Deployment Key Performance Indicators for Sustainable Manufacturing

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Abstract

The Zero-Defect Manufacturing (ZDM) strategy, particularly the Zero Defect Zero Waste (ZDZW) methodology, emerges as a crucial approach to enhance sustainability in the global manufacturing supply chain. The European Union project 'ZDZW', focusing on diverse industrial scenarios, addresses challenges faced by industries such as plastics, metals, energy, ceramics, and consumer goods. Within this framework, the integration of ZDZW technologies, including Non-Destructive Inspection Technologies (NDIT) and artificial intelligence (AI), becomes pivotal. The industrial use case presented involves implementing ZDZW solutions in the thermoforming process for refrigerator inner body parts. This integration aims to automate quality assessment, reduce defects, and optimize production quality. The application of AI-enhanced thermal imaging and digital twin models provides real-time data for quality control, minimizing scrap rates and energy consumption. Sustainable Key Performance Indicators (KPIs) are defined to evaluate the impact of NDIT, emphasizing the reduction of scrap rates, carbon dioxide emissions, and overall environmental impact. The ZDZW methodology, positioned as part of the smart manufacturing ecosystem, contributes to innovative quality assurance, control, and sustainability services, aligning with the growing demand for sustainable production in the face of global challenges and disruptions.

Keywords: Sustainability, Zero Defects, Zero Waste, KPI, Non-Destructive Inspection Technologies.

1. Introduction

The Zero-Defect Manufacturing (ZDM) strategy aims to minimize defects in industrial processes by prioritizing first-time accuracy. ZDM integrates four main strategies: detection, prediction, prevention, and repair [1]. The Zero Defects Zero Waste (ZDZW) methodology focuses on inspection equipment, detection of anomalies, identification using AI algorithms, and preventing faults from progressing [2]. To meet the growing demand for sustainable production, companies should prioritize ZDZW solutions employing non-destructive inspection technologies and AI for defect detection, ultimately reducing waste across their manufacturing process [3]. One of the final manufacturing steps is the quality control inspection, which often involves manual labour and sometimes destructive testing, impacting productivity, labour cost and generating waste. The integration of ZDZW technologies, based on automated inspection systems, to favor Sustainable Manufacturing will allow the deployment of real-time non-destructive inspection, ensuring traceability, reducing destructive testing, and optimizing operational costs.

The principal aim of the ZDZW European project is to test and validate solutions within six distinct use cases, covering diverse industrial scenarios, from equipment manufacturers to the production of

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parts, including plastic, metal, energy, white goods, ceramics, and consumer goods, representing multiple industrial sectors. The plastic industry and related manufacturing conforming processes are crucial in the European manufacturing value chain and face challenges impacting sustainable development. Disruptions from global events, such as China's growth, the COVID-19 pandemic, and the Ukrainian conflict, increase raw material and product prices [4]. Escalating gas and electricity prices and uncertainties in long-term supply contracts affect EU industry competitiveness, affecting operational profitability. Complex products with highly added value comprise multiple operation steps and an elevated amount of consumed productive resources (materials, labour, energy, equipment, etc.). There is a growing interest in enhancing the industrial sectors by implementing in-process control through Non-Destructive Inspection Technologies (NDIT), software, and databases, aiming to improve economic competitiveness by reducing material and energy consumption during production [1], [2], [3], [5]. The project addresses waste or discarded material from identified defective products or components that are complex to rework or recycle. System enhancements involve integrating control systems and in-line Non-Destructive Inspection (NDI) methods in demonstrative use cases to facilitate swift feedback and feedforward control. ZDZW methodology aims to be an integral part of the smart manufacturing ecosystem, offering innovative quality assurance monitoring, control, and sustainability services. It includes NDI solutions linked with key sustainability performance indicators to evaluate the impact on waste generation, energy consumption, and CO2 emissions. The main objective of ZDZW's key sustainable performance indicators is to measure, quantify and evaluate the impact of the integration of non-destructive inspection solutions on defective rate and material consumption in manufacturing environments.

2. Industrial Use Case

Under the current industrial pilot, the company is set to implement Zero-Defect and Zero-Waste (ZDZW) solutions to automate the quality assessment of inner body parts produced through thermoforming. Customer satisfaction is based on ensuring the high-quality production of a refrigerator's interior body through accurate dimensional precision and defect-free finished surfaces. High-impact polystyrene (HIPS) is the primary raw material employed to conform the refrigerator's inner body through thermoforming. The inner body of refrigerators is conformed by thermoforming, a production process where the thermoplastic is heated by electrical resistance to a specific value and later moulded in a vacuum chamber. The deviations in process parameters, such as the thickness of sheet plates, humidity, and ambient temperature, lead to the generation of defects by materials tearing and slimming. The process parameters are defined in the industrialization phase by employing sheet plates with mesh, with vacuum and resistance settings adjusted based on mesh structures for process reliability. Conventional thermoforming production lines rely on operators' experience to address these problems. Due to the intrinsic variability of industrial processes, the thermoforming process parameters should be adjusted daily to adapt to the raw material variations, reducing reliability risk. The flow diagram defined in Figure 1 summarizes the different manufacturing steps required to obtain the fridge's inner body part, the inspection methods employed to control the product quality, and the different data sources.

The lack of in-process control and decision-making tools in the thermoforming process increases the scrap rate, leading to higher plastic and energy consumption, increasing overall operational costs and environmental impact of the process. Integrating ZDZW Thermal Inspection solutions based on AI-enhanced thermal imaging and digital twin models will address and optimize current operations, reducing defects and enhancing overall production quality. The ZDZW methodology introduces a new thermal vision system and simulation tool that provides real-time data (Figure 2), which can automatically measure and calculate the quality-relevant properties of the semi-finished product and control the final product during production. This ZDM strategy aims to send feedback and close the loop of the thermoforming process by adjusting thermoforming parameters through artificial intelligent algorithms and digital twin, reducing the scrap rate and the related material and energy consumption.

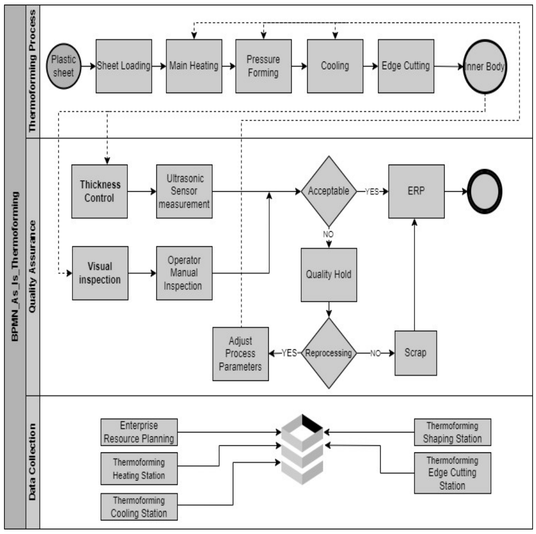

Figure 1. Business Process Model and Notation diagram for current quality assurance in thermoforming process.

The optimal process parameters will be defined by the Finite Element Analysis (FEA)-based AI model, considering the data gathered from different sources of sensors. The use FEM models, machine learning algorithms, and the acquisition of data through sensors in the thermoforming process enable the prediction of thickness and surface quality failures in real-time, optimizing material usage for sustainable production. Implementing ZDZW solutions will allow the real-time inspection and control required to adopt a sustainable manufacturing approach, where thinner sheets can be employed, reducing scrap ratio and energy consumption.

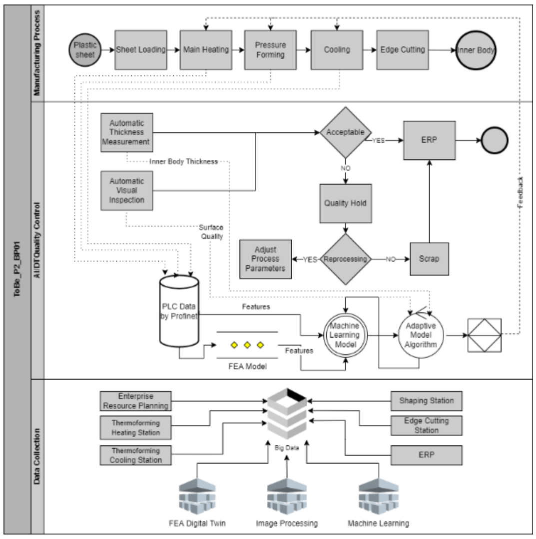

Figure 2. Business Process Model and Notation diagram for quality assurance after integrating ZDZW solutions in the thermoforming process.

3. Key Performance Indicators definition for sustainable manufacturing

For the current research, several Key Performance Indicators (KPIs) are defined to provide quantitative metrics to evaluate the impact of NDIT in the thermo-forming process to produce refrigerator inner body parts. Baseline values for KPIs are determined using historical data from production control records. Estimations are made based on experience or adaptation from similar products. The ZDZW solution's effectiveness will be assessed by evaluating Sustainable KPIs postimplementation, collecting data from new production batches or operations, and comparing it to the baseline. Implementing ZDZW solutions must assure the reduction of scrap rates based on fast, accurate, and preventive reactions to defect risk using a line monitoring and control system. In this subsection, the Sustainable Key Performance Indicators (KPIs) are defined to monitor, control, and improve the sustainable manufacturing of the thermoforming process. The ISO 22400 Automation Systems and Integration KPIs for Manufacturing Operations Management serve as a framework for defining, implementing, and visualizing the current article Sustainable KPIs [6]. Establishing well-defined KPIs is crucial for effectively assessing diverse processes and sustainable goals. Criteria, including alignment, balance, standardization, validity, quantifiability, accuracy, timeliness, predictiveness, trackability, relevance, correctness, completeness, automation, documentation, comparability, and inexpensiveness, are employed for the definition of the KPI and provide general industry guidelines. A standardized methodology employing ISO 22400 to prevent misleading information was employed to define each KPI represented in the current article, which is expressed using the structure in Table 1. KPIs monitoring is tailored to each enterprise or manufacturing plant since the compiled data can reveal trends related to specific operational or sustainable objectives.

The environmental sustainability KPI refers to the ecological impacts of the proposed thermoforming process depending on their As-Is (Fig. 1) and To-Be scenarios (Fig. 2). The current article has selected carbon dioxide emissions as the environmental sustainability to target and analyze the impact of deploying non-destructive inspection solutions for in-process quality assurance. The equation employed to calculate the CO2 emission is calculated considering the life cycle assessment (LCA) approach which follows DIN EN ISO 14040:2006 [7] and DIN EN ISO 14044:2006 norms [8]. The environmental KPI is expressed in terms of kg of carbon dioxide equivalent per unit produced (kg CO2 eq./unit produced) and is determined using the ReCiPe 2016 v1.1 Midpoint (H) [9] impact assessment methodology. The data source employed to calculate the emission factors is extracted from Ecoinvent 3.9.1 [10]. In the absence of emission factors, literature values from Chen et al. (2020) and Magnusson & Mácsik (2017) sources are considered [6], [7]. To establish the framework for the analysis of environmental impacts, the baseline scenario is considered to be the current production scenario before the implementation of non-destructive inspection (NDI) technology. In the context of the EU project 'ZDZW', 6 industrial use cases are considered. Out of those six industrial use cases, this article presents the baseline scenario of the industrial use case led by Arçelik (Turkey). In this industrial use case, thermoforming process is employed to produce desired plastic product using plastic sheet as raw material. In the current scenario, when NDI technology is not implemented, the carbon dioxide emissions 37.07 kg CO2 eq./unit produced. This includes te emissions from raw material and the energy consumption in thermoforming process. This sustainability KPI will be monitored during the entire project span and is expected to significantly reduce after the implementation of NDI technology.

4. Conclusions

Zero Defects Zero Waste (ZDZW), stands as a pivotal approach to address sustainability challenges in the manufacturing sector. The integration of ZDZW technologies, holds the promise of minimizing defects, reducing waste, and optimizing operational efficiency across diverse industrial sectors. The ZDZW European project's focus on six distinct use cases, spanning various industries, underscores the versatility and applicability of this methodology. The highlighted industrial use case, involving the implementation of ZDZW solutions in the thermoforming process for refrigerator inner body parts, exemplifies how advanced technologies can revolutionize quality control and contribute to sustainable manufacturing practices. By automating the quality assessment, employing AI-enhanced thermal imaging, and utilizing digital twin models, the project aims to enhance overall production quality while simultaneously reducing material and energy consumption. The establishment of environmental Key Performance Indicators (KPIs) further emphasizes the commitment to measuring and evaluating the impact of ZDZW solutions on defective rates, material consumption, and environmental sustainability. As the project progresses, it is expected to bring about significant reductions in carbon dioxide emissions and operational costs, ultimately contributing to a more sustainable and efficient manufacturing ecosystem. The ZDZW methodology, with its focus on innovation, quality assurance, and environmental impact, represents a crucial step towards achieving a more sustainable future in manufacturing. sustainable manufacturing.

Table1. Thermoforming Key Performance Indicators for sustainable manufacturing.

Name	Description and objective	Equation	Other information
KPI_{TRMU} Thermoforming raw material usage	Current KPI is used to study the forming process in thermoplastic materials based on the raw material consumed to manufacture the inner body part over a certain period. The raw material consumption can be reduced through the implementation of effective process controls. The goal is to reduce the consumption of plastic material.	$KPI_{TRMU}(\%) = \left(1 - \left(\frac{\mathrm{RMC_{BOM}} - \mathrm{RMC}_{MO}}{\mathrm{RMC_{BOM}}}\right)\right)$ Ec. 1 *Raw Material Consumption according to Bill of Material (kg/unit), RMC_{BOM}* *Raw Material Consumption according to Manufacturing Order (kg/unit), RMC_{MO}*	**Units of measure:** Percentage (%). **Source of data:** Enterprise Resource Planning software. **Measurement:** Each manufacturing order. **Reviewing period:** The Quality Assurance Engineers will conduct a monthly review of the KPI to analyze its behavior and determine if any adjustments to production parameters are necessary. **Range tolerances:** A decrease in raw material usage between 85% and 95% will be acceptable. **Responsible:** Supervisors. **Audience:** Managers.
KPI_{TSR} Thermoforming scrap ratio	By controlling the initial and final temperature of both the sheet and the mold body, it is possible to reduce the scrap ratio. This KPI will monitor the most critical items whose manufacturing process is crucial, subject to more defects or rejections, and whose production must be improved or controlled more exhaustively. The goal is to reduce the number of defective parts manufactured.	$KPI_{TSR}(\%) = \left(\frac{\mathrm{UM_{BOM}} - \mathrm{UM}_{MO}}{\mathrm{UM_{BOM}}}\right)$ Ec. 2 *Units manufactured according to Bill of Material (units), UM_{BOM}* *Units manufactured without any defect according to Manufacturing Order (units), UM_{MO}*	**Units of measure:** Percentage (%). **Source of data:** Enterprise Resource Planning software. **Measurement:** Each manufacturing order. **Reviewing period:** The Quality Assurance Engineers will conduct a weekly review of the KPI to analyze its behavior and determine if any adjustments to production parameters are necessary. **Range tolerances:** Anything less than five percent (<5%) is deemed acceptable. The presence of any noticeable defect classifies the product as defective. There is no discernible pattern in the occurrence of errors. **Responsible:** Supervisors. **Audience:** Managers.
KPI_{CO2PS} CO_2 Potential Savings	Amount of CO_2 emission (t CO2 eq.) based on KPI_{TRMU} and KPI_{TSR} Reducing the scrap ratio can lead to an increase in productivity and a decrease in energy consumption within the production line.	$=$ $KPI_{CO2PS}(t\ CO\_2\ eq. = RM_{CO_2-eq}\left(\frac{\mathrm{CO_2 Kg}}{\mathrm{RM\ Kg}}\right) \cdot \left(\mathrm{RMC}_{MO}(\mathrm{RM\ Kg}) + \left(\mathrm{UM}_{MO}(units) \cdot \rho\left(\frac{\mathrm{RM\ Kg}}{units}\right)\right)\right) \cdot \frac{1\ ton}{1000\ kg}$ Ec. 3 *CO_2 raw material equivalent employed in the thermoforming process (CO_2 Kg/ RM Kg), RM_{CO2-eq}* *Density of each part manufactured (Kg/units), ρ*	**Units of measure:** Ton carbon dioxide equivalent (t CO_2 eq.). **Source of data:** Enterprise Resource Planning software. **Measurement** each manufacturing order, monthly/yearly **Reviewing period:** Quality Assurance Engineer will review the KPI monthly to study behaviour and possibly change production parameters. **Range tolerances:** A decrease in CO_2 emission between 5% and 15% will be acceptable. **Responsible:** Supervisors. **Audience:** Managers.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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