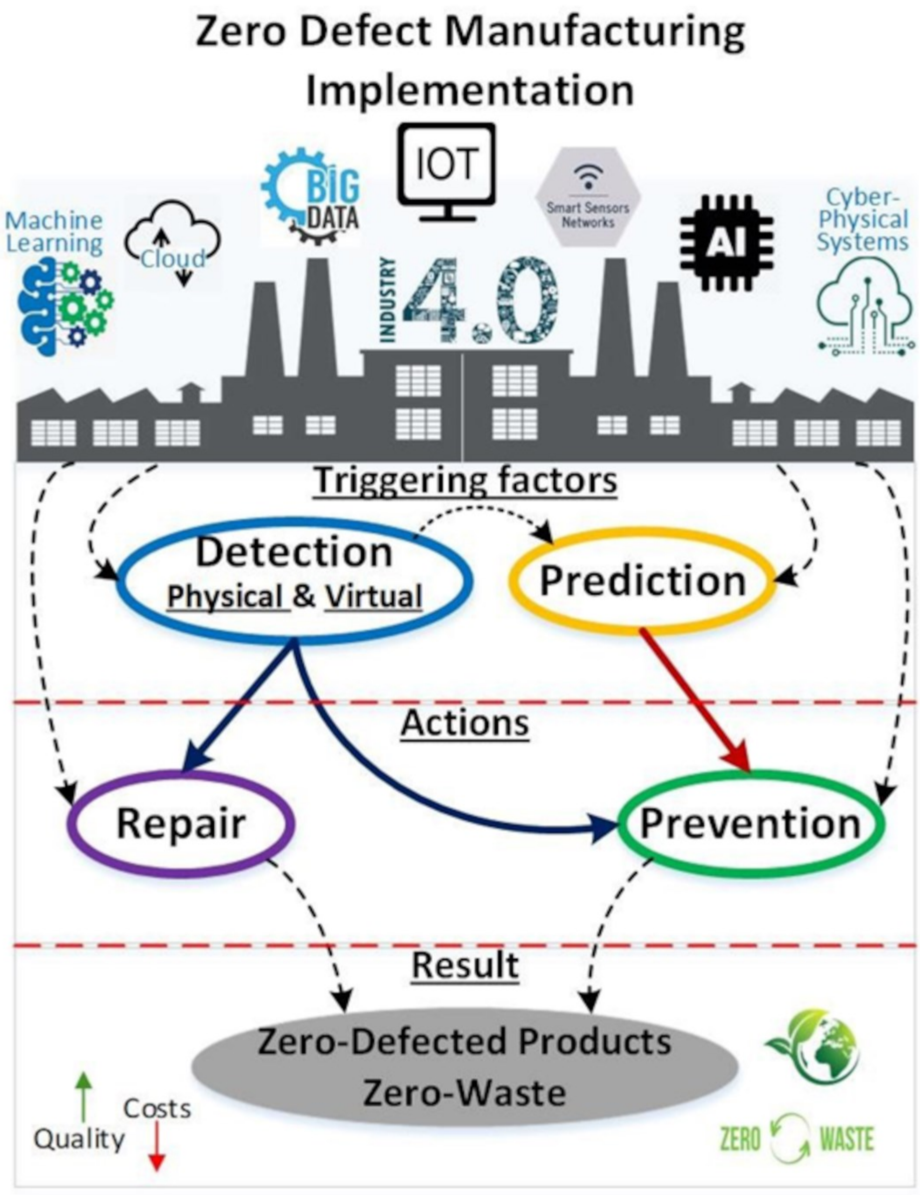

Figure 4: ZDM strategies

Figure 5 illustrates the steps that should be followed for the implementation of ZDM for a specific product[4]. 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 is more available data; therefore, the ZDM design 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 of the 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

[4] Psarommatis, F. and May, G., 2023. A practical guide for implementing Zero Defect Manufacturing in new or existing manufacturing systems. Procedia Computer Science, 217, pp.82-90.

assurance implementation. The first required information is identifying the most optimum ZDM approach: product-oriented, process-oriented or hybrid. 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. 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 for each for ZDM implementation. After ranking the tasks and starting from the task with the highest impact if defective, the three ZDM pair strategies are investigated to calculate the performance of each ZDM pair strategy for each case. Based on the produced ZDM performance maps, the proper ZDM technology will be developed or selected and deployed.

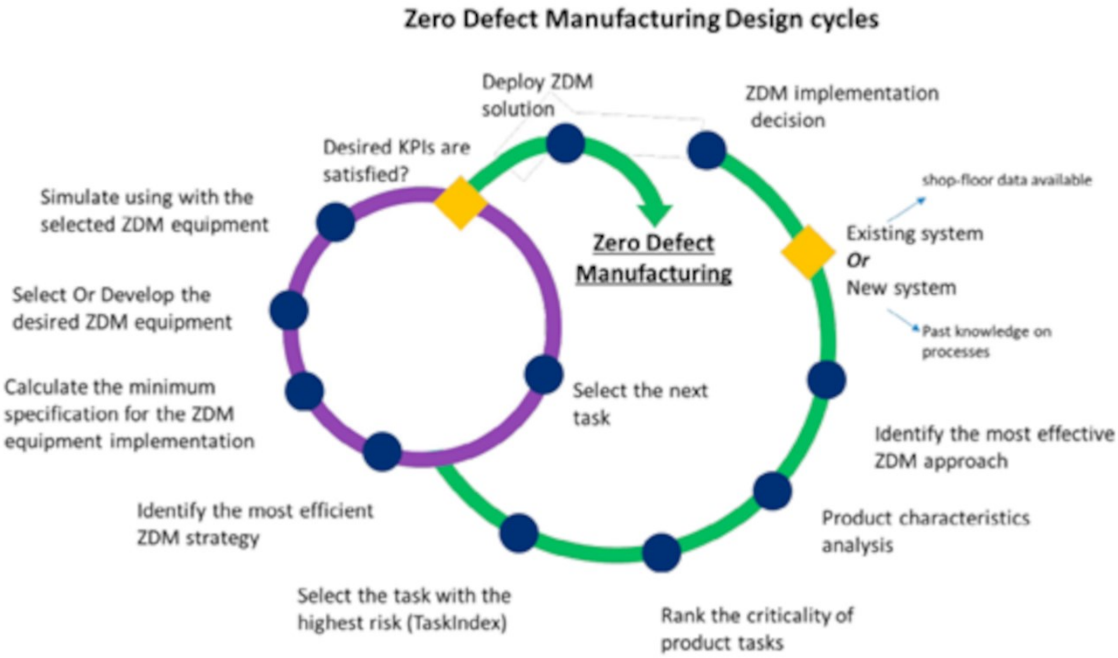

Figure 5: ZDM manufacturing design cycles[5]

4.2.2 Infrastructure and Procedures

- MES
- Dynamic scheduling tool
- Sensors
- Data analytics

[5] Psarommatis, F. and May, G., 2023. A practical guide for implementing Zero Defect Manufacturing in new or existing manufacturing systems. Procedia Computer Science, 217, pp.82-90.

- Type of inspection (inline, off line, in process etc.)
- Level of inspection automation
- Level of decision making automation
- Production flexibility
- Production adaptability
- Average response time to events
- Material tracking
- Data tracking
- Repairing capabilities
- Inspection capabilities
- Prediction capabilities
- Prevention capabilities
- Lifecycle monitoring and analysis capabilities
- Product traceability capabilities
- Explainability and trustworthiness of AI systems
- Defect identification and risk assessment

MES		
Level 5	Evolutionary Excellence	Efficient management of MES: clear implementation of optimized plans embedding ZDM strategies, according to dynamic scheduling tool and installed sensors
Level 4	Performance Excellence	Clear availability of traceable manufacturing and quality operations in terms of timing and monitoring (start-end) Integration with dynamic scheduling tool for adaptive ZDM strategies
Level 3	Systematic Excellence	Clear integration of MES with ERP systems in terms of tracked production orders, productivity and quality outcome.
Level 2	Process-Governed Excellence	Clear understanding of the automated execution of process operations. Process operations, without accounting for quality inspection, are initiated mostly automatically
Level 1	Opportunistic Excellence	Operations are started manually, according to the M-BOM. In case of rework, it is managed autonomously. Production plans are defined based on infinite capacity (ERP) and not updated according to disruptions occurring at shopfloor level.

Dynamic scheduling Tool

Level 5	Evolutionary Excellence	Clear understanding of the different events that will take place during the manufacturing process. The events are all those qualities or not events that can disrupt the normal production schedule. Such events are defects detection, defects prediction, new orders, machine break down etc..
Level 4	Performance Excellence	Based on the different events, make the mitigation actions as flexible as possible to be feasible
Level 3	Systematic Excellence	For each of these events, the problem must be analyzed at a high level and a plan developed to mitigate the events
Level 2	Process-Governed Excellence	Identify the reaction times for each of the events to have information for optimal rescheduling
Level 1	Opportunistic Excellence	Perform the rescheduling in fixed intervals

Data Analytics		
Level 5	Evolutionary Excellence	Implement a data-driven culture of continuous improvement, using advanced analytics to optimize processes in real-time and adapt quickly to change.
Level 4	Performance Excellence	Establish a real-time monitoring system to proactively detect and respond to anomalies (Need with ZDM). This will allow data to be actively analyzed and prevent errors or failures in production
Level 3	Systematic Excellence	Full integration of sensors and data acquisition systems in the plant (e.g. in alignment with the data source). Once this data is acquired, a tool must be implemented to assist in data cleansing and transformation to ensure data integrity and quality (necessary to analyze the data).
Level 2	Process-Governed Excellence	Deploy advanced data analytics tools and platforms to identify patterns, trends and potential defects in production, including staff training in data analysis tools and interpretation of results for informed decision making.
Level 1	Opportunistic Excellence	Communication with data resources must be considered. Implement basic data collection from sensors.

Type of inspection		
Level 5	Evolutionary Excellence	Inspection should integrate holisticness, i.e. can be linked with production, maintenance, and virtual metrology data.
Level 4	Performance Excellence	Detect-Prevent. Inspection data, together with other sources of data, allow for accurate adjustment to deviations. 100% inspection

Level 3	Systematic Excellence	Detect-'Prevent' - Inspection data offers root-cause analysis.
Level 2	Process-Governed Excellence	Data just in time. Establish the right inspection condition and sensor depending on the quality problem.
Level 1	Opportunistic Excellence	Inspection based on samples or manual inspection

Level of inspection automation		
Level 5	Evolutionary Excellence	Adjustable. Inspection can be highly physically (sensors) or cognitively (AI) automated. ZDM can still be achieved with manual inspection, but the cognition should be considered and evaluated for ZDM and vice-versa.
Level 4	Performance Excellence	The level of inspection automation can be increased or decreased depending on the ZDM strategies.
Level 3	Systematic Excellence	Inspection time can be reduced with the increase or decrease of the level of inspection automation.
Level 2	Process-Governed Excellence	Level of inspection automation allows for accurate and repeatable decisions upon conformity.
Level 1	Opportunistic Excellence	Manual inspection

Repairing/ rework and prediction capabilities		
Level 5	Evolutionary Excellence	Smart devices are utilized to reduce defectives to near zero levels of performance autonomously, and feedback is used to optimize the system continuously.
Level 4	Performance Excellence	Smart devices utilized to autonomously reduce (predict and prevent) defectives to near zero levels of performance.
Level 3	Systematic Excellence	Smart devices (sensors-actuators) are in place for the prediction and prevention of defective units. ML algorithms may be in place for some degree of autonomy, but Explainable AI (XAI) is used to inform operators of the best response.
Level 2	Process-Governed Excellence	Smart devices (sensors-actuators) in place for prediction of defective units, and operators are notified to and prevent occurrence
Level 1	Opportunistic Excellence	Smart devices (sensors-actuators) are in place for detection of defective units only. Operators must be notified of defect and manually recover system.

Sensors

Level 5	Evolutionary Excellence	At the highest maturity level, sensors enable fully autonomous defect prevention and quality control systems. They are embedded in cyber-physical systems and seamlessly integrated with advanced analytics platforms, including AI and digital twins. Sensor data is used not only for real-time monitoring but also for proactive optimization of processes. Adaptive networks of sensors can self-calibrate, detect anomalies, and respond to dynamic changes in the manufacturing environment. This level supports ZDM achievement by providing actionable insights for continuous improvement and aligning with sustainability goals such as energy efficiency and waste reduction.
Level 4	Performance Excellence	Sensors provide advanced real-time data analytics, enabling predictive maintenance and defect prevention. Sensor networks are tightly integrated with Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) systems, allowing for dynamic scheduling and real-time adjustments based on sensor feedback. The sensor data is used to calculate Key Performance Indicators (KPIs) such as process stability, defect rates, and energy efficiency. Machine learning models use sensor data to identify patterns and make data-driven predictions.
Level 3	Systematic Excellence	At this level, sensors are standardized and fully integrated into a centralized data collection system. They monitor critical processes and product parameters in real-time, providing consistent and reliable data. Sensor networks are designed with clear data communication and storage protocols, ensuring compatibility and interoperability. Historical sensor data is organized and accessible for defect analysis and process optimization. Calibration, maintenance, and security protocols are formalized to maintain sensor reliability.
Level 2	Process-Governed Excellence	Sensors are installed to perform routine measurements and are integrated into some parts of the manufacturing system. Data from sensors is collected systematically but primarily used for monitoring rather than defect prevention. There is limited automation, and data analysis depends on manual intervention. Calibration processes are in place to ensure sensor accuracy, but these are not standardized across all devices. Traceability of sensor data begins to emerge but is not comprehensive.
Level 1	Opportunistic Excellence	At this stage, sensors are either non-existent or minimally deployed. Any monitoring is manual or limited to basic measurements, such as temperature or pressure, without integration into a centralized system. Data collection is sporadic, lacks consistency, and is rarely used for defect prevention. There is no sensor type or configuration standardisation, and data is not leveraged for quality improvement or real-time decision-making.

Level of decision-making automation

Level 5	Evolutionary Excellence	Decision-making is fully autonomous, supported by artificial intelligence (AI) and machine learning (ML). Systems predict and prevent defects by analyzing patterns and trends in real-time data and dynamically adjusting processes without human intervention. Autonomous systems handle complex, high-stakes decisions using advanced AI algorithms considering multiple variables, including cost, efficiency, and sustainability. Explainable AI (XAI) ensures that decisions are transparent and auditable. Feedback loops enable continuous learning, improving the system's ability to make optimized decisions over time. This level aligns with achieving ZDM by ensuring consistent, precise, and proactive quality management.
Level 4	Performance Excellence	At this stage, decision-making automation leverages data analytics and predictive models. Systems use advanced algorithms to detect issues and recommend corrective actions based on historical and real-time data. Decision-making is semi-autonomous, requiring human input only for high-impact or unusual situations. Integration with MES, ERP, and dynamic scheduling tools enables automated responses to disruptions, such as adjusting production schedules or reallocating resources. Decisions are data-driven, reducing variability and improving consistency.
Level 3	Systematic Excellence	Decision-making processes are formalized and partially automated, with algorithms supporting routine decisions based on predefined logic. For instance, quality control systems might automatically reject defective products or stop production lines when specific conditions are met. Automated decision-making begins to integrate with systems like MES, providing a structured approach to handling common scenarios. Human oversight remains critical for exceptions or complex decisions, but decision traceability and justification are established.
Level 2	Process-Governed Excellence	Basic automation begins to support decision-making, with standardized workflows and predefined rules guiding actions. For example, alerts or notifications are triggered when sensor readings exceed thresholds. However, decisions still require human intervention for analysis and action. Data is collected and visualized in dashboards, but decision-making depends on the expertise of operators or managers. Automation supports repetitive or low-complexity tasks but lacks adaptability.
Level 1	Opportunistic Excellence	Decision-making is entirely manual, relying on human judgment and experience. Operators or quality control personnel identify issues and determine corrective actions based on observation or basic data reports. Processes are reactive, with decisions made after defects occur. There is no system for systematically analyzing data or predicting potential issues, leading to inconsistent and delayed responses.

Production flexibility

Level 5	Evolutionary Excellence	Fully flexible production systems autonomously adapt to changes in product types, volumes, or process conditions. AI and predictive models ensure seamless transitions, optimizing resources and minimizing downtime.
Level 4	Performance Excellence	Production becomes highly adaptable, supported by dynamic scheduling tools and integrated data systems. Real-time adjustments are made based on sensor feedback or external factors, such as demand shifts.
Level 3	Systematic Excellence	Processes are standardized to support moderate flexibility. Systems can handle variations in product designs or volumes, with automated tools aiding quick reconfiguration of production lines.
Level 2	Process-Governed Excellence	Basic flexibility allows for minor adjustments, such as small changes in production schedules or product specifications. Changes are implemented manually and are supported by predefined workflows.
Level 1	Opportunistic Excellence	Production processes are rigid and designed for specific tasks or products. Any changes require significant manual intervention and time, with limited adaptability to new requirements or disruptions.

Production adaptability		
Level 5	Evolutionary Excellence	Fully adaptive systems autonomously adjust to disruptions, new products, or shifts in demand. AI-driven models optimize production flows and resource allocation, ensuring minimal impact on efficiency and quality.
Level 4	Performance Excellence	Production systems actively respond to real-time data and external factors, making semi-autonomous adjustments to process parameters. Integration with dynamic scheduling and MES ensures smooth adaptability.
Level 3	Systematic Excellence	Processes are designed with flexibility in mind, enabling automated reconfiguration for new product designs or volumes. Systems can adapt to scheduled changes with minimal manual input.
Level 2	Process-Governed Excellence	Basic adaptability allows for predefined responses to common disruptions, such as switching between limited product variants. Changes are handled manually with some guidance from standard operating procedures.
Level 1	Opportunistic Excellence	Production processes are static and unable to adapt to changes in product requirements or unexpected disruptions. Any adjustments require manual intervention and result in significant downtime.

Average Response Time to Events		
Level 5	Evolutionary Excellence	Responses are fully autonomous and immediate, driven by AI and real-time analytics. Systems predict and prevent disruptions proactively, ensuring seamless operations with negligible downtime.
Level 4	Performance Excellence	Response times are significantly reduced through advanced analytics and predictive tools. Real-time monitoring and semi-autonomous systems initiate corrective measures with minimal human input.
Level 3	Systematic Excellence	Systems are designed for faster responses, with partially automated processes to handle routine events. Data is analyzed in near real-time, enabling quicker detection and action.
Level 2	Process-Governed Excellence	Response times improve slightly with the implementation of predefined workflows. Notifications or alerts are generated for specific events, but corrective actions still require manual decisions.
Level 1	Opportunistic Excellence	Response to events is slow and manual, with significant delays between identifying an issue and taking corrective action. Processes rely heavily on human intervention and experience.

Material Tracking		
Level 5	Evolutionary Excellence	Fully autonomous tracking systems integrate with AI and predictive analytics. Real-time insights drive automated decision-making, ensuring materials are optimally allocated and disruptions are preemptively addressed.
Level 4	Performance Excellence	Advanced systems like IoT-enabled sensors and digital twins provide comprehensive tracking. Material flow is monitored in real time, with data used for dynamic adjustments and optimization.
Level 3	Systematic Excellence	Material tracking is standardized and integrated into a centralized system. Real-time data on material location and status is available, enabling better coordination and inventory management.
Level 2	Process-Governed Excellence	Basic digital systems are implemented for material tracking, such as barcodes or RFID. Tracking is limited to key points in the process but lacks real-time visibility.
Level 1	Opportunistic Excellence	Material tracking is minimal and largely manual, relying on paper-based systems or basic spreadsheets. Errors and delays are common, and real-time tracking is absent.

Data Tracking

Level 5	Evolutionary Excellence	Data tracking is fully automated and integrated with AI and machine learning systems. Real-time insights drive autonomous adjustments, while historical data is leveraged for continuous improvement and long-term optimization.
Level 4	Performance Excellence	Advanced tracking systems use IoT devices and automated tools to ensure comprehensive data collection. Data is analyzed in real time, supporting dynamic decision-making and enabling predictive insights.
Level 3	Systematic Excellence	Data tracking is formalized and centralized, providing a clear, standardized view of production data. Real-time tracking is introduced, enabling continuous monitoring and traceability across the production line.
Level 2	Process-Governed Excellence	Basic digital tools are used for data tracking, with structured systems for capturing specific parameters. Data is tracked at key stages but lacks real-time accessibility or integration.
Level 1	Opportunistic Excellence	Data tracking is limited and manual, with information recorded sporadically and inconsistently. Data is often siloed, making it difficult to analyze or utilize effectively.

Prediction Capabilities		
Level 5	Evolutionary Excellence	Fully autonomous prediction systems use AI and deep learning to identify complex patterns and forecast outcomes. Predictions are integrated with real-time decision-making, enabling proactive adjustments and continuous process optimization.
Level 4	Performance Excellence	Advanced analytics and machine learning models are implemented for more accurate and dynamic predictions. Real-time data is continuously analyzed, allowing systems to anticipate issues with higher precision.
Level 3	Systematic Excellence	Prediction capabilities are formalized with the integration of rule-based algorithms and structured data analysis. Systems begin to forecast potential defects or disruptions based on predefined parameters.
Level 2	Process-Governed Excellence	Basic statistical tools are used to identify trends or patterns in historical data. Predictions are limited and largely manual, relying on operator expertise rather than automated systems.
Level 1	Opportunistic Excellence	There are no predictive capabilities in place. Processes are entirely reactive, addressing defects and disruptions only after they occur. Data is insufficient for any form of forward-looking analysis.

Prevention Capabilities		
Level 5	Evolutionary Excellence	Prevention capabilities are fully autonomous and optimized

		through AI-driven insights. Systems dynamically adapt to changing conditions, preemptively addressing risks and ensuring near-zero defect operations while supporting continuous improvement.
Level 4	Performance Excellence	Advanced preventive measures are powered by real-time analytics and predictive models. Systems continuously monitor key parameters and autonomously adjust processes to avoid potential defects or disruptions.
Level 3	Systematic Excellence	Preventive strategies are formalized and integrated into the production process. Systems use structured data and predefined rules to identify conditions that could lead to defects, enabling limited proactive interventions.
Level 2	Process-Governed Excellence	Basic preventive measures are introduced, such as scheduled maintenance and standard operating procedures. Actions are guided by historical data and human expertise but lack automation or real-time responsiveness.
Level 1	Opportunistic Excellence	Prevention capabilities are non-existent. Processes are reactive, addressing defects only after they occur. There are no systems or strategies in place to prevent recurring issues.

Lifecycle monitoring and analysis capabilities		
Level 5	Evolutionary Excellence	Fully autonomous and proactive sustainability systems are in place that leverage AI-driven insights to dynamically optimise processes to achieve near-zero waste and maximize system efficiency. Closed-loop systems are available for material reuse and energy recovery.
Level 4	Performance Excellence	Sustainable monitoring becomes predictive leveraging predictive analytics. AI models are used to predict and mitigate sustainability risks like waste spikes, while LCA, LCC and Social LCA are integrated into decision-making processes.
Level 3	Systematic Excellence	Sustainability practices are integrated into operational workflows. Broader sustainability metrics are incorporated into monitoring efforts focusing on human and societal impacts through Social LCA. Comprehensive LCA and LCC evaluations across product lifecycle are available, and automated frameworks calculate sustainability indicators like eco-efficiency. LCA and LCC tools have access to real-time data from MES and ERP systems.
Level 2	Process-Governed Excellence	Initial sustainability practices are introduced, with structured data collection and reporting frameworks in place. Efforts focus on specific metrics like energy usage or material efficiency. Tools such as LCA and LCC are implemented but focus on product-specific analysis and are not integrated across operations. They provide basic indicator calculations such as carbon footprint calculations.

Level 1	Opportunistic Excellence	Basic sustainability considerations are minimal or absent. Efforts focus on compliance with environmental regulations but data is sporadic or manually recorded. Examples may include manual data collection of basic sustainability indicators (e.g. energy consumption, waste generation, cost of poor quality, etc.). Lack of integration with production or quality monitoring systems

Product traceability capabilities		
Level 5	Evolutionary Excellence	Autonomous and seamless interoperability, enabling dynamic and predictive quality management and defect prevention for ZDM systems. The concept of AAS Type 3 is fully adopted enabling asynchronous manufacturing systems' control, while a fully digitalised DPP ensures end-to-end traceability of products including their environmental and social impact during and after their use.
Level 4	Performance Excellence	Full interoperability across manufacturing systems, with support for real-time data exchange and product lifecycle integration. Standards for AAS are comprehensively adopted to determine asset status through AAS Type 2 and DPP is fully implemented for traceability across the product lifecycle. Real-time data exchange with external systems through the AAS standard is also allowed.
Level 3	Systematic Excellence	Manufacturing systems are integrated and data exchange is done following standardise data exchange protocols. Open standards for data communication are used, such as MQTT or OPC UA. Basic interoperability is achieved by implementing Asset Administration Shells (AASs) for specific assets, while traceability is managed by DPP for only critical components of products.
Level 2	Process-Governed Excellence	Basic interoperability for limited systems is available. Data exchange is semi-automated but often proprietary. Structured data formats are available, for example through CSV or XML. Minimal to no product lifecycle traceability is available.
Level 1	Opportunistic Excellence	Systems are isolated and lack connectivity. Data exchange is either manual or non-existent. There is a lack of integration between production systems and no structured data format is followed for data exchange.

Explainability and trustworthiness of AI systems		
Level 5	Evolutionary Excellence	Fully autonomous XAI systems provide dynamic, real-time and contextual explanations for all decisions made by AI systems. Explainability systems are charged with the task of making alterations to production systems based on their understanding

		of the AI systems' recommendations and outputs.
Level 4	Performance Excellence	Explainability mechanisms are enhanced with analytics, enabling proactive defect prevention. Mechanisms are tied with real-time visual explanations of KPIs.
Level 3	Systematic Excellence	Model-agnostic explainability techniques are adopted and implemented, such as LIME or SHAP. Operators are trained to interpret these insights.
Level 2	Process-Governed Excellence	Basic mechanisms to explain AI systems' outputs are introduced such as visual dashboards displaying data trends and rule-based justifications.
Level 1	Opportunistic Excellence	AI systems are treated as black boxes. There is little to no effort to explain decisions made by AI systems. Operators rely on manual checks and external expert judgments for decision validation.

Defect identification and risk assessment		
Level 5	Evolutionary Excellence	Fully autonomous defect identification and risk assessment systems that dynamically optimise processes. Data analytics and process optimisation tools provide real-time root-cause analysis and systems are dynamically reconfigured to mitigate defect generation
Level 4	Performance Excellence	Data-driven systems proactively assess risks and prioritise defect resolution based on quantitative analysis. Integration with MES/ERP systems for real-time data access. Risk heatmaps available to guide resource allocation.
Level 3	Systematic Excellence	Processes and tools are in place for defect identification and risk management. Semi-automated detection systems are available (sensors, cameras etc.). An initial risk scoring framework is in place.
Level 2	Process-Governed Excellence	Basic systems for defect identification exist but risk assessment is manual and reactive. Defects identified through periodic inspections and quality checks. Risk assessment depends on operator expertise.
Level 1	Opportunistic Excellence	Defects are identified only after occurrence and no formal risk assessment framework is in place. Defect handling is reactive and there is a reliance on ad hoc inspections. Minimal focus on risk prevention

4.2.3 Company culture

4.2.3.1 Commitment to Quality

A strong commitment to quality aligns with ZDM's core principle of defect prevention and continuous improvement. It drives the organizational focus on delivering defect-free products and processes.

Maturity Levels

- **Level 1 (Opportunistic Excellence)**: Quality is seen as an isolated responsibility of specific departments (e.g., quality control). There is a minimal organizational focus on defect prevention. At this stage, the organization lacks a holistic quality management approach, with quality perceived as an isolated responsibility belonging to specific departments, such as quality control (QC) or inspection teams. There is minimal organizational focus on defect prevention, and quality efforts are often siloed within the QC function, with little interaction or collaboration with other departments like production, procurement, or design. As a result, miscommunications and inefficiencies are common. Defect detection primarily occurs at the end of the production process, with limited proactive measures in place, leading to costly rework and operational delays. Standardized quality processes are largely absent, with operations relying on inconsistent practices that vary between projects. Additionally, data collection related to quality is minimal or sporadic, and decisions are typically based on intuition rather than data-driven insights. Without formal documentation or structured processes, the organization operates in a reactive mode, responding to defects as they arise rather than preventing them at the source.
- **Level 2 (Process-Governed Excellence):** Quality expectations are defined, but commitment varies across teams. Actions are reactive, addressing defects post-production. In this stage, organizations begin to establish formal quality expectations, though commitment varies across teams and remains largely reactive. The organisation defines and communicates Basic quality objectives, focusing primarily on meeting regulatory requirements rather than proactive defect prevention. While quality goals are set, their implementation lacks consistency across departments, and many teams address defects only after they have occurred. Root cause analysis is conducted sporadically, with corrective actions focusing more on short-term fixes rather than addressing systemic issues. Quality performance is measured through basic key performance indicators (KPIs), such as defect rates and scrap percentages, but the data collected is rarely used for continuous improvement initiatives. Despite an increased awareness of quality, there remains an inconsistent commitment across different teams, with some embracing quality initiatives while others prioritize production speed over defect prevention. The organization still operates with a reactive mindset, addressing quality issues post-production rather than integrating proactive defect prevention measures.
- **Level 3 (Systematic Excellence):** Quality commitment is formalized across the organization. All teams understand their role in defect prevention. At this stage, the organization formalizes its commitment to quality by implementing standardized processes and aligning quality goals across all teams. A company-wide awareness of quality is fostered, ensuring that employees at all levels understand their role in achieving defect-free production. Quality policies are embedded into daily operations, and cross-functional collaboration is encouraged to identify and address potential defects proactively. Standard operating procedures (SOPs) are established, and formal quality management systems, such as ISO 9001, are adopted to provide a structured framework for maintaining high standards. Quality assurance (QA) measures extend across the entire production process, from design to delivery, with an emphasis on early-stage defect prevention techniques such as Failure Mode and Effects Analysis (FMEA) and Statistical Process Control (SPC). Data begins to play a more significant role in decision-making, as historical analysis is utilized to identify recurring issues and implement preventive measures. Structured employee training programs are introduced, equipping personnel with the necessary skills to maintain and improve quality standards. The

organization's approach to quality is increasingly proactive, focusing on long-term process improvements rather than short-term corrective actions.

- **Level 4 (Performance Excellence):** Quality is monitored and managed with measurable KPIs, aligning with organizational goals. Data supports proactive defect prevention. In this stage, quality management becomes data-driven, with measurable KPIs that align with organizational goals and support proactive defect prevention. Quality is monitored and managed using sophisticated data analytics tools that provide real-time insights into process performance. The organization integrates advanced quality control systems, such as Manufacturing Execution Systems (MES) and IoT-enabled monitoring, to ensure continuous oversight of production processes. Predictive analytics capabilities enable the identification of potential quality issues before they arise, allowing for preventive measures to be implemented. The organization establishes a culture of continuous improvement, with quality metrics such as First Pass Yield (FPY) and Cost of Poor Quality (CoPQ) being systematically analyzed and used to inform strategic decisions. Collaboration across departments is enhanced, with cross-functional teams working together to drive quality improvements and share best practices. Management regularly reviews quality performance, leveraging data to make informed, strategic decisions that prioritize defect prevention and process optimization. Employees are empowered to take a proactive approach to quality management, supported by advanced tools and structured methodologies such as Lean Six Sigma.
- **Level 5 (Evolutionary Excellence):** Quality commitment is ingrained in the company’s culture, with autonomous systems and real-time analytics ensuring consistent defect-free outcomes. At the highest level, quality commitment is deeply ingrained in the organization's culture, with autonomous systems and real-time analytics ensuring consistent defect-free outcomes. Advanced technologies such as artificial intelligence (AI), machine learning (ML), and digital twins are seamlessly integrated into the manufacturing processes, enabling autonomous monitoring and continuous process optimization. Real-time data analytics drive immediate corrective actions, minimizing human intervention and allowing for a fully optimized production environment. Quality management becomes a strategic function aligned with overall business objectives, ensuring that defect prevention contributes to operational excellence and customer satisfaction. Employees at all levels fully commit to a zero-defect mindset, actively participating in quality initiatives and continuous improvement efforts. Recognition and incentive programs are structured to reward teams for maintaining high-quality standards and achieving zero-defect goals. Sustainability also becomes a core focus, with defect prevention initiatives contributing to waste reduction, energy efficiency, and environmental sustainability. The organization continuously benchmarks its performance against industry leaders, staying ahead of trends and innovations in quality management. By achieving this level of maturity, the company ensures that quality excellence is not just a goal, but an ongoing process driven by innovation and data-driven insights.

4.2.3.2 Empowerment and Accountability

ZDM requires employees at all levels to take ownership of quality processes. Empowered and accountable teams actively contribute to defect prevention and rapid issue resolution.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Employees are reactive and follow instructions without significant involvement in quality improvement. At Level 1 (Opportunistic Excellence), employees are primarily reactive, following instructions without significant involvement in quality improvement efforts. Their roles are limited to executing predefined tasks, with little awareness or responsibility for defect prevention. Quality issues are addressed only after they occur, and employees rely on supervisors for guidance and corrective actions.

- **Level 2 (Process-Governed Excellence):** Some teams take ownership of localized quality issues but lack structured empowerment mechanisms. At Level 2 (Process-Governed Excellence), some teams begin to take ownership of localized quality issues, but empowerment remains inconsistent across the organization. There are no formal mechanisms to encourage proactive participation, and most quality-related actions are still driven by management rather than employees themselves. Efforts to address defects remain reactive rather than preventive.
- **Level 3 (Systematic Excellence):** Employees are trained and encouraged to take proactive roles in identifying and preventing defects. Accountability is formalized. At Level 3 (Systematic Excellence), employees are provided with structured training and are encouraged to take a proactive role in identifying and preventing defects. Accountability is formalized, with clear roles and responsibilities established for quality improvement initiatives. Employees begin to participate actively in quality-related discussions and contribute ideas for process enhancements.
- **Level 4 (Performance Excellence):** Employees use data-driven insights to make informed decisions, reducing dependency on managerial oversight. At Level 4 (Performance Excellence), employees utilize data-driven insights to make informed decisions, reducing their reliance on managerial oversight. They are equipped with analytical tools and methodologies to identify trends and take preventive actions. The organization fosters a culture where data supports decision-making, ensuring continuous quality improvement.
- **Level 5 (Evolutionary Excellence):** Teams operate autonomously, using predictive tools and advanced analytics to prevent defects. Accountability is seamless across all levels. At Level 5 (Evolutionary Excellence), teams operate autonomously, leveraging predictive tools and advanced analytics to prevent defects before they occur. Accountability is seamlessly integrated across all levels, with employees empowered to take real-time corrective actions and drive continuous improvement. The organization achieves a culture of self-sustaining quality excellence, where proactive defect prevention becomes second nature.

4.2.3.3 Data-Driven Decision-Making

Effective implementation of ZDM relies on real-time data analysis and evidence-based decisions, ensuring processes are continuously optimized.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Decisions are based on intuition or basic metrics, with limited reliance on data. At Level 1 (Opportunistic Excellence), decision-making is largely intuitive, relying on experience and basic metrics rather than structured data analysis. There is minimal use of data to guide quality improvements, and decisions are often reactive, addressing issues only after they become evident.
- **Level 2 (Process-Governed Excellence):** Teams use historical data for trend analysis, but decision-making is still largely manual. At Level 2 (Process-Governed Excellence), teams begin to incorporate historical data for trend analysis, identifying recurring patterns and potential issues. However, decision-making remains manual, with operators and managers relying on personal judgment rather than automated insights.
- **Level 3 (Systematic Excellence):** Data collection and analysis are formalized. Teams use standardized tools to make evidence-based decisions. At Level 3 (Systematic Excellence), data collection and analysis processes are formalized, with standardized tools and methodologies to support evidence-based decision-making. Teams have access to structured reports and dashboards that provide insights into quality trends, enabling more consistent and informed decisions.
- **Level 4 (Performance Excellence):** Real-time data analytics drive proactive decision-making. Automated systems support semi-autonomous processes. At Level 4 (Performance Excellence), real-

time data analytics drive proactive decision-making, with automated systems providing recommendations and alerts. Decision-making processes become semi-autonomous, reducing the dependency on human intervention and allowing for quicker responses to emerging quality issues.

- **Level 5 (Evolutionary Excellence):** Fully autonomous systems make real-time, data-driven decisions with minimal human input, optimizing processes dynamically. At Level 5 (Evolutionary Excellence), fully autonomous systems leverage advanced analytics and artificial intelligence to make real-time, data-driven decisions with minimal human input. These systems continuously optimize processes dynamically, adapting to changing conditions and ensuring consistent quality without manual oversight.

4.2.3.4 Continuous Improvement Culture

Continuous improvement supports ZDM by ensuring processes evolve to minimize defects and adapt to new challenges.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Improvements are ad hoc and driven by immediate needs or crises. At Level 1 (Opportunistic Excellence), improvements are carried out in an unstructured manner, typically in response to immediate needs or crises. Efforts are reactive, with no formal approach to continuous improvement, leading to inconsistent and short-term fixes rather than long-term enhancements.
- **Level 2 (Process-Governed Excellence):** Teams implement occasional improvements based on specific goals, but processes lack a structured improvement framework. At Level 2 (Process-Governed Excellence), teams begin to implement occasional improvements based on specific goals or customer feedback. However, these efforts are sporadic and lack a structured framework, resulting in fragmented initiatives that may not be consistently applied across the organization.
- **Level 3 (Systematic Excellence):** Continuous improvement is standardized, with formal processes for gathering feedback and identifying areas for optimization. At Level 3 (Systematic Excellence), continuous improvement becomes a formalized process with established mechanisms for gathering feedback and identifying opportunities for optimization. Standardized improvement frameworks, such as PDCA (Plan-Do-Check-Act), are introduced, ensuring that enhancements are systematically pursued across departments.
- **Level 4 (Performance Excellence):** Data from defect tracking and process performance metrics drives systematic improvements. Feedback loops are robust and actionable. At Level 4 (Performance Excellence), improvements are driven by data from defect tracking and process performance metrics. Feedback loops are well-established, providing actionable insights that allow for proactive adjustments. Continuous improvement efforts are data-driven and aligned with business objectives to enhance overall efficiency and quality.
- **Level 5 (Evolutionary Excellence):** Improvements are driven autonomously through advanced analytics and predictive insights. Processes continuously evolve without manual intervention. At Level 5 (Evolutionary Excellence), improvements are autonomously driven by advanced analytics and predictive insights. The organization leverages real-time data to identify opportunities for optimization continuously, with minimal manual intervention. Self-learning systems adapt dynamically to changing conditions, ensuring sustained excellence and innovation.

4.2.3.5 Collaboration and Communication

Effective ZDM implementation depends on cross-functional collaboration and transparent communication to align teams and share insights across the organization.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Communication is siloed, with limited collaboration between departments. At Level 1 (Opportunistic Excellence), communication within the organization is fragmented and siloed, with minimal collaboration between departments. Information flow is often inconsistent, leading to misunderstandings, inefficiencies, and delays in addressing quality issues. Departments work independently, with little to no integration of efforts toward common quality goals.
- **Level 2 (Process-Governed Excellence):** Basic collaboration mechanisms exist, such as inter-departmental meetings, but communication remains inconsistent. At Level 2 (Process-Governed Excellence), basic collaboration mechanisms, such as inter-departmental meetings and informal discussions, are introduced. However, communication remains inconsistent, with information often being shared reactively rather than proactively. While some coordination exists, it lacks a structured approach, leading to occasional misalignment between teams.
- **Level 3 (Systematic Excellence):** Structured communication channels and collaboration platforms are implemented, enabling real-time information sharing. At Level 3 (Systematic Excellence), structured communication channels and collaboration platforms are implemented to facilitate real-time information sharing. Formal processes are established to ensure departments stay informed and aligned on quality objectives. Digital tools such as shared dashboards and reporting systems help enhance transparency and cross-functional teamwork.
- **Level 4 (Performance Excellence):** Data and insights are shared seamlessly across teams using integrated systems. Collaboration is data-driven and efficient. At Level 4 (Performance Excellence), data and insights are seamlessly shared across teams using integrated systems that provide real-time visibility into production and quality performance. Collaboration becomes data-driven, with teams leveraging analytics to make informed decisions and proactively address potential quality issues.
- **Level 5 (Evolutionary Excellence):** Cross-functional teams work in real time with AI-driven insights, fostering collaboration for predictive and preventive quality management. At Level 5 (Evolutionary Excellence), cross-functional teams collaborate in real time using AI-driven insights, fostering a culture of continuous improvement and predictive quality management. Collaboration is fully automated and adaptive, allowing departments to work together seamlessly to prevent defects and optimize processes dynamically.

4.2.3.6 Sustainability Orientation

A sustainability-focused culture aligns with ZDM's goals of reducing waste and optimizing resources, contributing to environmental and social objectives.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Sustainability is not prioritized, and waste management is reactive. At Level 1 (Opportunistic Excellence), sustainability is not a priority, and waste management is handled reactively. The organization focuses primarily on production efficiency and cost reduction, with little attention given to environmental impact. Waste is often generated without structured tracking or reduction efforts, leading to inefficiencies and compliance risks.

- **Level 2 (Process-Governed Excellence):** Basic sustainability practices, such as recycling, are implemented but not integrated into ZDM processes. At Level 2 (Process-Governed Excellence), basic sustainability practices, such as recycling and energy conservation initiatives, are introduced. However, these efforts are isolated and not integrated into Zero Defect Manufacturing (ZDM) processes. Sustainability actions are primarily compliance-driven rather than strategically aligned with the organization's quality and efficiency goals.
- **Level 3 (Systematic Excellence):** Sustainability goals are formalized and aligned with defect prevention efforts. Teams actively work to reduce waste and optimize resource use. At Level 3 (Systematic Excellence), sustainability goals are formalized and closely aligned with defect prevention efforts. Teams actively work on reducing waste and optimizing resource use through structured initiatives. Sustainability considerations become part of process design and production planning, ensuring that environmental impact is systematically addressed alongside quality objectives.
- **Level 4 (Performance Excellence):** Sustainability metrics are integrated into production KPIs. Teams use data-driven strategies to improve efficiency and reduce environmental impact. At Level 4 (Performance Excellence), sustainability metrics are integrated into production key performance indicators (KPIs), allowing for data-driven decision-making to improve efficiency and reduce environmental impact. Teams use advanced analytics to monitor resource consumption, energy usage, and waste reduction, enabling proactive measures to enhance sustainability performance.
- **Level 5 (Evolutionary Excellence):** Autonomous systems ensure sustainable practices are optimized dynamically, with AI-driven insights minimizing waste and maximizing resource efficiency. At Level 5 (Evolutionary Excellence), autonomous systems dynamically optimize sustainable practices using AI-driven insights. Real-time data analytics minimize waste and maximize resource efficiency by continuously adapting production processes. Sustainability becomes an intrinsic part of operations, ensuring long-term environmental responsibility and alignment with corporate sustainability goals.

4.2.3.7 Recognition and Incentives

Rewarding defect-free performance reinforces a culture of quality and motivates teams to align their efforts with ZDM principles.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Recognition is informal and sporadic, with no structured incentive program. At Level 1 (Opportunistic Excellence), recognition of quality efforts is informal and sporadic, with no structured incentive program. Employees may occasionally receive verbal appreciation, but there are no consistent mechanisms to acknowledge or reward contributions to quality improvement. As a result, motivation to focus on defect prevention remains low, and quality achievements are often overlooked.
- **Level 2 (Process-Governed Excellence):** Basic incentives exist for meeting quality benchmarks but lack alignment with ZDM goals. Basic incentive programs are introduced at Level 2 (Process-Governed Excellence), typically rewarding employees for meeting general quality benchmarks. However, these incentives are not directly aligned with Zero Defect Manufacturing (ZDM) objectives and tend to focus on short-term goals rather than long-term quality improvements. Recognition efforts remain inconsistent and vary across departments.
- **Level 3 (Systematic Excellence):** Structured programs reward teams for achieving ZDM-related goals, such as defect-free production runs. At Level 3 (Systematic Excellence), structured recognition programs are established to reward teams and individuals for achieving specific ZDM-related goals, such as defect-free production runs and process improvements. Incentives are linked

to predefined criteria, fostering a culture of accountability and encouraging employees to take an active role in quality enhancement initiatives.

- **Level 4 (Performance Excellence):** Recognition is tied to measurable KPIs, with real-time tracking of achievements and automated incentives for performance. At Level 4 (Performance Excellence), recognition programs are integrated with measurable key performance indicators (KPIs), ensuring that rewards are based on objective quality metrics. Achievements are tracked in real time, and automated systems provide timely recognition to employees, creating a data-driven and transparent approach to performance incentives.
- **Level 5 (Evolutionary Excellence):** AI-driven systems monitor quality metrics and autonomously deliver personalized recognition and incentives to teams and individuals. At Level 5 (Evolutionary Excellence), AI-driven systems autonomously monitor quality metrics and deliver personalized recognition and incentives to teams and individuals. These systems analyze real-time data to identify outstanding performance and dynamically adjust rewards based on contributions to continuous quality improvement. Recognition becomes an integral part of the organizational culture, driving sustained engagement and excellence in defect prevention.

4.2.3.8 Adaptability and Resilience

A culture of adaptability supports ZDM by enabling teams to respond effectively to changes in demand, disruptions, or emerging challenges.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Teams struggle to adapt to changes, with disruptions causing significant delays and quality issues. At Level 1 (Opportunistic Excellence), teams struggle to adapt to changes, with disruptions causing significant delays and quality issues. There are no structured processes in place to handle unexpected events, and responses are often reactive and uncoordinated. As a result, production efficiency and product quality suffer whenever unforeseen challenges arise.
- **Level 2 (Process-Governed Excellence):** Processes allow for basic adaptations, but responses are slow and require significant manual effort. At Level 2 (Process-Governed Excellence), basic adaptation processes are introduced, allowing for some level of responsiveness to changes. However, these adaptations are slow and heavily reliant on manual efforts, requiring significant intervention from management and frontline workers. The organization's ability to respond to disruptions remains limited, often leading to inefficiencies and increased costs.
- **Level 3 (Systematic Excellence):** Teams are trained to handle disruptions, with predefined processes for adapting to changes. At Level 3 (Systematic Excellence), teams are trained to handle disruptions effectively, with predefined processes and guidelines in place to facilitate smoother adaptations. Standard operating procedures (SOPs) are established to provide clear steps for responding to changes, ensuring a more structured and consistent approach across different production scenarios.
- **Level 4 (Performance Excellence):** Adaptability is supported by predictive tools and real-time analytics, enabling faster and more effective responses. At Level 4 (Performance Excellence), adaptability is enhanced using predictive tools and real-time analytics. These technologies enable faster and more informed decision-making, allowing the organization to anticipate potential disruptions and respond proactively. Data-driven insights help optimize resource allocation and minimize the impact of changes on production schedules.
- **Level 5 (Evolutionary Excellence):** Autonomous systems ensure dynamic adaptation to changes, optimizing processes and resources seamlessly. At Level 5 (Evolutionary Excellence), autonomous systems ensure dynamic adaptation to changes by continuously monitoring production conditions

and adjusting processes in real time. Advanced AI-driven algorithms optimize workflows and resource utilization seamlessly, minimizing disruptions and maximizing efficiency. Adaptability becomes an integral part of the organization's operations, allowing it to remain resilient in the face of evolving demands and challenges.

4.2.3.9 Democratisation of AI systems

Democratisation of AI systems refers to the process of making AI tools, insights and capabilities accessible, understandable and usable by all stakeholders in the manufacturing organisation, regardless of technical expertise.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** AI systems are limited to technical experts of the manufacturing organisation. The systems do not provide any accessibility features and no training on their use has been conducted to the general workforce of the company. Insights generated by AI systems are not shared across teams, leaving most employees to rely on manual processes and traditional defect identification and prevention methods.
- **Level 2 (Process-Governed Excellence):** Basic access to AI systems is provided to specific teams. Such teams receive minimal training on how to interpret results and recommendations provided by such systems. Dashboard and visualisations of results generated by AI systems offer basic understanding of their outputs, but decision-making remains reactive and limited to selected groups.
- **Level 3 (Systematic Excellence):** AI tools are integrated across departments with standardised workflows. Employees are trained to not only consume AI outputs but also be able to understand them and extract insights relevant to their roles.
- **Level 4 (Performance Excellence):** Role-specific AI insights are generated by respective AI systems in real time, allowing employees to make proactive decisions. Training programs are enhanced, and feedback loops ensure continuous refinement of AI tools based on user inputs.

Level 5 (Evolutionary Excellence): AI systems are fully democratised and explainable. They provide dynamic and real time contextual information through integration of advanced explainability techniques. Employees are able to interact seamlessly with AI tools and consume recommendations provided by AI systems.

4.2.4 Personnel

4.2.4.1 Skill Development and Training

Personnel must be trained in ZDM tools, technologies, and methodologies, including data analysis, defect prevention strategies, and the use of automated systems.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Minimal or no training on quality management or ZDM principles. Employees rely on basic knowledge and traditional methods. At Level 1 (Opportunistic Excellence), there is minimal or no formal training on quality management or Zero Defect Manufacturing (ZDM) principles. Employees primarily rely on their basic knowledge and traditional methods to perform their tasks, often lacking a comprehensive understanding of quality improvement strategies. Without structured training, there is a high dependence on experience-based practices, leading to inconsistencies in quality outcomes and limited awareness of defect prevention techniques.

- **Level 2 (Process-Governed Excellence):** Limited training programs introduce basic concepts of quality management and defect detection. Training is reactive and role-specific. At Level 2 (Process-Governed Excellence), limited training programs are introduced to provide employees with a basic understanding of quality management concepts and defect detection methods. However, these training efforts are often reactive and focused on specific roles rather than adopting a holistic approach. Employees receive guidance only when issues arise, and there is little emphasis on proactive quality management or process improvement.
- **Level 3 (Systematic Excellence):** Structured training programs focus on ZDM methodologies, including data-driven decision-making and defect prevention. Employees understand their role in ZDM. At Level 3 (Systematic Excellence), structured training programs are established to systematically educate employees on ZDM methodologies. These programs focus on essential aspects such as data-driven decision-making, defect prevention, and continuous improvement techniques. Employees gain a clear understanding of their roles in achieving zero defects and are equipped with standardized tools and procedures to support quality initiatives across the organization.
- **Level 4 (Performance Excellence):** Regular training incorporates advanced tools, such as predictive analytics and AI, ensuring employees can handle complex systems. At Level 4 (Performance Excellence), training becomes an integral part of the organization's quality strategy, incorporating advanced tools such as predictive analytics and AI-driven quality management systems. Employees are regularly trained to handle complex systems and utilize data insights to proactively prevent defects. Training programs are data-driven, ensuring employees remain updated with the latest industry practices and technologies.
- **Level 5 (Evolutionary Excellence):** Continuous learning and development are embedded in the organization’s culture. Employees are trained in cutting-edge technologies and proactive problem-solving. At Level 5 (Evolutionary Excellence), continuous learning and development are deeply embedded in the organization’s culture. Employees are consistently trained in cutting-edge technologies and proactive problem-solving techniques, enabling them to adapt to evolving quality challenges. Autonomous learning systems provide personalized training recommendations based on performance data, ensuring a highly skilled workforce that drives innovation and excellence in quality management.

4.2.4.2 Ownership and Accountability

ZDM requires personnel to take ownership of processes and be accountable for defect prevention and resolution.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Employees follow instructions without taking responsibility for quality outcomes. Accountability is unclear. At Level 1 (Opportunistic Excellence), employees follow instructions without a clear responsibility for quality outcomes. Accountability is unclear, and there is a lack of ownership when defects occur. Employees rely heavily on supervisors to address quality issues, leading to a reactive approach rather than proactive engagement in defect prevention. Quality management is considered an external responsibility rather than an integral part of daily operations.
- **Level 2 (Process-Governed Excellence):** Basic accountability mechanisms are established, with employees responsible for their specific tasks but lacking a holistic understanding of ZDM goals. At Level 2 (Process-Governed Excellence), basic accountability mechanisms are introduced, with employees being held responsible for their specific tasks. However, their understanding of Zero Defect Manufacturing (ZDM) goals remains limited, and quality is often seen as the responsibility of designated departments rather than a shared effort. While employees begin to recognize their role

in maintaining quality, their focus is primarily on meeting immediate performance targets rather than long-term defect prevention.

- **Level 3 (Systematic Excellence):** Roles and responsibilities are clearly defined, with employees empowered to take proactive steps in defect prevention and quality assurance. At Level 3 (Systematic Excellence), roles and responsibilities related to quality are clearly defined, fostering a culture of accountability across the organization. Employees are empowered to take proactive measures in defect prevention and quality assurance, contributing to continuous improvement efforts. Structured processes and guidelines help individuals understand their impact on overall quality objectives, and they are encouraged to identify and address potential issues before they escalate.
- **Level 4 (Performance Excellence):** Personnel use data to take accountability for process performance, implementing corrective actions based on analytics. At Level 4 (Performance Excellence), accountability is data-driven, with employees leveraging analytics to monitor and enhance process performance. Personnel are equipped with real-time data that enables them to take corrective actions promptly, reducing dependency on managerial intervention. Decision-making becomes more informed and strategic, aligning individual efforts with broader ZDM objectives and organizational goals.
- **Level 5 (Evolutionary Excellence):** Teams operate autonomously, continuously monitoring and improving processes with minimal managerial oversight. Accountability is seamlessly integrated into workflows. At Level 5 (Evolutionary Excellence), teams operate autonomously with minimal managerial oversight, continuously monitoring and improving processes through self-directed initiatives. Accountability is seamlessly integrated into workflows, supported by advanced analytics and AI-driven insights. Employees are fully engaged in defect prevention and process optimization, fostering a culture of continuous improvement where quality is everyone's responsibility.

4.2.4.3 Engagement and Motivation

Engaged and motivated personnel contribute actively to achieving zero defects, fostering innovation and commitment to quality.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Engagement is low, with employees performing tasks mechanically without understanding ZDM goals. At Level 1 (Opportunistic Excellence), employee engagement is minimal, with individuals performing their tasks mechanically without a clear understanding of Zero Defect Manufacturing (ZDM) goals. There is little to no connection between their daily activities and the broader quality objectives of the organization. Employees often see their work as routine and lack motivation to contribute beyond their responsibilities, leading to a reactive and compliance-driven approach to quality.
- **Level 2 (Process-Governed Excellence):** Basic initiatives, such as periodic meetings or recognition programs, improve engagement but are not tied to ZDM outcomes. At Level 2 (Process-Governed Excellence), basic initiatives such as periodic meetings, suggestion programs, and occasional recognition efforts are introduced to improve engagement. However, these initiatives are not systematically aligned with ZDM objectives, resulting in limited impact on defect prevention and process improvement. Employees may feel more involved, but their motivation remains largely extrinsic, and participation in quality initiatives is inconsistent across teams.
- **Level 3 (Systematic Excellence):** Employees are motivated through structured incentives linked to defect reduction and quality improvement. ZDM goals are clearly communicated. At Level 3 (Systematic Excellence), structured incentive programs are established to motivate employees by linking rewards to defect reduction and quality improvement targets. ZDM goals are clearly

communicated across all levels, and employees begin to understand their role in achieving these objectives. A sense of ownership is fostered, with teams actively contributing ideas and improvements to support the organization's zero-defect ambitions.

- **Level 4 (Performance Excellence):** Engagement is enhanced through real-time tracking of achievements, with employees receiving feedback and recognition based on measurable KPIs. At Level 4 (Performance Excellence), employee engagement is driven by real-time tracking of achievements, providing continuous feedback and recognition based on measurable key performance indicators (KPIs). Employees are empowered to take ownership of their performance, as they can see the direct impact of their efforts on production quality. Data-driven insights help them proactively contribute to quality enhancement, fostering a culture of accountability and pride in their work.
- **Level 5 (Evolutionary Excellence):** Employees fully align with ZDM objectives and take pride in contributing to quality and sustainability goals. Motivation is sustained through AI-driven recognition and continuous professional growth opportunities. At Level 5 (Evolutionary Excellence), employees fully align with ZDM objectives and take pride in their contributions to quality and sustainability goals. Motivation is sustained through AI-driven recognition systems that provide personalized feedback and rewards, promoting continuous professional growth. Employees are highly engaged and proactive in driving innovation and quality excellence, ensuring long-term commitment to the organization's zero-defect culture.

4.2.4.4 Collaboration and Cross-Functional Teams

ZDM success depends on collaboration among cross-functional teams, enabling seamless integration of processes and data across departments.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Teams operate in silos, with minimal collaboration or communication across departments. At Level 1 (Opportunistic Excellence), teams operate in silos with little to no collaboration or communication across departments. Each team focuses on its individual responsibilities, and there is minimal interaction or sharing of information. This lack of coordination leads to inefficiencies, duplication of efforts, and delays in addressing quality issues, as there is no collective approach to problem-solving or defect prevention.
- **Level 2 (Process-Governed Excellence):** Basic collaboration mechanisms, such as periodic meetings, exist but lack integration with ZDM goals. At Level 2 (Process-Governed Excellence), basic collaboration mechanisms are introduced, such as periodic inter-departmental meetings or informal discussions. While these initiatives improve communication slightly, they remain inconsistent and are not aligned with Zero Defect Manufacturing (ZDM) goals. Collaboration is often reactive, focused on addressing issues as they arise, rather than proactively working toward shared quality objectives.
- **Level 3 (Systematic Excellence):** Teams collaborate through formalized workflows, with clear communication channels and shared goals related to defect prevention. At Level 3 (Systematic Excellence), formalized workflows and structured communication channels are implemented to facilitate collaboration among teams. Shared goals for defect prevention and quality improvement are established, ensuring alignment across departments. Teams work together systematically, leveraging their combined expertise to identify and address quality challenges more effectively.
- **Level 4 (Performance Excellence):** Collaboration is data-driven, supported by integrated systems that facilitate real-time information sharing and joint problem-solving. At Level 4 (Performance Excellence), collaboration becomes data-driven and is supported by integrated systems that enable real-time information sharing and joint problem-solving. Teams have access to shared dashboards

and analytics tools, allowing them to monitor quality metrics collectively and respond to emerging issues proactively. Cross-functional collaboration is strengthened by technology, fostering efficiency and transparency in decision-making.

- **Level 5 (Evolutionary Excellence):** Fully collaborative teams work autonomously with advanced tools like digital twins and AI, ensuring seamless integration of processes across all departments. At Level 5 (Evolutionary Excellence), teams collaborate fully, supported by advanced tools like digital twins and AI-driven systems. These technologies enable seamless integration of processes across all departments, allowing teams to operate autonomously and make data-informed decisions in real time. Collaboration is dynamic and proactive, ensuring continuous improvement and alignment with ZDM objectives, while fostering a culture of innovation and shared accountability.

4.2.4.5 Adaptability and Resilience

Personnel must be adaptable to changing production requirements and resilient in addressing challenges to maintain zero-defect operations.

Maturity Levels

- **Level 1 (Opportunistic Excellence):** Employees struggle to adapt to changes or disruptions, often resulting in delays or quality issues. At Level 1 (Opportunistic Excellence), employees struggle to adapt to changes or disruptions, often leading to significant delays and quality issues. There are no established processes to handle unexpected events, and responses are typically reactive. Employees lack the skills and tools to effectively address disruptions, resulting in production inefficiencies and inconsistent product quality.
- **Level 2 (Process-Governed Excellence):** Teams are given basic training to handle known disruptions but lack flexibility for unforeseen challenges. At Level 2 (Process-Governed Excellence), basic training programs are introduced to help teams handle known disruptions. While employees gain some ability to respond to predictable challenges, their flexibility in dealing with unforeseen issues remains limited. Processes are rigid, and responses often require significant manual intervention, leading to slow recovery times and potential production bottlenecks.
- **Level 3 (Systematic Excellence):** Personnel are equipped with the skills and tools needed to adapt to changes in production processes or requirements. At Level 3 (Systematic Excellence), personnel are equipped with the necessary skills and tools to adapt to changes in production processes or evolving requirements. Standardized procedures and structured frameworks are implemented to guide employees through disruptions, allowing for more consistent and timely responses. Teams become more proactive in identifying potential risks and are better prepared to implement corrective actions efficiently.
- **Level 4 (Performance Excellence):** Employees use predictive insights to anticipate and respond to disruptions proactively, maintaining production efficiency. At Level 4 (Performance Excellence), employees leverage predictive insights and data-driven tools to anticipate and respond to disruptions before they impact production. Real-time analytics enable teams to identify trends and potential issues, allowing them to take preventive measures. These capabilities maintain production efficiency, and disruptions are managed proactively with minimal impact on quality.
- **Level 5 (Evolutionary Excellence):** Teams autonomously adapt to dynamic conditions, leveraging AI-driven insights to optimize processes and prevent disruptions. At Level 5 (Evolutionary Excellence), teams operate autonomously, adapting to dynamic conditions with the support of AI-driven insights and advanced analytics. Processes are continuously optimized in real time, with systems automatically adjusting to disruptions and resource constraints. Employees are empowered by intelligent decision-support tools, ensuring seamless operations and sustained high-quality production without manual intervention.

4.3 Production phase

- **KPIs in the ZDM Achieved Stage: An In-Depth Analysis**

In the Zero Defect Manufacturing (ZDM) achieved stage, manufacturing processes are fully optimized to ensure zero defects, leveraging continuous monitoring, real-time corrections, and preventive actions. At this stage, businesses focus on achieving operational excellence by integrating advanced quality control measures and aligning their objectives with key performance indicators (KPIs). These KPIs span four critical areas: process performance, product quality, cost, and sustainability. Each area contributes to maintaining high-quality standards and ensuring a competitive edge in the market.

4.3.1 Vaulues: Guiding Principles for ZDM Excellence

The values underlying ZDM form the foundation of a company's commitment to producing defect-free products and continuously improving its processes. They serve as the driving force behind every initiative undertaken to achieve manufacturing excellence.

- **Quality Excellence:** This involves consistently delivering products that meet or exceed customer expectations. The focus is on eliminating variability in production and ensuring that each product adheres to the highest standards of quality, reliability, and performance.
- **Continuous Improvement (Kaizen):** The philosophy of continuous, incremental improvement across all aspects of manufacturing is crucial to sustaining zero defects. Organizations can identify and implement small yet impactful changes by fostering a culture of innovation and feedback.
- **Customer Satisfaction:** The ultimate goal of ZDM is to provide customers with high-quality products free from defects, thereby increasing trust, loyalty, and brand reputation. Customer feedback plays a pivotal role in driving improvements and refining manufacturing processes.

4.3.2 Principles: The Core Tenets of ZDM Implementation

To achieve and sustain zero defects, ZDM relies on a set of well-defined principles that guide the organization's approach to quality management and defect prevention. These principles ensure that operations are aligned with strategic goals and regulatory requirements.

- **Data-Driven Decision Making:** Leveraging real-time production data and analytics allows manufacturers to make informed decisions that drive quality improvements. Statistical process control (SPC), predictive maintenance, and machine learning models provide actionable insights to optimize processes.
- **First Time Right:** This principle emphasizes producing high-quality products on the first attempt without the need for rework or corrections. It encourages error-proofing techniques such as poka-yoke (mistake-proofing) and rigorous process controls.
- **100% Inspection:** Implementing comprehensive inspection processes, including in-line, end-of-line, and virtual metrology, ensures that every product meets the required quality standards before leaving the production line.
- **Prediction Algorithms:** Advanced AI algorithms and machine learning models predict potential failures and defects, enabling proactive measures to address quality concerns before they escalate.
- **Prevent Over Repair:** The focus is on balancing repair efforts by addressing root causes rather than over-correcting, which could lead to unnecessary costs and inefficiencies.

- **Employee Empowerment:** Empowering employees through training, responsibility, and involvement in quality initiatives fosters a culture of accountability and continuous improvement. Workers are encouraged to identify defects and contribute to process optimization.

4.3.3 Objectives and key results (OKRs): Goals to Achieve Zero Defects

OKRs are used to align organizational efforts with ZDM goals, ensuring continuous improvement and operational excellence. These objectives focus on eliminating defects and optimizing production for greater efficiency and cost-effectiveness.

- **Eliminate All Defects:** The ultimate goal is to ensure that no defective products leave the production line by leveraging advanced defect detection, prevention methods, and predictive analytics.
- **Optimize Production Processes:** Streamlining workflows through automation, lean principles, and real-time monitoring helps achieve maximum efficiency with minimal waste and downtime.
- **Enhance Product Reliability:** Ensuring long-term product performance and customer trust by incorporating robust quality control measures that prevent defects from occurring.
- **Reduce Costs:** The focus is on cutting down expenses related to defective products, rework, scrap, and warranty claims, leading to increased profitability and cost efficiency.
- **Improve Customer Satisfaction:** Delivering consistent quality and reliability enhances customer trust and fosters long-term relationships with stakeholders.
- **Compliance and Standards:** Meeting or exceeding industry quality standards such as ISO 9001, IATF 16949 (automotive), and ISO 13485 (medical devices) ensures regulatory adherence and global market competitiveness.

4.3.4 Key performance indicators (KPIs): Measuring ZDM Success

A. Process Performance KPIs

Monitoring production processes is essential for maintaining zero defects and optimizing operational efficiency. Key metrics include:

- **First Pass Yield (FPY):** The percentage of products that pass quality inspections without requiring rework or corrective actions, reflecting process efficiency and accuracy.
- **Cycle Time:** Measures the time taken to complete a production cycle, providing insights into operational efficiency and identifying potential bottlenecks.
- **Machine Uptime/Downtime:** Tracks the availability of production equipment, ensuring that unplanned downtimes are minimized through predictive maintenance strategies.
- **Throughput:** The number of defect-free units produced within a given time frame, reflecting the overall productivity of the manufacturing process.

B. Product Quality KPIs

Ensuring product quality is a cornerstone of ZDM. Relevant KPIs include:

- **Defect Rate:** Measures the proportion of defective products within total production, providing insights into quality control effectiveness.
- **Scrap Rate:** Evaluates the percentage of materials wasted due to defects, helping identify opportunities for reducing production losses.

- **Rework Rate:** Tracks the number of units requiring additional work to meet quality standards, reflecting process consistency and efficiency.
- **Customer Complaints:** Monitors the frequency and nature of complaints, providing valuable insights into product performance and customer satisfaction.

C. Cost KPIs

Evaluating the financial impact of zero-defect initiatives is crucial for long-term sustainability. Key cost-related KPIs include:

- **Cost of Poor Quality (CoPQ):** The total cost incurred due to quality failures, including rework, scrap, warranty claims, and customer dissatisfaction.
- **Return on Investment (ROI) for ZDM:** Measures the financial benefits achieved through defect prevention relative to the cost of implementing quality initiatives.
- **Cost per Unit:** The total cost associated with producing one unit of defect-free product, including production, inspection, and quality assurance costs.

D. Sustainability KPIs

Sustainability in manufacturing is becoming increasingly important, and ZDM plays a crucial role in achieving environmental goals. Relevant sustainability KPIs include:

- **Waste Reduction:** The amount of waste minimized through improved defect prevention and process optimization strategies.
- **Energy Efficiency:** Measures the energy consumption per unit produced, emphasizing sustainable resource utilization and cost savings.
- **Carbon Footprint Reduction:** Tracks the reduction in greenhouse gas emissions through efficient operations and process improvements.
- **Material Efficiency:** Ensures optimal utilization of raw materials by reducing scrap and rework.

Integration with Existing Quality Frameworks

The ZDM approach builds on widely recognized quality frameworks such as Total Quality Management (TQM), Lean Manufacturing, Six Sigma, and the ISO 9000 family. By leveraging these established methodologies, ZDM enhances predictive capabilities and defect prevention strategies. Aligning with ISO 31000's proactive risk management approach helps identify and mitigate potential risks before they impact production, while ISO 14001 ensures adherence to environmental standards, reducing waste and promoting sustainability.

4.4 KPIs in ZDM Achieved Stage

In the ZDM achieved stage, KPIs typically fall under four broad categories: process performance, product quality, cost, and sustainability. These KPIs help monitor and control the production process to ensure it remains at zero defects. Below are some of the essential KPIs measured during this phase:

4.4.1 Process Performance KPIs

These KPIs focus on ensuring the manufacturing process is stable, consistent, and capable of producing defect-free products.

- **Process Capability:** Measures how well a process can produce products within the specified limits.
- **Cycle Time:** Measures the time taken for one complete cycle of the process. A shorter cycle time often indicates efficiency but must not compromise quality.
- **Machine Uptime/Downtime:** The percentage of time that machines are operational versus when they are down. A higher uptime is essential for ZDM to avoid defects due to breakdowns.
- **First Pass Yield:** The percentage of products that pass through the manufacturing process without rework or scrap.
- **Throughput:** The number of defect-free units produced per time period.

4.4.2 Product Quality KPIs

Product quality KPIs measure the output in terms of defects and adherence to quality standards.

- **Defect Rate:** The percentage of products that do not meet quality standards (should be close to 0 in ZDM).
- **Rework Rate:** The number of products requiring rework after initial production.
- **Scrap Rate:** The percentage of products that are scrapped due to being non-repairable or unfit for sale.
- **Non-Conformance Rate:** The percentage of products that fail to meet customer or regulatory requirements.
- **Quality Incidents:** The number of instances where quality issues are raised during production.

4.4.3 Cost KPIs

Cost KPIs measure how the implementation of ZDM impacts overall costs. Even with zero defects, it's crucial to maintain cost-effectiveness.

- **Cost of Poor Quality (CoPQ):** The total cost of rework, scrap, and warranty claims.
- **Cost of Quality (CoQ):** The cost of maintaining quality, including inspection, testing, and preventive measures.
- **Return on Investment (ROI) for ZDM:** Measures the financial benefits of achieving zero defects, considering savings on rework, reduced warranty claims, etc.
- **Cost per Unit:** The cost of producing one product unit, including quality assurance measures.

4.4.4 Environmental sustainability KPIs

Environmental sustainability KPIs relate to minimizing waste and ensuring environmentally friendly processes, which is often a part of ZDM in modern manufacturing.

- **Waste Reduction:** The percentage reduction in waste material from the production process, driven by fewer defects.
- **Energy Efficiency:** Measures the energy consumed in relation to the number of defect-free units produced.

- **Material Efficiency:** The ratio of raw material used to defect-free finished goods, emphasizing material conservation.

4.4.5 Economic Sustainability KPIs

Economic sustainability KPIs relate to optimizing economic parameters such as cost efficiency, resource utilization, and profitability, while minimizing waste and financial risks associated with defect generation.

- **Value performance:** The inverse of the life cycle cost to produce a certain product. Assess how cost-effective manufacturing systems and products are over their lifecycle serving as a key indicator for economic sustainability of manufacturing systems[6].
- **Cost of implementation:** The addition of setup cost and downtime cost for a manufacturer to adopt a certain circular economy strategy in the process of adopting ZDM4.

4.4.6 Social Sustainability KPIs

Social Sustainability KPIs assess the human and societal impact of transitioning to ZDM processes.

- **Workplace Safety:** Incident rates and safety improvements related to defect reduction and process optimisation strategies employed to achieve ZDM.
- **Customer Trust and Satisfaction:** Customer feedback scores, emphasizing trust in consistent, defect-free and sustainable products.
- **Job Quality Improvement:** Measure employee satisfaction after the adoption of automation and defect-free processes during the transition to the ZDM philosophy.

4.4.7 Monitoring and Feedback Loop in ZDM Achieved

In addition to measuring KPIs, the ZDM achieved step includes the following mechanisms for maintaining zero defects:

- **Real-Time Monitoring:** Continuous data collection through sensors, automated inspections, and other Industry 4.0 technologies to detect and correct issues before defects occur.
- **Predictive Maintenance:** Using data analytics to predict and prevent equipment failures that could lead to defects.
- **Closed-Loop Feedback:** Implementing systems that automatically adjust processes in response to deviations from set KPIs to maintain zero defects.
- **Human feedback integration:** Implementation of mechanisms that take into consideration the feedback provided from human operators to automatically adjust AI systems' behaviour which are responsible for the control of the manufacturing system to prevent the generation of defects[7].

[6] N. Nikolakis, P. Catti, A. Chaloulos, W. Van De Kamp, M. P. Coy, and K. Alexopoulos, "A methodology to assess circular economy strategies for sustainable manufacturing using process eco-efficiency," Journal of Cleaner Production, vol. 445, p. 141289, Mar. 2024, doi: 10.1016/j.jclepro.2024.141289.

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5 Classification of KPIs in ZDM Achieved

KPI Type	Examples	Focus
Process Performance KPIs	Process Capability, Cycle Time, Machine Uptime	Stability and efficiency of the process
Product Quality KPIs	Defect Rate, Rework Rate, Scrap Rate	Product quality and adherence to standards
Cost KPIs	CoPQ, CoQ, ROI for ZDM, Cost per Unit	Financial efficiency and cost savings
Environmental Sustainability KPIs	Waste Reduction, Energy Efficiency, Material Efficiency	Environmental impact and resource efficiency
Economic Sustainability KPIs	Value performance, cost of implementation	Economic impact of transitioning to ZDM practices
Social Sustainability KPIs	Workplace safety, customer trust and satisfaction, job quality improvement	Human and social impact of transitioning to ZDM practices

KPIs - efficiency and effectiveness for Prediction

Efficiency – time, energy, repeatable

Effectiveness – Hallucination percentage (no false positive or negative) / accuracy, prescriptive

Effectiveness: Measures how well the model generalizes to unseen data. This can be evaluated by comparing training accuracy with validation/test accuracy. LLMs are prone to hallucination.

- Prediction Accuracy: Measures how often the algorithm’s predictions are correct. For classification problems, it is the ratio of correct predictions to the total predictions.
- Precision: The ratio of true positive predictions to the total predicted positives. It is useful when the cost of false positives is high.
- Recall (Sensitivity): Measures the algorithm’s ability to correctly identify true positives out of all actual positives. It’s important when false negatives carry a high cost.
- Model Robustness: Measures how well the model performs when exposed to noisy or unexpected data. This can be tested through adversarial inputs or noisy data sets.
- Model Drift Detection: A metric for detecting how much the model's performance degrades over time due to changes in the data distribution (also known as "concept drift"). It helps in deciding when to retrain the model.

Efficiency

- Prediction Speed (Latency): The time it takes for the algorithm to generate predictions. This is critical in real-time applications where low latency is required.

- Throughput: The number of predictions the algorithm can make per unit of time. High throughput is essential for processing large data volumes.
- Scalability: Measures how well the algorithm performs as the dataset grows. This can be measured through the system's capacity to handle increasing data loads without significantly degrading prediction speed or accuracy.
- Energy: The percentage of processing power used by the algorithm during training and inference.

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