www.zdzw-project.eu

NON-DESTRUCTIVE INSPECTION SERVICES FOR DIGITALLY ENHANCED ZERO WASTE MANUFACTURING

D9.29 IMPACT ASSESSMENT & KPI VALIDATION OF ZDZW SOLUTIONS – M18

V1.0

DOCUMENT INFORMATION

CONTRACT NUMBER	101057404
PROJECT WEBSITE	www.zdzw-project.eu
CONTRACTUAL DEADLINE	12/03/2024
DISSEMINATION LEVEL	PU – Public
NATURE	R — Document, report
AUTHOR(S)	AIM – Ana Rodriguez, Álvaro Souto, Eric López
CONTRIBUTORS	Pilots & Technology Providers
REVIEWER	ICE – Noel Tomas, ARC –Sena Karadağ, EURA – Shashank Goyal, IKER – Oscar Salgado
KEYWORDS	ZDZW, KPIs, Metrics, Impact.

Funded by the European Union

The ZDZW project has received funding from the European Union's Horizon Europe programme under grant agreement No 101057404. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Funded by the European Union

ABBREVIATIONS / ACRONYMS

ACRONYM	MEANING
AI	Artificial Intelligence
AR	Augmented Reality
AV	Artificial Vision
DT	Digital Twin
EMAT	Electro Magnetic Acoustic Transducer
FEA	Finite Element Analysis
FTR	First Time Right
GHG	Greenhouse Gas
HIPS	High Impact Polystyrene
HW	Hardware
IoB	Internet of Bodies
IR	Infrared
KET	Key Enabling Technology
KPI	Key Performance Indicator
LCM	Lithography-based Ceramics Manufacturing
MIR	Medium Infrared
NDI	Non-Destructive Inspection
OCT	Optical Coherence Tomography
OEE	Overall Equipment Effectiveness
PBT	Polybutylene Terephthalate
PP	Polypropylene
QA	Quality Assurance
RFID	Radio Frequency Identification
SAW	Submerged Arc Welding
SW	Software
UT	Ultrasonic Testing
UV	Ultra-Violet
ZDZW	Zero Defects Zero Waste

Funded by the European Union

EXECUTIVE SUMMARY

The primary objective of the *Impact Assessment and KPI Validation* of ZDZW *Solutions* report is to evaluate the effectiveness of ZDZW solutions based on the defined Key Performance Indicators (KPIs) for each demonstrator (a.k.a. pilots and use cases) within the project. This evaluation encompasses both purely technical KPIs and those related to the Zero Waste / Zero Defects paradigm. The deliverable is divided into two iterations, with the first iteration occurring mid-project and the second at the project's conclusion.

This document represents the first iteration of the deliverable, which builds upon the demonstrator scenarios and their respective KPIs reported in the confidential deliverable *D2.4 Demonstration Scenarios and Monitoring KPIs Definition*. In this case, the present document provides a concise summary of the various use cases where ZDZW solutions are being implemented, outlines the expected improvements following the introduction of these solutions, and thoroughly explains the KPIs defined to evaluate the results of the ZDZW solutions in the demonstrator use cases.

The second iteration of the deliverable (D9.32), conducted at the project's conclusion, will present an analysis of the KPIs defined in deliverable D2.4, and collected in this initial document, D9.29 (M18). The analysis will showcase the specific improvements introduced by the different solutions developed in ZDZW, once implemented in the real demonstration scenarios, described throughout this document.

1 INTRODUCTION

The main goal of the ZDZW project is to contribute to a zero defect and zero waste manufacturing paradigm through improved manufacturing process monitoring and innovative quality control services. The project proposes different solutions and addresses several use cases in 6 pilots, covering different manufacturing perspectives from five industrial sectors (automotive, home appliances, renewable energies, e-health, and food & beverages industry).

The deliverable *Impact assessment and KPI validation of ZDZW solutions* aims to evaluate the effectiveness of the solutions developed within the ZDZW project by tracking their performance on the pilots, based on the analysis of the thoroughly defined KPIs. This iteration of the derivable is focused on the definition of use cases for each pilot, and the mapping between the use cases and the selected ZDZW solutions to enhance their inspection processes. The report includes a brief reminder of the initial expectations of improvement due to the implementation of ZDZW solutions for each pilot. The document also lists the KPIs (see Table 1) defined in an earlier stage of the project (deliverable D2.4), including the formulas to calculate them. Finally, some conclusions are pointed out.

A second iteration of this report (deliverable *D9.32*) will take place at the end of the project and will evaluate the effectiveness of the ZDZW solutions in each use case by comparing the KPIs before and after the implementation of the respective ZDZW solution(s).

TABLE 1. SUMMARY OF KPIS DEFINED FOR EACH PILOT AND INVOLVED ZDZW SOLUTIONS.

Pilot	KPIs defined	ZDZW solutions
Pilot 1: Plastic parts mass production quality assurance	Reduction of scrap BP01-BC1a – Coffee Capsule	ZDZW Volumetric Inspector ZDZW Surface Anomaly Detector
	Reduction of scrap BP04-BC3 – PISTON PSS3	
	Reduction of scrap BP05-BC4 – MV CASE CODE	
	Part Energy Consumption	
	Productivity	
	Material waste	
Pilot 2: Thermoplastics forming excellence	Reduction of raw material usage	ZDZW Thermoforming Digital Twin Solution ZDZW Thermal Imaging Inspector ZDZW Volumetric Inspector
	Decrease in scrap ratio	
	Increase of OEE	
Pilot 3: Wind turbine tower production enhancement	Welding FTR ratio	ZDZW EMAT UT Solution. ZDZW AI-Enhanced Artificial Vision. ZDZW AR-enhanced Inspector ZDZW Welding Process Inspector
	Welding Repairing Cost	
	Welding Wire Scrap Reduction	
	Welding Flux Scrap Reduction	
	Painting Inspection Time per Section	
	Painting Inspection Cost	
Pilot 4: Durable fastening solutions	Set-up Time Reduction	ZDZW Mechanical Hardness Inspector ZDZW AE-based Integrity Evaluator
	Reduction of raw material waste	
	Part Energy Consumption	
	Productivity	

Pilot	KPIs defined	ZDZW solutions
Pilot 5: Lithography-based eHealth parts production	Reduction of Scrap Antenna Modules	ZDZW Volumetric Inspector ZDZW Surface Anomaly Detector ZDZW AI-enhanced Artificial Vision ZDZW MIR-OCT Solution
	Part Energy Consumption	
	FTR ratio	
	Material waste	
Pilot 6: Plastic packaging AV AI-based quality control	Destructive testing samples in the assembling capsules phase	ZDZW AI-enhanced Artificial Vision ZDZW Surface Anomaly Detector ZDZW Thermal Imaging Inspector
	Destructive testing samples in the filling & welding capsules phase	
	Destructive testing samples in the packaging capsules phase	
	Material waste in the assembling capsules phase	
	Material waste in the filling & welding capsules phase	
	Material waste in the packaging capsules phase	

2 PILOT 1: PLASTIC PARTS MASS PRODUCTION QUALITY ASSURANCE (GLN)

2.1 Pilot line description

GLN is an industrial group from Portugal focusing its activity on mould manufacturing and the production of plastic injection parts for different sectors, such as automotive, electronic, and food packaging.

Three different demonstrators were defined in this pilot covering the automotive and food sectors. All proposed demonstrators involve the manufacturing of injected plastic parts sharing certain characteristics and common defects (mainly aesthetic and geometric), which allows the implementation of a common quality assurance pipeline:

- Coffee Capsules: Produced for use in espresso machines in a domestic environment. It's a product used in the food industry that requires dimensional and composition inspection of all produced capsules. Since this product has a high production rate, the only way to ensure an inspection of 100% of production is via an automated system.
- Piston PSS3: It forms part of a safety device in automobiles, so quality control is a special sensitive phase of the manufacturing process. The current human-dependent visual defect quality inspection increases cost and reduces efficient production.
- MV Case Code: Part in charge of guaranteeing good electrical connection in cars with sealing functions. It is manufactured by a sophisticated plastic injection process involving 2 types of plastic.

The inspection approach before the ZDZW project heavily relies on the human factor, it's far from achieving the ideal of controlling 100% of the production and takes a high portion of the manufacturing process time, which translates into improvable levels of waste rate, energy consumption, and productivity. ZDZW *Visual Inspection Suite*, namely ZDZW *Volumetric Inspector* and ZDZW *Surface Anomaly Detector*, will provide the technical developments needed to overcome those issues.

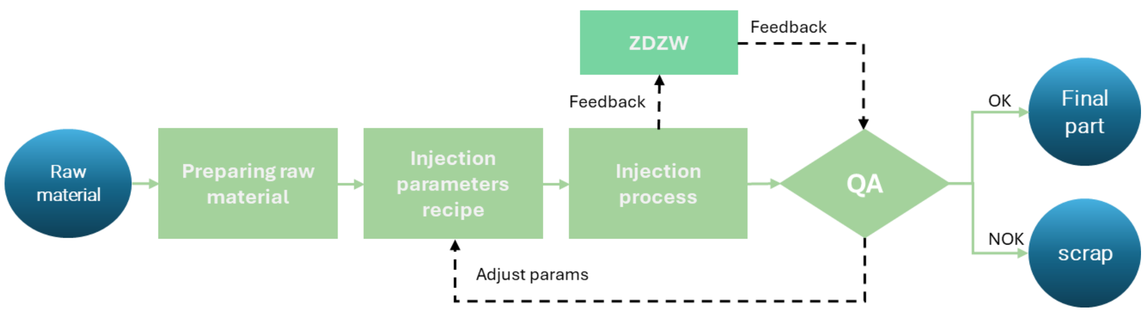

FIGURE 1. PILOT 1: SIMPLIFIED PRODUCTION FLOWCHART AFTER ZDZW

ZDZW solutions are being integrated into the manufacturing lines of the defined demonstrators (Figure 1). Data from the injection process is gathered by specific artificial vision HW and is processed by machine learning algorithms. The exploited information is served to qualified personnel who can use it to adjust the parameters of the injection machine and to make decisions on the current production batch or regarding the maintenance services.

2.2 Original Objectives

TABLE 2. ORIGINAL OBJECTIVES PILOT 1: PLASTIC PARTS MASS PRODUCTION ASSURANCE (GLN)

Manufacturing process	Product	Raw Materials	Main Defects	Increase FTR (%before to %after)	Annual waste reduction expected	Annual GHG reduction (t CO_2 eq)[1]
Injection moulding	Custom plastic injection parts	Thermoplastic (PBT, TPE, PP, PA)	Flashes, burns, colour, deformation	94% to 99%	6 t (6%)	12

Expected Improvements: 9% - 12% reduction in Energy consumption based on the reduction of downtimes; 8% - 12% GHG emissions reduction based on the computation of the GHG impact for 1 kg of good parts ready for the market; 4 - 6% of waste reduction; 2-3% less waste forward to landfills; Increase of 7-10% of productivity; 2-3% reduction of the rejection rates; 3-5% of the global savings of the core business.

2.3 KPIs description and metrics

The methodology adopted to evaluate the impact has as the initial point the collection of production details on the injection process. This process will be improved by implementing two solutions developed within the ZDZW project, the ZDZW *Volumetric Inspector* and ZDZW *Surface Anomaly Detector*. This initial step is followed by the identification of KPIs for the specific pilot, Plastic part mass production quality assurance.

Six different performance indicators were defined based on the number of defective parts fabricated, the subsequent scrap generated, and the possible impact on the energy and time consumed during fabrication:

- Reduction of scrap Coffee capsule (reference BP01-BC1a): Measurement of the scrap by comparing the number of defective parts vs the total number of produced parts.
- Reduction of scrap Piston PSS3 (reference B04-BC3): Number of defective parts vs total number of produced parts.

[1] Preliminary calculations obtained from ZDZW use case. As a reference, the average CO_2 emission of a person living in Belgium is 8 t per year. To limit global warming to 2°C, the average level of CO_2 emission per capita on our planet must not exceed 2,1 t by 2050.

- Reduction of scrap MV Case Code (reference BP05-BC4): Measurement of the scrap by comparing the number of defective parts vs the total number of produced parts.
- Part Energy Consumption: Energy consumption required for manufacturing of plastic injection moulding references (BC1a, BC3, BC4).
- Productivity: Number of produced units in the number of hours spent during the manufacturing for the plastic injection moulding references (BC1a, BC3, BC4).
- Material waste: Amount of material scraped (kg) divided by the amount of material consumed.

TABLE 3. PILOT 1: DEFINED KPIS AND CALCULATION DETAILS

KPI	Metric	unit
Reduction of scrap BP01-BC1a – Coffee Capsule	$\frac{\text{BC1a wasted amount (ea)}}{\text{BC1a total production (ea)}} \times 100$	% units
Reduction of scrap BP04-BC3 – PISTON PSS3	$\frac{\text{BC3 wasted amount (ea)}}{\text{BC3 total production (ea)}} \times 100$	% units
Reduction of scrap BP05-BC4 – MV CASE CODE	$= \frac{\text{BC4 wasted amount (ea)}}{\text{BC4 total production (ea)}} \times 100$	% units
Part Energy Consumption	$\left(1 - \frac{BC1_{EC}}{BC1_{ECpy}}\right) + \left(1 - \frac{BC3_{EC}}{BC3_{ECpy}}\right) + \left(1 - \frac{BC4_{EC}}{BC4_{ECpy}}\right)$ EC = Energy Consumption (kWh) ECpy = Energy Consumption previous year (kWh)	kWh
Productivity	$\left(\frac{BC1_{TP}}{BC1_{TPT}}\right) + \left(\frac{BC3_{TP}}{BC3_{TPT}}\right) + \left(\frac{BC4_{TP}}{BC4_{TPT}}\right)$ TP = Total Production Qty (ea) TPT = Total Production Time (h)	pieces/hour
Material waste	$\left(\frac{BC1_{TMS})}{BC1_{TMC}}\right) + \left(\frac{BC3_{TMS})}{BC3_{TMC}}\right) + \left(\frac{BC4_{TMS})}{BC4_{TMC}}\right)) \times 100$ TMS = Total raw Material Scraped (kg) TMC = Total raw Material Consumed (kg)	% kg

3 PILOT 2: THERMOPLASTICS FORMING EXCELLENCE (ARC)

3.1 Pilot line description

Arçelik (ARC), headquartered in Turkey and with a global presence, is one of the largest manufacturers of home appliances. With a strong orientation towards innovation, ARC looks forward to the total digitalization of the entire value chain as a pillar to increase the sustainability of its activities.

Plastic thermoforming process is key for ARC in many of its products. It consists in heating plastic sheets and shaping them against moulds to achieve parts with the desired geometry. Pressure, heat up, and cold down gradients must be thoroughly controlled to get the optimum result, since disturbances on these parameters or in ambient conditions lead to defective geometries or bad surface finish that can increase material waste and energy consumption or customer dissatisfaction. Within the ZDZW scope, the Inner Body Thermoforming is the selected manufacturing process to demonstrate the capabilities of some of the ZDZW solutions. The inner body refers to the tub-shaped part that constitutes the internal part of a refrigerator, which is manufactured by thermoforming a single sheet of a particular plastic, HIPS, mixed with certain chemicals. Guaranteeing a thickness inside tolerances along all the inner body following an FTR approach is a complex task that would lead to important optimization in material and energy consumption.

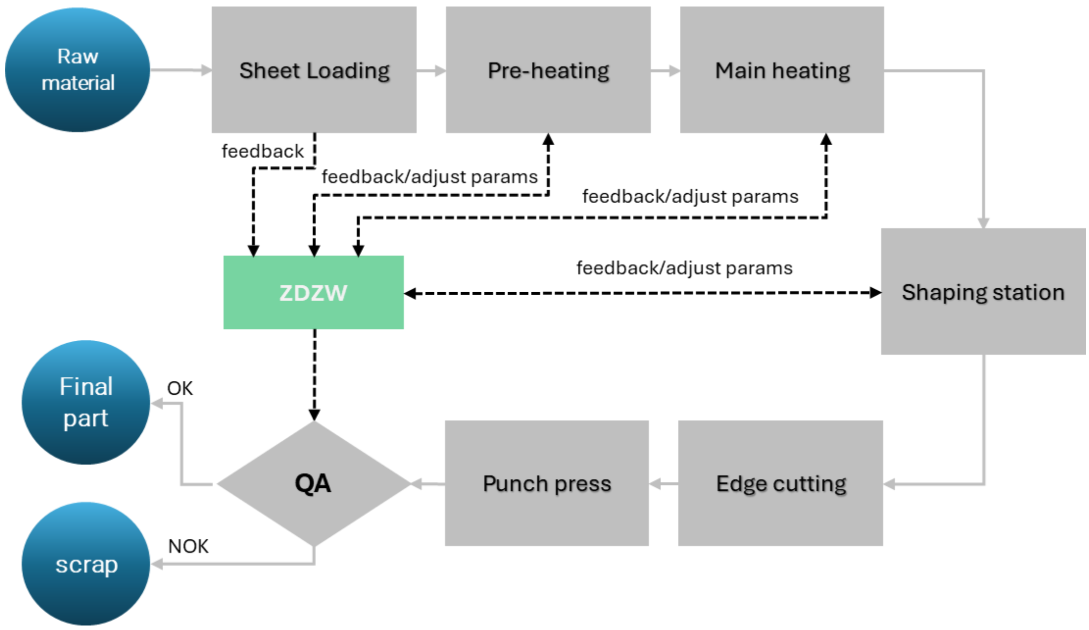

FIGURE 2. PILOT 2: SIMPLIFIED PRODUCTION FLOWCHART AFTER ZDZW

A combination of the ZDZW *Thermoforming Digital Twin Solution* and the ZDZW *Thermal* Imaging Inspector solutions, belonging to the ZDZW Thermal Inspection Suite, is proposed to enhance the specified manufacturing process. A heat transfer digital twin (DT) of the thermoforming process is being developed based on the physical principles of heat transfer applied to the actual thermoforming machines. The DT is continuously fed with information from the working stations at each manufacturing stage (Figure 2) and from IR imaging systems installed between them, being able to adapt process parameters in real time. Furthermore, the IR images will be processed using AI techniques to detect defects in the inner body and relevant variations in its thickness during the manufacturing process.

3.2 Original Objectives

TABLE 4. ORIGINAL OBJECTIVES PILOT 2: THERMOPLASTICS FORMING EXCELLENCE (ARC)

Manufacturing process	Product	Raw Materials	Main Defects	Increase FTR (%before to %after)	Annual waste reduction expected	Annual GHG reduction (t CO_2 eq)
Thermo-forming	Refrigerator inner parts	Thermoplastic (HIPS)	Minimum thickness not reached.	92% to 97%	1350 t (62.5%)	5100

Expected Improvements: Increasing quality of the manufacturing process and decreasing the scrap ratio; increase the controllability of the manufacturing process; Successfully giving feedback to the machine to optimize its parameters automatically; 2.3 M €/year saving is foreseen as a result of this project; 8% average scrap ratio that Arçelik currently has, will be decreased to 3% of scrap ratio at the end of the project (5% improvement in raw material use in the production line); efficiency of the production line is improved by 10% by reducing the downtimes with the feedback system; cycle of the production line is reduced, and the energy consumption indicators of the line are improved by 10%; quality data of the production line will be improved by 25%.

3.3 KPIs Description and Metrics

In this pilot, Thermoplastic Forming Excellence, the implementation of ZDZW *Thermoforming Digital Twin Solution* and the ZDZW *Thermal Imaging Inspector* designed to reduce the scrap rates and its efficacy will be assessed by monitoring the evolution of the following KPIs:

- Reduction of raw material usage: Measurement of the reduction of raw material due to the optimization of the thickness of the plastic sheet in the final piece.
- Decrease in scrap ratio: Measurement of the reduction in produced defective parts.
- Increase of OEE: Improvement in performance of production line.

TABLE 5. PILOT 2: DEFINED KPIS AND CALCULATION DETAILS

KPI	Metric	Unit
Reduction of raw material usage	$\frac{\mathrm{t_{prev}} - \mathrm{t}_{final}}{\mathrm{t}_{prev}} \times 100$ $\mathrm{t_{prev}} = previous\ thickness\ (mm)$ $\mathrm{t}_{final} = final\ thickness\ (mm)$	%
Decrease in scrap ratio	$\frac{\left(\frac{\mathrm{defective}_{production_{new}}}{\mathrm{total}_{production\_new}}\right)}{\left(\frac{\mathrm{defective}_{production_{old}}}{\mathrm{total}_{production\_old}}\right)} - 1$	%
Increase of OEE (Overall equipment effectiveness)	$\%\mathrm{P} \times \%\mathrm{A} \times \%\mathrm{Q}$ P = Performance A = Availability Q = Quality	%

4 PILOT 3: WIND TURBINE TOWER PRODUCTION ENHANCEMENT (GRI)

4.1 Pilot line description

Over fifteen years of experience have turned GRI Renewable Industries into a solid company within the wind energy industry with a total of 16 factories in 8 countries. Their expertise focuses on the manufacturing of towers and flanges for wind turbines.

Two demonstrator cases are defined in the scope of this pilot based on the two subprocesses of tower manufacturing that concentrate on the most critical defects:

- Seam Weld Inspection: The wind turbine towers are manufactured using the SAW process, optimized for joining large parts. Usual defects are lack of fusion, pores, spatters, or slag inclusions. Defective parts are detected in a later QA stage, when the whole part is finished, using classic inspection techniques, which require qualified personnel. In most cases, it is not possible to inspect 100% of the production.
- Painting Inspection: Small imperfections (mm) produced during the painting process may lead to flaking paint and corrosion. Depending on the final location of the wind turbine, undetected defects can lead to repair costs surpassing manufacturing expenses. Expert operators inspect the painted surface visually using rudimentary tools such as light flashes or magnifying glasses. The human factor together with the difference between the inspected area and the defect sizes cause the inspection methodology to present a low degree of detectability.

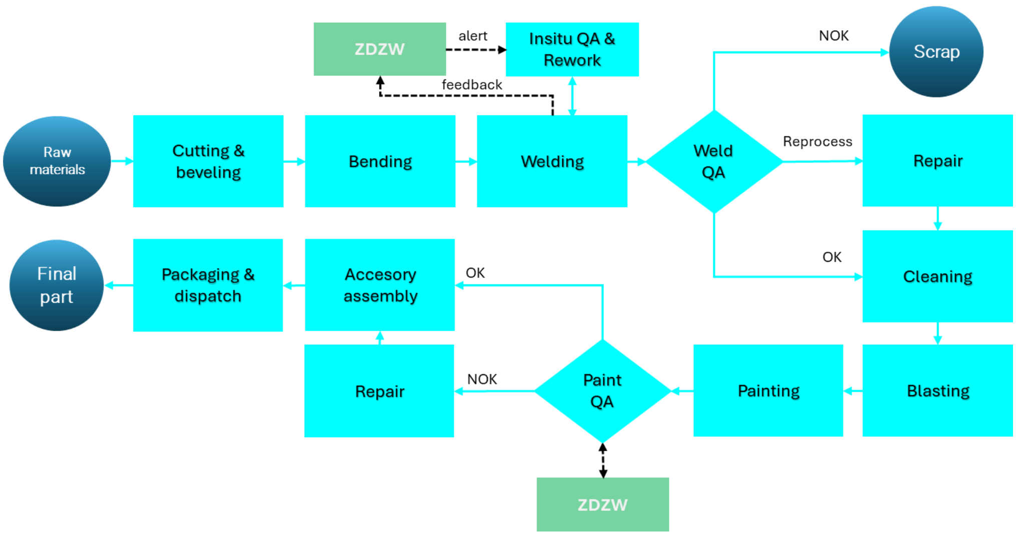

FIGURE 3. PILOT 3: SIMPLIFIED PRODUCTION FLOWCHART AFTER ZDZW

ZDZW *EMAT UT Solution*, from the ZDZW *Integrity Inspection Suite*, and the ZDZW *Welding Process Inspector*, from the ZDZW *Thermal Inspection Suite*, will be separately demonstrated in the Seam Weld Inspection use case. On one hand, an EMAT UT system is being designed for the GRI welding use case to be installed just after a welding torch, pursuing a production-inspection in-line scheme. On the other hand, several sensors are installed on the working station to monitor different welding parameters. A dataset is generated and cross-referenced with traditional inspection results to build a data model that can be used during the welding process to alert about abnormal behaviours with a high probability of generating defects.

Within the scope of the Painting Inspection use case, a couple of solutions from the ZDZW *Visual Inspection Suite* are being implemented in the production line. ZDZW *AI-enhanced Artificial Vision* techniques are being adapted and integrated into a mobile platform that will scan the whole surface of the painted towers searching for paint defects. The system will detect the presence of a defect and alert the ZDZW *AR-enhanced Inspector* system which will indicate the location of the defect to the operator using AR. Both developments work together to automate the inspection process.

4.2 Original Objectives

TABLE 6. ORIGINAL OBJECTIVES PILOT 3: WIND TURBINE TOWER PRODUCTION ENHANCEMENT (GRI)

Manufacturing process	Product	Raw Materials	Main Defects	Increase FTR (%before to %after)	Annual waste reduction expected	Annual GHG reduction ($t\ CO_2$ eq)
Welding & Painting	Wind turbine tower components	Steel, welding wire, flux & Paint, dissolvent	Lack of fusion/ penetration & Defective coating	50% to 60% (15% reduction of repairing Costs + detect and repair 98% of all defects)	1.500t steel, 90t paint, 110t solvent, 171t wire, 1628t welding flux (90%)	6400

Expected Improvements: 15% reduction of repairing costs for welding processes; minimization of direct involvement of operators during welding under complex conditions (<10% of cases); improvement of automatic defect detection and feedback for real-time monitoring and welding control (>90%); 25% improvement of inspection repair time in the painting process; guarantee the detection and repair of at least 98% of all the defects prior delivery.

4.3 KPIs Description and Metrics

For the Wind turbine tower production enhancement pilot, up to six KPIs have been defined to measure raw material consumption and manufacturing time. Comparison between KPIs measured before and after the ZDZW implementation will serve as an assessment method for the ZDZW *EMAT UT Solution* and ZDZW *Welding Process Inspector* solutions in the Seam Weld Inspection use case, and ZDZW *AI-enhanced Artificial Vision* and ZDZW *AR-enhanced Inspector* in the Painting Inspection use case.

- Welding FTR ratio: Percentage of FTR-produced towers contemplating the welding use case.
- Welding Repairing Costs: Number of hours dedicated to repairing welding beads and cost associated.
- Welding Wire Scrap Reduction: Amount of saved welding wire due to reduction in reparation work.
- Welding Flux Scrap Reduction: Amount of saved flux due to reduction in reparation work.
- Painting Inspection Time per section: Measurement of the total time spent in the painting inspection.
- Painting Inspection Cost: Measurement of the inspection cost per inspected tower calculated by the number of operators necessary.

TABLE 7. PILOT 3: DEFINED KPIS AND CALCULATION DETAILS

KPI	Metric	units
Welding FTR ratio	$\frac{\text{FTR }(Pieces)}{Total\ production\ (Pieces)} \times 100$	%
Welding repairing costs	$\frac{\text{Number of Repairs (ea)} \times \text{Hours (h)} \times \text{Cost of Repairing(€/h)}}{Total\ Production\ (ea)}$	€
Welding Wire Scrap reduction	$[RWNP - TWNP] \times PL \times WD$ TWNP = Theorical Wire Number of Passes per section (ea) RWNP = Real Wire Number of Passes per section (ea) PL = Pass Length (m) WD = Wire Density (ton/m)	ton
Welding Flux Scrap reduction	$[RFNP - TFNP] \times PL \times WD$ TFNP = Theorical Flux Number of Passes per section (ea) RFNP = Real Flux Number of Passes per section (ea) PL = Pass Length (m) FV = Flux Volume per meter (m^3/m) FD = Flux Density (ton/m^3)	ton
Painting Inspection Time per section	$\frac{IT(min)}{\text{Surface Section }(\text{m}^2)}$ IT = Time spent in inspecting one tower. Considers the number of operators, e.g. 6 hours *3 operators= 18 hours	min/m2
Painting inspection cost	$OIR - OR$ OIR = Operators Initially Required. Number of inspectors/operators needed in manual painting inspection task per tower. (ea) OR = Operators Required. Number of inspectors/operators required for ZDZW inspection of painting per tower. (ea)	operators

Funded by the European Union

5 PILOT 4: DURABLE FASTENING SOLUTIONS (ERRE)

5.1 Pilot line description

Erreka (ERRE) is a consolidated company with more than 60 years of experience and with an area of influence that exceeds 50 countries specialized in fastener production, plastic injection, and automation. One of the five main business cases of ERRE is the production of high-quality large-metric fasteners for sectors like aerospace or energy, where the mechanical requirements are especially demanding.

The main requirements in bolt and fastener production are to obtain the right internal microstructure and to assure a specific hardness gradient from the surface to the core of the produced parts, which are achieved through different induction heating stages alongside the production chain. A couple of solutions from the ZDZW *Integrity Inspection Suite* will be assessed within the scope of the Fasteners Quality Control demonstrator. These solutions seek to move from an offline and destructive inspection paradigm to a non-destructive and online one.

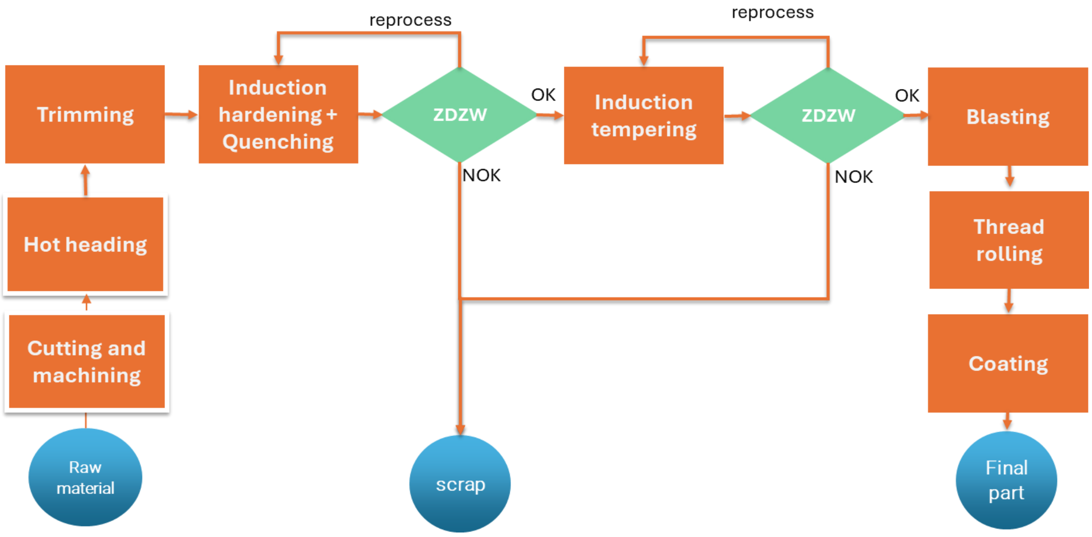

FIGURE 4. PILOT 4: SIMPLIFIED PRODUCTION FLOWCHART AFTER ZDZW

ZDZW *Mechanical Hardness Inspector* will provide manufacturing process digital twins (DT) elaborated using AI techniques trained with data from validated Multiphysics FEA simulation models. DTs are continuously fed with real-time manufacturing data from the three different induction subprocesses (Figure 4), monitoring and providing diagnostics for each part produced. At the same time, ZDZW *AE-based Integrity Inspector* is deployed on the *Induction hardening + Quenching* stage (Figure 4) to evaluate the microstructure of the produced part. When a magnetic field is applied to a ferromagnetic piece, some acoustic waves are produced inside the material called Barkhausen noise. Martensitic phase decreases the Barkhausen noise, allowing good and bad thresholds for internal microstructures to be detected.

The new quality control process reduces the destructive testing to the normative minimum, resulting in important reductions in production time and material waste. In addition, ZDZW technologies enable the traceability of each produced component.

5.2 Original Objectives

TABLE 8. ORIGINAL OBJECTIVES PILOT 4: DURABLE FASTENING SOLUTIONS (ERR)

Manufacturing process	Product	Raw Materials	Main Defects	Increase FTR (%before to %after)	Annual waste reduction expected	annual GHG reduction (t CO_2 eq)
Induction treatment	Fastening bolts	Iron-based alloys	Structural defects	92% to 96%	6t (50%)	25

Expected Improvements: 25% reduction of energy consumption, 50% waste reduction, production improved by 33%, production costs reduced by 100 000 € annually.

5.3 KPI description and Metrics

For this pilot, the effectiveness of the ZDZW *Mechanical Hardness* and *the* ZDZW *AE-based Integrity Inspector* solutions is measured using the following KPIs:

- Set-up time reduction: Average time spent on the preparation task. Measured by batches.
- Reduction of raw material waste: Amount of wasted plastic.
- Part energy consumption: Energy consumption required for manufacturing a batch of pieces.
- Productivity: Manufactured parts per hour.

TABLE 9. PILOT4: DEFINED KPIS AND CALCULATION DETAILS

KPI	Metrics	units
Set-up time reduction	$$\left(\frac{\sum_{i=1}^{N} ST_i}{N}\right)$$ ST = Set up time (h) N = total parts produced in a batch	h
Reduction of raw material waste	$$\sum_{i=1}^{N} NOK_{parts_i}\ (pieces) \times NOK_{weight_i}\left(\frac{kg}{piece}\right)$$ N = total parts produced in a batch	kg
Part energy consumption	$$\frac{\sum_{i=1}^{N} \mathrm{TEC_i} \times 1000}{\mathrm{TKPG}}$$ TEC = Total Energy Consumption per fabrication order during Production Process, Set Up not included. (kWh) TKGP = Total Kilograms Produced per fabrication order (kg) N= total parts produced in a batch	kWh/ton
Productivity	$$\left(\frac{\sum_{i=1}^{N} \mathrm{OK\_parts}_{\ i}(\mathrm{ea})}{\sum_{i=1}^{N} \mathrm{Production\_time}_{\ i}(\mathrm{h})}\right)$$	pieces/h

Funded by the European Union

6 PILOT 5: LITHOGRAPHY-BASED E-HEALTH PARTS PRODUCTION (AIR)

6.1 Pilot line description

AirCode (AIR) is a burgeoning German startup with a primary focus on pioneering IoT solutions leveraging RFID technology. The company's endeavours are particularly geared towards the healthcare sector, where they're spearheading the development of cutting-edge Key Enabling Technologies (KETs) for out-of-body communication, often referred to as IoB (Internet of Bodies).

An important part of the AIR activity is focused on the production of implantable ceramic antennas using lithography technology. This additive manufacturing process entails the deposition of ceramic material alongside complementary chemicals, which are subsequently consolidated using UV light. Following this, various thermal post-processing steps are employed to eradicate any undesirable chemical residues. Even though current quality control tasks are performed between most of the manufacturing steps, there is no possibility of reprocessing defective parts. Since the manufacturing process is being developed and it is quite slow, the need for inline quality control strategies arises as a requirement for a closed-loop control approach to the LCM process. The LCM inspection and quality control scenario is defined to demonstrate a combination of several solutions from the ZDZW *Integrity Inspection Suite* and the ZDZW *Visual Inspection Suite*.

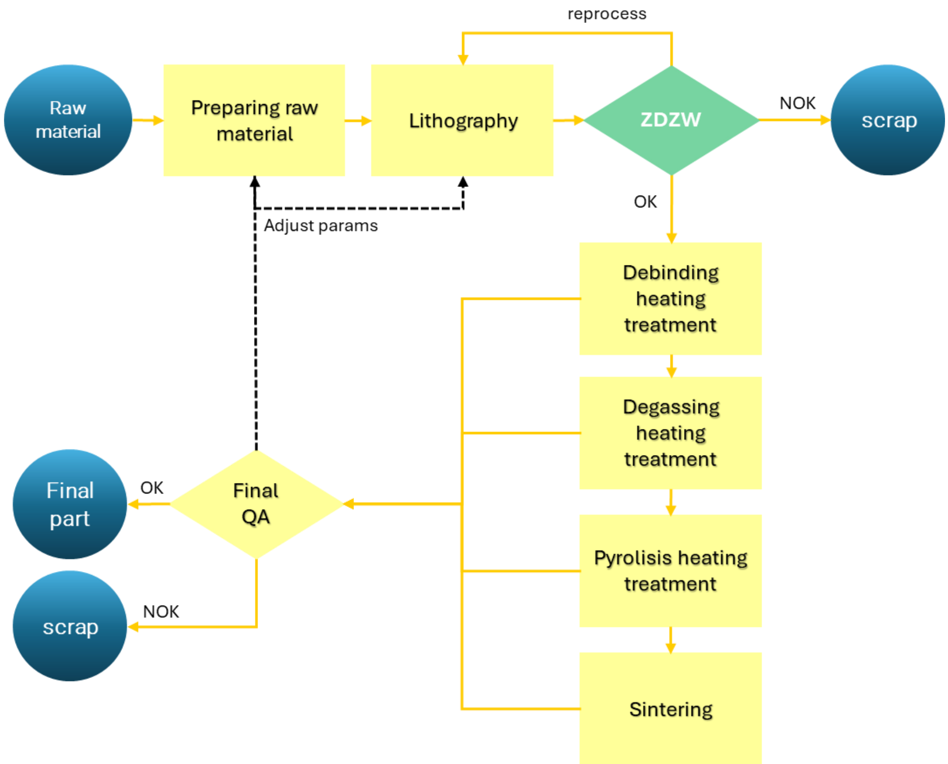

FIGURE 5. PILOT 5: SIMPLIFIED PRODUCTION FLOWCHART AFTER ZDZW

Figure 5 shows the manufacturing process of the antennas, the different steps of the target manufacturing chain, and the location of the ZDZW solutions. ZDZW *MIR-OCT Solution*, from the ZDZW *Integrity Inspection Suite*, furnishes specific HW to be integrated into the lithography machine, enabling it to perform mid-infrared tomography during the LCM subprocess. The MIR-OCT HW offers sub-surface 3D inspection of ceramic antennas, providing insight into the internal integrity of the manufacturing piece. This information is treated by different solutions belonging to the ZDZW *Visual Inspection Suite*, namely the ZDZW *Volumetric Inspector*, ZDZW *Surface Anomaly Detector*, and ZDZW *AI-enhanced Artificial Vision*. These solutions will analyse the tomographic images during the LCM process to detect geometrical, superficial, and sub-superficial defects and decide if the part can be reprocessed or must be discarded.

6.2 Original Objectives

TABLE 10. ORIGINAL OBJECTIVES PILOT 5: LITHOGRAPHY-BASED E-HEALTH PARTS PRODUCTION (AIR)

Manufacturing process	Product	Raw Materials	Main Defects	Increase FTR (%before to %after)	Annual waste reduction expected	annual GHG reduction (t CO_2 eq)
Lithography	Ceramic-based medical antennas	Ceramic slurries	Porosity, sub-surface defects	75% to 87.5%	2.5t (50%)	3-9

Expected Improvements: Reduction of rejected antenna modules by 50%; for an anticipated 10M antenna modules/year and ~2g per antenna module, this yield improvement translates into a waste reduction of up to 2.5 t of ceramic / year. In terms of production cost this results in savings of > 9M€ / year; and a reduction in energy consumption of up to 12.5%. This will facilitate the scale-up of the AIR antenna module and lead to significant savings in machine costs.

6.3 KPIs description and Metrics

Three KPIs are defined for the Lithography-based e-Health parts production pilot. Reduction rate in defective final parts, energy savings, and FTR are the selected variables to evaluate the effectiveness of the ZDZW *MIR-OCT Solution*, ZDZW *Volumetric Inspector*, ZDZW *Surface Anomaly Detector* and ZDZW *AI-enhanced Artificial Vision* solutions:

- Reduction of Scrap Antenna Modules: Percentage of defective antennas produced (scrap rate).
- Part Energy Consumption: Total energy employed to manufacture a non-defective antenna.
- FTR ratio: Number of non-defective units by the number of hours
- Material wasted: Amount of material scraped divided by the amount of material consumed.

Table 11. Pilot 5: Defined KPIs and calculation details

KPI	Metrics	units
Reduction of Scrap Antenna Modules	$\frac{defective\ antenna\ modules\ (ea)}{total\ antenna\ modules\ produced\ (ea)} \times 100$	% Number of items
Part Energy Consumption	$\frac{Total\ energy\ used\ for\ 1000\ antenna\ modules\ (kWh)}{1 -\ scrap\ rate\ (‰)}$	kWh
FTR ratio	$\frac{\text{first time right amount (Units)}}{\text{hour (h)}}$	Units/hour
Material waste	$\frac{weight\ of\ scrapped\ antenna\ modules\ (kg)}{total\ weight\ of\ produced\ antenna\ modules\ (kg)} x100$	Kg

7 PILOT 6: PLASTIC PACKAGING (ILLY)

7.1 Pilot line description

While Illy has evolved into a renowned multinational coffee company, it proudly retains its identity as a family-owned business, with its beginnings dating back to 1933 in Trieste, Italy. Spanning across more than 140 countries, its global presence underscores its enduring dedication to excellence and tradition.

Coffee pods and capsules, which represent a relevant share of the market, introduce a greater level of complexity in the coffee packaging process. A single capsule comprises different sub-parts and involves different raw materials. In addition, as is understandable, the food and beverage industry is governed by very strict regulations and standards, so in this case, the structure of the finished capsules must be perfectly assembled to preserve the product in optimal conditions. A defective packaging ultimately leads to inadequate preservation of the product, thereby impacting its quality and shelf life.

Quality inspection for coffee capsules is the scenario envisioned to demonstrate how a couple of NDI techniques from the ZDZW *Visual Inspection Suite* and the ZDZW *Thermal Inspection Suite* can be combined to go from the current destructive inspection paradigm to an automatic non-destructive inspection procedure.

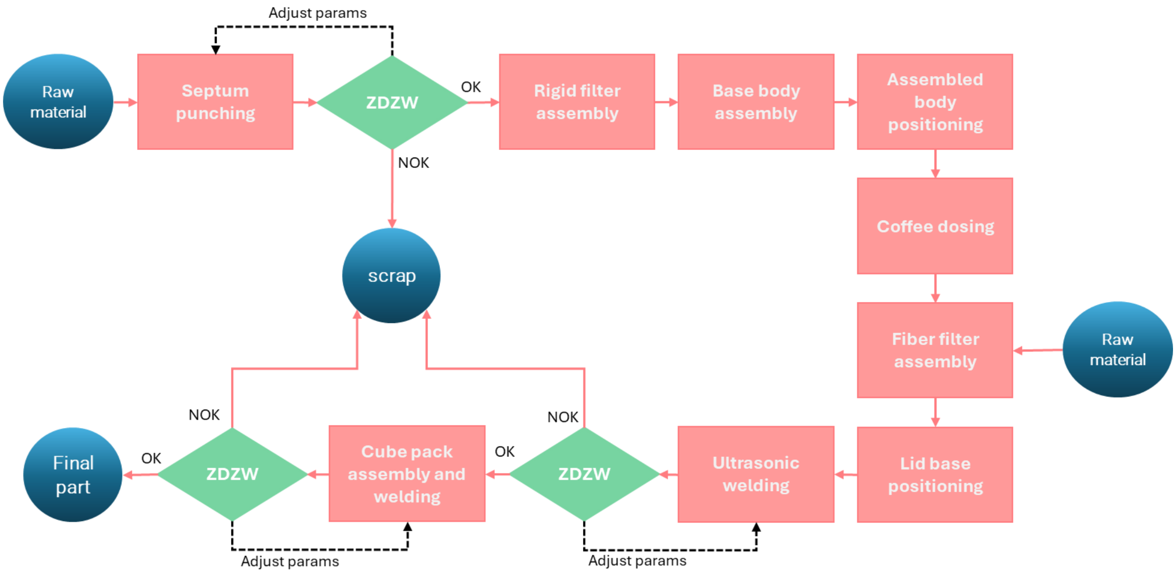

FIGURE 6. PILOT 6: SIMPLIFIED PRODUCTION FLOWCHART AFTER ZDZW

As can be observed in Figure 6, specific implementations of the ZDZW *AI-enhanced Artificial Vision* and ZDZW *IR Thermal Imaging Inspector* solutions will be deployed after the subprocesses that accumulate the most critical failures of the manufacturing chain of the coffee capsules. These critical stages include the septum punching task, the ultrasonic welding of the lid and capsule body, and the thermal assembly subprocess for the Cube Pack. The introduced NDI techniques facilitate the identification and removal of faulty capsules during production, enabling swift real-time adjustments to process parameters to prevent the occurrence of further defects.

7.2 Original Objectives

TABLE 12. ORIGINAL OBJECTIVES PILOT 6: PLASTIC PACKAGING (ILLY)

Manufacturing process	Product	Raw Materials	Main Defects	Increase FTR (%before to %after)	Annual waste reduction expected	annual GHG reduction (t CO_2 eq)
Packaging	Coffee capsules	Thermoplastic, aluminium	Sealing issues	97.9% to 99%	10t (50%)	30.3

Expected Improvements: reduction of 10 t per year of generated waste; 1% reduction of defects, 1% reduction of energy consumption.

7.3 KPIs description and Metrics

Due to the characteristics of ILLY's production chain, which rely on a tightly cycled assembly line, the selected KPIs for evaluating the effectiveness of the implemented ZDZW *AI-enhanced Artificial Vision* and ZDZW *IR Thermal Imaging Inspector* solutions mainly focus on controlling the rates of defective parts and wasted raw materials. The ZDZW effectiveness in the Plastic Packaging pilot will be evaluated using the following KPIs:

- Destructive testing samples in the assembling capsules phase: Calculation made based on the Ratio between tested pieces (destructive techniques) vs total pieces.
- Destructive testing samples in the filling & welding capsules phase: Calculations are made based on the Ratio between tested pieces (destructive techniques) vs total pieces.
- Destructive testing samples in the packaging phase: Calculations are made based on the Ratio between tested pieces (destructive techniques) vs total pieces.
- Material waste in the assembling capsules phase: pieces rejected (weight) for after-production quality checks divided by the total pieces produced.
- Material waste in the filling & welding capsules phase: pieces rejected (weight) for after-production quality checks divided by the total pieces produced.
- Material waste in the packaging capsules phase: pieces rejected (weight) for after-production quality checks divided by the total pieces produced.

TABLE 13. PILOT 6: DEFINED KPIS AND CALCULATION DETAILS

KPI	Metrics	units
Destructive testing samples in the assembling capsules phase	$\frac{\text{tested samples (pieces)}}{\text{total produced samples (pieces)}} \times 100$	% Pieces
Destructive testing samples in the filling & welding capsules phase	$\frac{\text{tested samples (pieces)}}{\text{total produced samples (pieces)}} \times 100$	% Pieces
Destructive testing samples in the packaging phase	$\frac{\text{tested samples (pieces)}}{\text{total produced samples (pieces)}} \times 100$	% Pieces

Material waste in the assembling capsules phase	$\frac{\text{waste amount (Kg)}}{\text{total production (Kg)}} \times 100$	% kg
Material waste in the filling & welding capsules phase	$\frac{\text{waste amount (Kg)}}{\text{total production (Kg)}} \times 100$	% kg
Material waste in the packaging capsules phase	$\frac{\text{waste amount (Kg)}}{\text{total production (Kg)}} \times 100$	% kg

8 CONCLUSIONS

An analysis of the initial status of the KPIs listed in this document was performed at an earlier stage of the project but is not depicted in this document as it may contain sensitive data. This first analysis will be considered the baseline against which the KPI values will be compared once the ZDZW solutions are fully operational in the respective pilots.

This first version of the document revisits the initial definition of the industrial scenarios and KPIs carried out in D2.4. The indicators selected continue to be valid at the current stage of the project, however, updated calculations (M18) could not be part of the deliverable, since the ZDZW solutions are currently in the implementation phase, and the necessary data are not available yet.

Next iteration of the deliverable will be submitted in M36. Process data will be collected in the upcoming months to perform a comparison between the pilot situation before and after the ZDZW project. Results will serve to evaluate the performance success of solutions developed in the ZDZW project after being implemented in a real industrial environment in the end-users premises.

CHANGE LOG

VERSION	DESCRIPTION OF CHANGE
V0.1	First draft
V0.2	First review
V0.3	Second review
V0.4	Coordinator Review
V1.0	Submitted version