ZDZW

www.zdzw-project.eu

NON-DESTRUCTIVE INSPECTION SERVICES FOR DIGITALLY ENHANCED ZERO WASTE MANUFACTURING

D2.2 Benchmarking of Sustainable Manufacturing Technologies

V1.0

DOCUMENT INFORMATION

CONTRACT NUMBER	101057404
PROJECT WEBSITE	www.zdzw-project.eu
CONTRACTUAL DEADLINE	31/12/2022
DISSEMINATION LEVEL	PU – Public
NATURE	R – Document, report
AUTHOR	VSYS-Mauro Fabrizioli
CONTRIBUTORS	All technical partners
REVIEWER	AIMEN-Alvaro Souto, UPV-Adrian Colomer Granero
KEYWORDS	ZDZW, ZDM, ZDMP, NDIT, KPIs, Waste, Inspection, Monitoring, Thermal, Integrity, Defect, AI-Enhanced, Artificial Vision, Anomaly Detection

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

ABBREVIATIONS / ACRONYMS

ACRONYM	MEANING
AE	Acoustics Emissions
AI	Artificial Intelligence
AM	Additive Manufacturing
ANN	Artificial Neural Network
AR	Augmented Reality
AV	Artificial Vision
CA	Consortium Agreement
CAD	Computer-Aided Design
CMM	Coordinate Measure Machine
CT	Computed Tomography
DOA	Description of Action
DT	Digital Twin
EC	European Commission
EMAT UT	Electro Magnetic Acoustic Transducer Ultrasonic Testing
FEM	Finite Element Model
GPU	Graphics Processing Unit
HMD	Head-mounted Display
HW	Hardware
IMU	Inertial Measurement Unit
IoT	Internet of Things
IIoT	Industrial Internet of Things
IP	Intellectual Property
IR	Infrared
IT	Information technologies
KER	Key Exploitable Result
KPI	Key Performance Indicator
LCM	Lithography-based Ceramics Manufacturing
MQTT	Message Queuing Telemetry Transport
MIR	Mid-Infrared
NDI	Non-destructive Inspection
NDIS	Non-destructive Inspection Services
NDT	Non-destructive testing
OCT	Optical Coherence Tomography
OER	Other Exploitable Result
OEM	Original Equipment Manufacturer
OpenCV	https://opencv.org/
OPS	Executive Operations Board
PBT	Polybutylene terephthalate
RTO	Research and Technology Organisation
SME	Small and Medium Enterprise
SAW	Submerged Arc Welding
SW	Software
TBA	To Be Assessed
UCI	Ultrasonic Contact Impedance
UT	Ultrasonic Testing
VT	Visual Testing

Funded by the European Union

WP	Work Package
ZD	Zero-defect
ZDM	Zero-defect Manufacturing
ZDMP	Zero-defect Manufacturing Platform (https://www.zdmp.eu/)
ZG3D	Zero-gravity 3D (https://www.zerogravity3d.com/)
ZW	Zero-waste
3D	Three dimensional

EXECUTIVE SUMMARY

The scope of Work Package WP2 – DESIGN: Industrial Scenarios and Requirements Analysis is to provide a view on the vision, technologies and benchmarks, use cases and requirements to develop the next generation solutions for industrial manufacturing that will be part of the ZDZW project.

Deliverable D2.2 is the result of Task 2.2 Benchmarking of Technologies for Sustainable Manufacturing and includes an extensive presentation of relevant inspection technologies of ZDZW provided under a production efficiency, zero-defect, and sustainable manufacturing perspective. They are grouped into three different sections that cover respectively the inspection technologies presented in the three work packages implementing the ZDZW inspection suite:

- WP4: Integrity inspection.
- WP5: Vision Inspection.
- WP6: Thermal Inspection.

Each inspection technology is displayed along with a description of alternative inspecting solutions. Technical partners' expertise and knowledge in their specific area as well as academic and professional sources are fundamental to establish several characteristics which are used in a throughout comparison between each technology and its alternatives to cover the benchmarking purposes of the task.

Section 1 Introduction introduces the content of the deliverable in the context of ZDM, starting from ZDZW project and zooming to WP2 objectives, finally providing the list of technical partners contributing to the deliverable and their covered inspection technologies.

Section 2 Methodology describes the content structure used to describe and benchmark the ND inspection technologies of ZDZW and the main process adopted to recover and refine inputs from several partners.

Section 3 Technological Demands gives a brief overview of the matching between demands from project use cases, more extensively described in Deliverable D2.3, and ZDZW inspection solutions.

Sections 4, 5, 6, respectively ZDZW Integrity Technologies for Sustainable Manufacturing, ZDZW Vision Technologies for Sustainable Manufacturing, ZDZW Thermal Inspection Technologies for Sustainable Manufacturing, one for each of the mentioned technological areas corresponding to the three equally numbered WPs, are the core of the deliverable and provide for each Non-Destructive Inspection (NDI) technology of ZDZW an exhaustive description and comparison with other destructive and non-destructive solutions, as anticipated above.

Section 7 Conclusions reports the final conclusions and a summary table of the alternative inspecting technologies taken into consideration.

Funded by the European Union

1 INTRODUCTION

Zero-Defect Manufacturing concept plays a crucial role in guaranteeing the minimization of defects and errors in industry processes by trying to act at the first time properly.[1] Detection, prediction, prevention and repair are described as the four main strategies for ZDM integration in the manufacturing industry.[2] The detection strategy aims at the early detection of anomalies and faults using inspection equipment and classifying them through the employment of Artificial Intelligence algorithms, avoiding their propagation to the next stages of production. Prediction attempts to give timely forecasting of defect generation. Defect prevention implies high knowledge of the underlying process, which is often translated into advanced model-based Digital Twins of the systems for the proactive identification of deviating operating conditions leading to defective output.[3] Digital Twins enable to simulate of several manufacturing processes (such as heat treatment, thermoforming, etc.) via ultra-realistic and dynamically optimized simulation models, thus reducing the cost and time for design, industrialization and maintenance, improving overall manufacturing performance[4]. The repair ZDM strategy aims to reduce work and time employed once a repairable defect is detected, preventing parts from flowing downstream, which increases the costs and material usage. ZDZW manufacturing is implemented to improve production quality and, by extension, to reduce the amount of materials and energy required for a specific quantity of products, which in turn leads to more sustainable manufacturing.

An increasing emphasis on sustainable production requires that manufacturing companies continuously deliver higher quality products of increasing complexity at lower cost, while simultaneously limiting the use (and particularly waste) of resources within entire industrial ecosystems. To address this demand, companies[5] should put their efforts increasingly into implementing ZDZW solutions based on non-destructive inspection technologies and AI algorithms for defect detection. Emerging key enabling technologies, such as EMAT, AE, Artificial Vision, Digital Twin, together with in-line data gathering solutions, data storage and communication standards, data analytics tools and digital manufacturing technologies offer new opportunities for reduction of manufacturing defects and waste. All in all, inspection technologies have a massive impact on reducing defects and waste in almost every manufacturing industry. This is a key aspect in the ZDZW project and a common denominator of the technologies that are presented in this document.

[1] Caiazzo, B., et al. (2022), Towards Zero Defect Manufacturing paradigm: A review of the state-of-the-art methods and open challenges, *Computers in Industry*, Vol. 134, 103548, ISSN 0166-3615.

[2] Psarommatis, F., et al. (2020), Zero defect manufacturing: state-of-the-art review, shortcomings and future directions in research, *International Journal of Production Research*, Vol. 58:1, pp. 1-17, ISSN 0020-7543.

[3] Powell, D., et al. (2022), Advancing zero defect manufacturing: A state-of-the-art perspective and future research directions, *Computers in Industry*, Vol. 136, 103596, ISSN 0166-3615.

[4] Xu, Y., et. Al. (2019), A Digital-Twin-Assisted Fault Diagnosis Using Deep Transfer Learning, *IEEE Access*, Vol. 7, pp. 19990-19999, ISSN 2169-3536.

[5] Colledani, M., et al. (2014), Design and Evaluation of In-line Product Repair Strategies for Defect Reduction in the Production of Electric Drives, *Procedia CIRP*, Vol. 21, pp. 159-164, ISSN 2212-8271.

Deliverable D2.2 is part of Work Package WP2 and focuses in investigating all the inspection technologies involved to create the basis for the ZDZW project. A deep understanding of these technologies is paramount since it will be reflected in the subsequent tasks T2.3 and T2.4, the first concerning the chosen use case pilots, with all their functional and structural specifications and key performance indexes, the latter the requirements that must be fulfilled to achieve minimum working results.

The inspection technologies proposed by each partner addressed in this document are studied under several aspects, specifically:

- A description of the technology and its scientific basis
- The state of development, maturity, and industrial/academic relevance
- The flexibility of application in the industry and how can be integrated in the production lines
- Some examples of industrial application, and/or related academic publications
- A description of competitive inspection technologies, whether destructive or not
- Advantages and limitations of the proposed technology with respect to the competitive ones

After an all-round depiction of each inspection technology, several tables of characteristics are presented in order to establish a benchmark framework between the proposed technology and its competitive ones. The criteria chosen are both qualitative and quantitative and derive from existing industrial solutions, academic research or partner's experience.

The main objective of this benchmarking framework is to add value to the selection of the technologies being developed in the ZDZW project and show what can they offer compared to its alternatives.

ZDZW Inspection Suite solutions cover three main technical areas of non-destructive inspection, namely Part Integrity Evaluation, Visual Inspection and Thermal Process Monitoring. In the project consortium these Non-destructive inspection techniques are supplied and will be further developed to become integrated and mature KERs by technological partners' expertise in their respective sectors; these partners have been selected from both technology providers and research and development centres, to obtain an optimal balance and cover all the areas:

- Technology providers:
  - Innerspec Technologies Europe SL (INN): Ultrasonic Testing
  - Norblis APS (NOR): OCT Technologies
  - Video Systems SRL (VSYS): Artificial Vision
  - Yoran Imaging LTD (YOR): Thermal Imaging
  - Dira Reliability SL (DIRA): Acoustic Emissions
  - Simularge Bilisim ve Muhendislik Teknolojileri AS (SIM): Digital Twin technologies
  - Siemens Sanayi ve Ticaret AS (SIE): Thermal Imaging
- Research and Development Centres:
  - Asociacion de Investigacion Metalurgica del Noroeste (AIM): Welding Process
  - Instituto Tecnologico de Informatica (ITI): Artificial Vision

- Universitat Politècnica de València (UPV): Vision and Integrity inspection
- Ikerlan S. Coop (IKER): Mechanical Hardness Process
- Danmarks Tekniske Universitet (DTU): OCT Technologies
- Fraunhofer Gesellschaft zur Forderung der Angewandten Forschung EV (IGD): Augmented Reality Technologies

The inspection technologies involved in the project are grouped into three different sections that map to the three work packages implementing the ZDZW inspection suite, as shown in the following list. For each WP also the list of all technical experts contributing is reported (starting from the WP lead, bolded).

- WP4: Integrity inspection (**IKER**, DIRA, NOR, INN, DTU, UPV, AIM)
    - 4.1 Mechanical Hardness Digital Twin Inspection
    - 4.2 Acoustic Emission based Integrity Evaluation
    - 4.3 MIR-OCT Sub-surface Anomaly Detection
    - 4.4 EMAT Ultrasonic Inspection
- WP5: Vision Inspection (**ITI**, VSYS, IGD, AIM, UPV)
    - 5.1 Volumetric Inspection
    - 5.2 Surface Anomaly Detection
    - 5.3 AI-Enhanced Artificial Vision Inspection
    - 5.4 AR-Enhanced Vision Inspection
- WP6: Thermal Inspection (**SIE**, SIM, YOR, AIM, DIRA, UPV)
    - 6.1 Thermoforming Digital Twin Inspection
    - 6.2 Thermal Imaging Inspection
    - 6.3 Welding Process Inspection

2 METHODOLOGY

The information summarized in this document has been provided by all project partners involved in the technical Work Packages covering the Inspection suite of ZDZW, and is based on several sources, among which:

- Partners' general expertise in the relevant fields
- Ownership of specific technologies or solutions
- Intended usage of technologies or solutions as part of the partners' contribution to the project in Tasks or Work Package of their responsibilities

Such information was collected by the document editors via workshops held during face-to-face meetings, phone, or web audio conferences, email exchanges and finally through a comprehensive table of content to uniformly collect information for each of the identified elements. To support the process, an example of necessary input was provided by one of the contributors, after being reviewed by deliverable supervisor in coordination with project coordinator and WP2 leader.

For each ZDZW NDI technology foreseen in the project, all the technical partners involved, and most of all the leader of the task developing the NDI, have been asked to describe in detail the inspection solution supplied and to be further developed, more precisely covering the following content:

- A description of the technology and its scientific basis
- The state of development, maturity
- The industrial/academic relevance
- The flexibility of application in the industry
- How can be integrated in the production lines
- Some examples of industrial application
- A description of competitive inspection technologies, whether destructive or not
- Advantages and limitations of the proposed technology with respect to the competitive ones
- References or related academic publications

The explanation had to be focused at first to the general technology and then eventually moved to the specific partners' solutions.

The subsequent activity for each of the partners was to compose a table of specifications, capabilities or more general characteristics associated with the proposed technology. All of these so-called criteria were attributed a score and a similar exercise was done for all the identified competitive technologies using the same criteria, in order to consent a comparison in a standardized benchmark framework. If the pinpointed criterium was quantitative, the actual numeric value or range was filled in, while for qualitative ones a four-level scale similar to the one in the Table 1 was used.

TABLE 1. EXAMPLE OF QUALITATIVE COMPARISON AND COLOUR SCALE

Very Low	Low	High	Very high

Finally, a summary table comparing criteria values for all competitive solutions including the one proposed in the project is completed, using the colour scale to highlight respective advantages and limitations.

After partners inserted their contribution in the document, a first round of peer review was started among partners covering the same ZDZW solution, since their efforts mostly concurred in the same technical task. The review allowed further refinement of the text and validation of the references, while also ensuring the coherence between partners' vision.

3 TECHNOLOGICAL DEMANDS

Sustainable inspection technologies are the core asset of the ZDZW project. It should be noted that ZDZW Inspection Solutions will be designed for any industrial sector, and not limited to the challenges of the defined pilot cases described in detail in Deliverable D2.3. Anyway, these pilots will be used to deploy and validate the ZDZW Inspection Solutions in pre-defined use cases, namely:

- Pilot 1: Plastic parts mass production quality assurance [GLNPlast SA (GLN)]. Custom plastic injection parts (PBT, PP and BioPBS raw materials) manufactured by Injection Moulding.
- Pilot 2: Thermoplastics forming excellence [Arcelik AS (ARC)]. Refrigerator Inner body parts (from HIPS raw material) manufactured by Thermo-forming.
- Pilot 3: Wind turbine tower production enhancement [GRI Towers Galicia SL (GRI)]. Wind turbine tower components (steel) processed per welding and painting.
- Pilot 4: Durable fastening solutions production [Matz-Erreka S. Coop. (ERR)]. Fastening bolts hardening per Induction heat process.
- Pilot 5: Lithography-based e-health parts production [airCode UG (AIR)]. Ceramic based medical antennas manufactured by LCM.
- Pilot 6: Plastic packaging AV AI-based Quality Inspection [illycaffè SPA (ILLY)]. Inspection of coffee packaging integrity.

One of the main objectives of ZDZW is to test and validate the ZDZW Inspection Solutions in these 6 use cases, covering different manufacturing perspectives (industrial equipment manufacturers, parts and components manufacturers and final products manufacturers) and industrial sectors (plastic, metal, energy, white goods, ceramics, and consumer goods).

The following table summarises how the inspection suites (integrity, vision, thermal) are expected to contribute to solve the defined pilots and with each specific technology. Some solutions are parenthesised as they were not initially planned in DoA, but as far as the project started, a potential interest raised from both end users and technology providers in exploiting them to control other details of products and processes of the defined use cases, widening the ZD perspective.

TABLE 2. INVOLVEMENT BETWEEN PILOTS AND INSPECTION TECHNOLOGIES

PILOT	INTEGRITY	VISION	THERMAL
Pilot 1: Plastic Parts Mass Quality Assurance [GLN]		5.1, 5.2	
Pilot 2: Thermoplastics Forming Excellence [ARC]		(5.1, 5.2)	6.1, 6.2
Pilot 3: Wind turbine tower production enhancement [GRI]	4.4	(5.2, 5.3)	6.3
Pilot 4: Durable fastening solutions production [ERR]	4.1, 4.2		
Pilot 5: Lithography-based e-health parts production [AIR]	4.3		
Pilot 6: Plastic packaging AV AI-based Quality Inspection [ILLY]		5.3	6.2

4 ZDZW INTEGRITY TECHNOLOGIES FOR SUSTAINABLE MANUFACTURING

As a final step of manufacturing processes, such as welding, coating, or hardening, quality control measures are performed regularly. Most of those quality controls are done using destructive testing which reduces productivity and increases costs as well as it generates a considerable quantity of scraps.

ZDZW Integrity Technologies for Sustainable Manufacturing, foreseen within WP4 activities, will provide quality data and defect identification with online process data from non-destructive inspection techniques. They will be implemented as an in-situ and real-time process monitoring and non-destructive inspection methods. This will allow the traceability of each component and minimize destructive testing required. Additionally, several process parameters will be optimized to increase the quality and will be integrated into a fully automated production system.

4.1 Mechanical Hardness Digital Twin Inspection

4.1.1 Description

The proposed technology for the mechanical hardness inspector is a FEM trained and real time Digital Twin (DT). The DT also requires some experimental in-situ measurements, such as actual process parameters and variables, mainly to improve the quality of the inspection. The development of the DT is performed with machine learning and Artificial Neural Network (ANN) techniques, which are trained using a FEM-based database. In the ZDZW project, this technology is going to be developed and implemented in an induction hardening manufacturing process, where the objective is the non-destructive inspection of the microstructure or the formation of martensitic phase and hardness profile inside the component, from surface to core, during the process. The required experimental measurements by the DT are the current in the coil and its frequency (induction machine variables), which could be measured with a current probe, and surface temperature evolution on the workpiece, which could be measured with pyrometers. For the induction hardening FEM data generation, a general-purpose multi-physic software like Ansys could be employed, and the ANN implementation could be done in Matlab™ software.

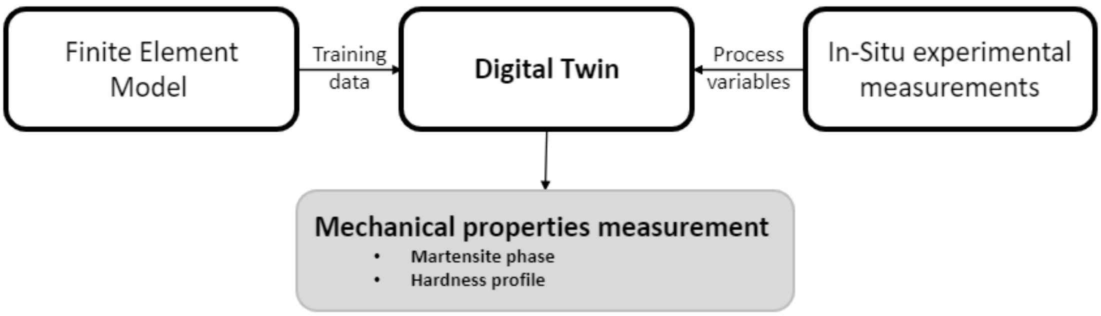

FIGURE 1. SCHEMATIC REPRESENTATION OF THE NON-DESTRUCTIVE MECHANICAL HARDNESS INSPECTION BASED ON FEM TRAINED AND REAL TIME DIGITAL TWIN

Funded by the European Union

FEM modelling of induction heat treatments has been used in several applications to predict mechanical properties. However, performing real-time calculations with FEM models is not currently achievable, as they typically require long computational times. This opens the opportunity to the development of reduced order FEM-based models or DTs than can run in real time, using the aforementioned machine learning and artificial intelligence techniques.

4.1.1.1 State, Maturity and Relevance

As technology advances and FEM models are more efficient and accurate in multiphysics manufacturing process simulations, FEM-based Digital Twins or Hybrid Twins[1] can be developed for industrial applications. Although they have not yet been widely used in the industry (TRL5), it is considered a promising technology for NDT and adaptive control applications.

4.1.1.2 Flexibility and Level of Integration

This kind of solution can be implemented in manufacturing workflows where the specific FEM model is available, or can be formulated, and where the necessary process variables are technically accessible. Regarding the level of integration, one of the major advantages of DTs is that they can be implemented in real time inspections.

The need for a specific FEM model, on the contrary, results into a lack of flexibility since model refining is required for each studied manufacturing process and its individual characteristics (for example, part geometry or material).

4.1.1.3 Industrial applications and References

In the latest years, several authors have developed and implemented DTs in different industrial applications. A Digital Twin for the plastic injection manufacturing process combining FEM data obtained from a design of experiments and a machine learning approach[2] and a Hybrid Twin built with neural network methodologies to study the induction heating process and determine the temperature inside a cylindrical bar[3] are two relevant examples.

4.1.1.4 Competitive destructive or non-destructive inspection technologies

There are several competitive destructive and non-destructive inspection technologies that can be used for hardness inspection. The most conventional destructive test used for hardness inspection is the indentation-based hardness measurement. This requires cutting and microstructural preparation of the sample.

[1] Chinesta, F., et al. (2020), Virtual, Digital and Hybrid Twins: A New Paradigm in Data-Based Engineering and Engineered Data, *Archives of Computational Methods in Engineering*, Vol. 27, No. 1, ISSN 1134-3060.

[2] Hürkamp, A., et al. (2020), Combining simulation and machine learning as digital twin for the manufacturing of overmolded thermoplastic composites, *Journal of Manufacturing and Materials Processing*, Vol. 4, No. 3, ISSN 2504-4494.

[3] Asadzadeh, M. Z., et al. (2019), Inverse Model for the Control of Induction Heat Treatments, *Materials*, 12, ISSN 1996-1944.

Alternatively, non-destructive inspection technologies are typically based on ultrasonic technologies, magnetic methods such as Barkhausen noise or Eddy Current inspection, or mechanical testing such as the Leeb rebound test.

4.1.1.5 Advantages and Limitations of supplied technology

The proposed NDI method has big advantages as a real-time hardness inspection method, but it has its limitations especially concerning flexibility. The following table summarizes the main criteria to consider when evaluating these kind of inspection methods.

TABLE 3. INSIGHTS OF MECHANICAL HARDNESS DIGITAL TWIN INSPECTION TECHNOLOGY

CRITERIUM	VALUE/LEVEL	NOTES
Depth of measurement	No limit	Core inspection could be performed
Measurement capabilities	Hardness and microstructural phase	Other capabilities (stresses, defects) are possible
Real-time inspection	Yes	
Precision	High	Needs to adjust the model
Rate of inspection	High	100%
Integrable and automatable	Yes	
Flexibility and interchangeability	No	Part and process dependence
Specimen requirements	None	

4.1.2 Benchmarking Technologies/Solutions

4.1.2.1 Barkhausen Emission techniques

Barkhausen Emission techniques are typically based on acoustic noise or magnetic noise, being the latter the most widely used in the industry. Barkhausen noise analysis consists of the measurement of a noise-like magnetic signal, which is induced in a ferromagnetic material by an externally applied magnetic field. Its use is mainly focused on material characterization and evaluation of surface defects generated by heat treatments. Generally speaking, the main applications of the Barkhausen magnetic noise method are divided into three main categories: evaluation of hardness, residual stresses and surface defects.[4] Several sensors are commercially available[5] and commercial systems can be integrated into production line.

TABLE 4. INSIGHTS OF BARKHAUSEN EMISSION TECHNIQUES

CRITERIUM	VALUE/LEVEL	NOTES
Depth of measurement	0.01-1 mm	[4]
Measurement capabilities	Hardness, defects, residual stresses	

[4] Stresstech company, Barkhausen Noise Analysis (Available, accessed on 2022/10/24).

[5] Deveci, M. (2016). Nondestructive Determination of Case Depth by Barkhausen Noise Method (Available, accessed on 2022/06/12).

Funded by the European Union

Real-time inspection	Yes	
Precision	High	Must be calibrated for specific case.
Rate of inspection	High	100%
Integrable and automatable	Yes	
Flexibility and interchangeability	Yes	
Specimen requirements	Material	Materials must be ferromagnetic.

4.1.2.2 Ultrasonic inspection techniques

There are several non-destructive inspection methods that are based on the ultrasonic technology. Ultrasonic backscatter method is probably the most effective technique for measuring the case-depth of induction hardened parts.[6] Using the mechanical and structural differences between the microstructures of the surface hardened layer and the base material in combination with ultrasonic frequencies optimized for backscattering, it is possible to achieve reliable and reproducible surface hardening depth measurements.[7]

TABLE 5. INSIGHTS OF ULTRASONIC BACKSCATTER METHOD

CRITERIUM	VALUE/LEVEL	NOTES
Depth of measurement	1.5-2 mm ÷ 6 mm	6
Measurement capabilities	Hardness	
Real-time inspection	No	
Precision	Medium	The scatter can be influenced by different factors (pores, inclusions…)
Rate of inspection	High	100%
Integrable and automatable	Yes	
Flexibility and interchangeability	Yes	
Specimen requirements	None	

Ultrasonic Contact Impedance (UCI) testing utilizes a diamond indenter similar to that used in a classic Vickers Microhardness test. While conventional Vickers requires optical evaluation of the area of an indent, the UCI method electronically detects by a shift of an ultrasonic frequency[8]. It offers a good inline-measuring capability as the measuring

[6] Baqeri, R., et al. (2012), Case Depth Profile Measurement of Hardened Components Using Ultrasonic Backscattering Method, *18th World Conference on Nondestructive Testing* (Available, accessed on 2022/10/24).

[7] Fraunhofer IZFP (2022), Surface Hardening Depth (SHD) Nondestructive Inspection of Inductively Hardened Parts and Components using Ultrasonic Backscattering (Available, accessed on 2022/10/24).

[8] Buehler company, Non-Destructive Hardness Testing (Available, accessed on 2022/10/24).

equipment is portable.[9] DIN 50159 and ASTM A1038 standardize UCI method measurements.[10]

TABLE 6. INSIGHTS OF ULTRASONIC CONTACT IMPEDANCE TESTING.

CRITERIUM	VALUE/LEVEL	NOTES
Depth of measurement	Superficial	Relationship between hardness value (HV), test force F (N) and indentation depth h (µm): $h = 0.062 \cdot \sqrt{F/HV}$ [11]
Measurement capabilities	Surface hardness	
Real-time inspection	No	Needs indentation
Precision	High	Strongly affected by a change in material therefore must be calibrated specifically
Rate of inspection	High	100%
Integrable and automatable	Yes	
Flexibility and interchangeability	No	Strongly affected by a change in material therefore must be calibrated specifically
Specimen requirements	Minimum weight and thickness Maximum surface roughness	≥ 0.5 inches thick[8] (specified in DIN 50159 respectively ASTM A1038) ≥ 300 g weight[10]. Roughness depth should not typically exceed 5 µm[12] (specified in DIN 50159-1 respectively ASTM A1038)

4.1.2.3 Eddy current

In Eddy current testing, a current is induced in the material by means of an externally applied magnetic field. Changes in the current based on the material are picked-up in a secondary coil, which provide valuable workpiece information such as flaws and surface cracks. Eddy current testing can also be used to specify material hardness as well as material and coating thickness determination, but the measurement depth is limited by the used frequency.[8]

[9] Stebner, S. C., et al. (2021), A System Identification and Implementation of a Soft Sensor for Freeform Bending, *Materials*, Vol. 14, 4549, ISSN 1996-1944.

[10] Gogolinskii, K. V., et al. (2019), Mechanical properties measurements with portable hardness testers: advantages, limitations, prospects, *Journal of Physics: Conference Series*, Vol. 1384, 012012, ISSN 1742-6588.

[11] Time Group Inc., Q&A about UCI hardness tester (Available, accessed on 2022/11/17).

[12] Frehner, C., et al. (2017), Advancements of ultrasonic contact impedance (UCI) hardness testing based on continuous load monitoring during the indentation process, and practical benefits, *15th Asia Pacific Conference for Non-Destructive Testing* (Available, accessed on 2022/12/06).

Table 7. Insights of eddy current testing

CRITERIUM	VALUE/LEVEL	NOTES
Depth of measurement	< 5 mm (steel)	Not suitable for thick hardened cases
Measurement capabilities	Hardness, defects	
Real-time inspection	Yes	
Precision	High	
Rate of inspection	High	100%
Integrable and automatable	Yes	
Flexibility and interchangeability	Yes	
Specimen requirements	None	

4.1.2.4 Leeb Rebound test

Leeb Rebound hardness testing evaluates the hardness of a test specimen striking it at a controlled velocity and measuring the height and velocity of its rebound. The hardness is indirectly measured via the loss of energy of an impact body. It will lose more speed at softer material.[13] This is a widely used on-site testing method for evaluating the strength of large pieces of equipment and structures that are difficult to test with a stationary hardness tester.[13] Leeb hardness measurement method is standardized on the national and international level: DIN 50156 (1-3), ASTM A956, ISO 16859 (1-3)[10].

Table 8. Insights of Leeb rebound hardness testing

CRITERIUM	VALUE/LEVEL	NOTES
Depth of measurement	Superficial	
Measurement capabilities	Hardness	
Real-time inspection	No	On-site inspection; needs indentation
Precision	High	
Rate of inspection	Low	To replace the traditional stationary when a laboratory setting is not available.
Integrable and automatable	Yes	
Flexibility and interchangeability	Yes	Potable equipment
Specimen requirements	Minimum weight and maximum surface roughness	Good surface finish and a minimum weight of 5 kg[10]

[13] Hegazy, R., et al. (2017), Empirical Relation between Leeb Rebound Hardness and Tensile strength for Austenitic Ductile Cast Iron, *IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference* (Available, accessed on 2022/11/17).

4.1.3 Summary of the Benchmarks

TABLE 9. COMPARISON BETWEEN MECHANICAL HARDNESS DIGITAL TWIN INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	FEM TRAINED DIGITAL TWIN	BARKHAUSEN EMISSION TECHNIQUES	ULTRASONIC BACKSCATTER METHOD	ULTRASONIC CONTACT IMPEDANCE (UCI)	EDDY CURRENT	LEEB REBOUND TEST
Depth of measurement	No limit	0.01 ÷ 1 mm	1.5-2 mm ÷ 6 mm	Superficial	Not suitable for thick hardened cases	Superficial
Measurement capabilities	Hardness and microstructural phase	Hardness, defects, residual stresses	Hardness	Hardness	Hardness, defects	Hardness
Real-time inspection	Yes	Yes	No	No. Needs indentation	Yes	No
Precision	High	High	Medium	High	High	High
Rate of inspection	High	High	High	High	High	Low
Integrable and automatable	Yes	Yes	Yes	Yes	Yes	Yes
Flexibility and interchangeability	No	Yes	Yes	No.	Yes	Yes
Specimen requirements	None	Ferromagnetic materials	None	Minimum weight and thickness. Maximum surface roughness	None	Maximum surface roughness. Weight > 5 kg

4.2 Acoustic Emission based Integrity Evaluation

4.2.1 Description

Acoustic Emission (AE) technology is a NDI technique that relies on the detection of sudden bursts of ultrasonic stress waves generated in different components of machines when subjected to loads, phase transformation or temperature changes.[1] Such waves are in the range 20 kHz to 1 MHz[2], and its detection is particularly useful in non-destructive tests, since they are the earliest fault indicator to appear. In the ZDZW project context, Acoustic Emission is going to be developed and implemented in an induction hardening manufacturing process, with the goal of evaluating structural integrity of manufactured fasteners.

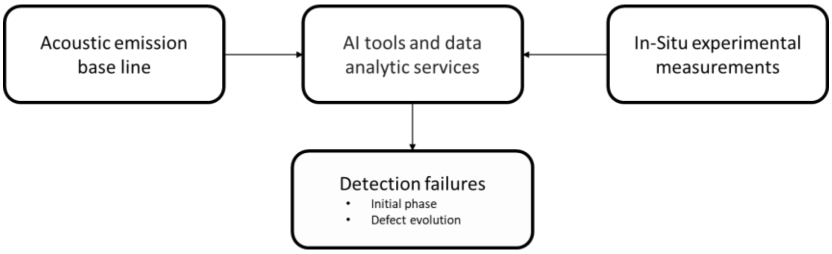

FIGURE 2. SCHEMATIC REPRESENTATION OF THE NON-DESTRUCTIVE INSPECTION BASED ON AE INTEGRITY EVALUATOR

There are two methods of acoustic emission measurement: transient and continuous. The first method captures AE bursts over a certain loudness level and can extract information like peak amplitude, signal energy and duration of the burst, which can be used to assess component integrity and condition. It is very useful to detect defects or cracks. The latter method gathers AE information for a set period of time and then uses it to obtain features such as average signal level and root squared values. This method is best suited when there is a lot of background noise or the AE amplitude is low, such as bearing and gearbox testing or leakage detection.

4.2.1.1 State, Maturity and Relevance

Acoustic Emission analysis was first used in 1971[3] and further developed by the United States Government Laboratories, but it was not until 1980s that this technique started to gain relevance, being used to address damage onset, fracture activity and intensity. Microscopic damage identification had to wait until the 1990s to be successful. Since then, Acoustic Emission has been in constant evolution and development, and so it is currently, expecting it to be completely reliable stand-alone inspection technique in the upcoming years.

[1] Miettinen, J., Pataniitty, P. (1999), Acoustic emission in monitoring extremely slowly rotating rolling bearing, *Proceedings of COMADEM '99*, pp. 289-297.

[2] International Organization for Standardization (2007), Condition monitoring and diagnostics of machines — Acoustic emission (ISO standard no. 22096:2007).

[3] Fitz-Randolph, J., et al. (1971), Acoustic Emission Studies of a Boron-Epoxy Composite, *Journal of Composite Materials*, Vol. 5:4, pp. 542-548, ISSN 0021-9983.

AE testing is a relatively new technique, and it is yet to be standardized and its use is not very extended. Because so, one of the goals using this technique in the ZDZW project is to make a stride in standardizing and disseminating it.

4.2.1.2 Flexibility and Level of Integration

AE is able to perform adequately when testing all kind of materials, even composite reinforced polymers. It is also implementable in almost any kind of industry, no matter how severe the conditions are, to the point of being operable in extreme temperature or radiative environments, making it an extremely versatile and integrable technique.

4.2.1.3 Industrial applications and References

Given the versatility of this technique and its non-destructive character, it can be applied in a wide range of industries, processes, machines, and materials such as metals or composites. For instance, AE testing can assess the structural integrity of concrete bridges, metallic structures such as pipelines, vessels, or steel cables, as well as composite aircraft or motorsport structures. Moreover, it can detect bearing and gearboxes early wear on rotating machinery, and partial discharges on electrical transformers and bushings. Regarding processes, one can find AE testing in additive manufacturing, leak detection in pipelines, particle impact and frictional processes. This technique excels in detecting faulty components in extremely slow rotating machines (<10rpm)[1], since there is almost no background noise compared to conventional low-frequency detection techniques.

4.2.1.4 Competitive destructive or non-destructive inspection technologies

Early failure detection and machinery prognosis regarding cracks, wear or corrosion has always been a concern in industry and given that AE testing is a relatively new technique, one can find several non-destructive methods that could be competitive.

For instance, the biggest non-destructive inspection competitive to AE is Ultrasound Testing. Besides, induced current testing and penetrating liquid testing can also be highly effective when detecting structural flaws, such as cracks or corrosion sites.

4.2.1.5 Advantages and Limitations of supplied technology

Acoustic Emission is a very powerful non-destructive technique that can detect a wide variety of damages in machinery, such as fibre breakages, friction, impacts or even early-stage corrosion. One of the biggest advantages this technique provides is its ability to be conducted during different implementation stages, from development testing to operation. Furthermore, it can provide global monitoring and assessment of the structure or machine, under real operational conditions. Additionally, machine monitoring can be made remotely, even on hazardous environments.

However, despite its great advantages, this technique has also a few limitations. To begin with, AE testing is sometimes not absolutely reliable since it is a fairly new NDI method[4]. On the other hand, though it can be very precise when locating a defect, it may not detect it if it does not grow or move and usually requires further inspection to describe such defect in detail. Finally, AE might be hard to use, given that AE is very dependent on the signal-noise ratio, which makes its implementation slower since noise reduction and

[4] Flyability SA, Acoustic Emission Testing: a Guide (Available, accessed on 2022/12/06).

signal discrimination becomes crucial, and can even give non-conclusive results if the signal-noise ratio is low (high background noise environments)[5].

TABLE 10. INSIGHTS OF ACOUSTIC EMISSION INSPECTION

	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	Very dependent on the signal-noise ratio
Inspectable features	Structural integrity	Cracks and manufacturing defects, fibre breakages, corrosion sites, friction
Detection depth	To be assessed (TBA)	
Minimum detectable damage	TBA	
Testing scale range	Very high	Implementation from development to operation
Assessment scale range	Very high	From independent components to overall machinery
Materials suitable to inspection	All kinds	
Real-time	Yes/no	Transient measurements are not real-time, but Continuous measurements are
Rate of inspection	Very low/medium	Transient inspection rate is very low, but Continuous inspection rate is higher
In-process or post-process	Post/in process	
Automation	Low/high	Higher on Continuous measurements
Human interaction/supervision	High	
Harsh Environment	Yes	Suitable for high temperature or radioactive environment

4.2.2 Benchmarking Technologies/Solutions

4.2.2.1 Vibrations

Vibration testing is one of the widely used non-destructive analysis techniques for integrity diagnosis.[6] [7] This technique relates the vibration response of the material with its structural properties. This response is compared to that characterized in a "healthy" state of the equipment. Thus, any change of the vibration behaviour indicates a physical change

[5] Iowa State University, Acoustic Emission Testing (Available, accessed on 2022/12/06).

[6] Raišutis, R., et al. (2008), The review of non-destructive testing techniques suitable for inspection of the wind turbine blades, Ultrasound, Vol. 63(1), pp. 26-30, ISSN 1392-2114.

[7] Lacey, S.J. (2008), An Overview of Bearing Vibration Analysis.

such as the presence of a damage. The material properties as dimensions, dynamic modulus of elasticity or density are determined from the analysis of several vibration characteristics including natural frequency, propagation velocity, mechanical impedance, attenuation coefficient, etc. This technique is focused on surface damage detection due to the most noticeable changes in vibration mode are caused by changes in the contact surface geometry.[8] [9]

The most common sensors are presented below, according to their frequency of operation.[6] [10]

- Position transducer for the low-frequency range
- Velocity transducers for the middle frequency range
- Accelerometers for the high-frequency range
- Spectral Emitted Energy (SEE) sensors for very high frequencies

TABLE 11. INSIGHTS OF VIBRATION INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Inspectable features	Structural integrity	Machinery structural integrity.
Detection depth	Surface	
Minimum detectable damage	<100µm	[11]
Testing scale range	Very High	Implementation from development to operation.
Assessment scale range	Low	Overall machinery.
Materials suitable to inspection	All kinds	
Real-time	Yes	
Rate of inspection	Medium	
In-process or post-process	In-process	
Automation	High	
Human interaction/supervision	High	Post-processing requires qualified personnel.
Harsh Environment	Yes	

[8] Yang, K., et al. (2022), A new intelligent bearing fault diagnosis model based on triplet network and SVM, *Scientific Reports*, Vol. 12, 5234, ISSN 2045-2322.

[9] Nelias, D., Yoshioka, T (1998), Location of an acoustic emission source in a radially loaded deep groove ball-bearing, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, Vol. 212:1, pp. 33-45, ISSN 2041-305X.

[10] Hameed, Z., et al. (2009), Condition monitoring and fault detection of wind turbines and related algorithms: A review, *Renewable and Sustainable energy reviews*, Vol. 13:1, pp. 1-39, ISSN 1364-0321.

[11] Amarnath, M., Praveen Krishna, I. R. (2019), Experimental investigations to assess surface contact fatigue faults in the rolling contact bearings by enhancement of sound and vibration signals, *Journal of Nondestructive Evaluation*, Vol. 38:1, pp. 1-23, ISSN 0195-9298.

4.2.2.2 *Ultrasound Testing technique*

This NDI technique is very similar to AE since they both rely on the ultrasonic wave propagation within the material. However, the methodology differs since AE captures passive stress waves generated within the component, while UT creates an active wave and checks its propagation through the material. Because so, UT is more dependent on part geometry and is difficult to use on thin materials. Besides, it cannot be used in such a variety of materials and the surface of the tested component must be relatively smooth to couple the transducer. Ultrasound techniques are highly used in applications related to the quality control of materials and structures, increasing its relevance in this field especially in the last decade due to technological advances and the emergence of new sensors. This test method only needs limited access to the component, and its use is suitable for harsh environments.

TABLE 12. INSIGHTS OF ULTRASOUND INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Inspectable features	Structural integrity	Cracks and manufacturing defects.
Detection depth	~1-2mm	[12] [13]
Minimum detectable damage	~200µm	[12] [13]
Testing scale range	Very wide	
Assessment scale range	Very wide	From independent components to overall machinery.
Materials suitable to inspection	All kinds	Excluding wood and paper-based materials.
Real-time	Yes	
Rate of inspection	Very low	
In-process or post-process	Post-process	
Automation	High	
Human interaction/supervision	High	Post-processing requires qualified personnel. Complexity due coupling problems.
Harsh Environment	Yes	

4.2.2.3 *Eddy current*

Based on electromagnetism, this technology is applied in the study of conductive materials. Eddy current techniques use a time-varying electrical current generated in the material by a variable magnetic field, according to Faraday's law of induction. Any discontinuities or breaks in the material interact with the current, which is collected and subsequently analysed with a magnetic sensor. Due to its high sensitivity and its easy

[12] Kim, C., et al. (2021), Evaluating Rolling Contact Fatigue Damage Precursors with Rayleigh Waves in 1060 Steel, *Journal of Nondestructive Evaluation*, Vol. 40:4, pp. 1-18, ISSN 0195-9298.

[13] Rezaei, A., et al. (2011), A comparison study between acoustic sensors for bearing fault detection under different speed and load using a variety of signal processing techniques, *Tribology Transactions*, Vol. 54:2, pp. 179-186, ISSN 1547-397X.

assembly because no coupling is required, it is also a method highly valued in non-destructive evaluation.

The technique is mainly limited in static tests due to its low detection speed. For high-speed moving materials, a higher excitation frequency is required to increase the resolution, however this results in a decrease in penetration capability.[14] Some research has focused on such limitations, associated with typical electromagnetics-based tools, but considers quasi-static cases.[15] In addition, this technique has demonstrated a lack of sensitivity for small breaks below the surface and, therefore, it is not suitable for early detection of damage.

TABLE 13. INSIGHTS OF EDDY CURRENT INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	Surface restricted
Inspectable features	Structural integrity	Cracks and manufacturing defects
Detection depth	Surface	
Minimum detectable damage	<1mm[16]	Depends on the visual methodology implemented
Testing scale range	Wide	Implementation from development to operation
Assessment scale range	Low	
Materials suitable to inspection	All kinds	Non-porous surfaces required
Real-time	No	
Rate of inspection	low	
In-process or post-process	Post-process	
Automation	No	
Human interaction/supervision	Low	
Harsh Environment	No	

4.2.2.4 Liquid Penetrant testing technique

While some superficial defects on materials can be detected by the naked eye, there are cases in which the defect is too small to be detected or it is necessary to assess where the limits of the defect are. To do that, it is possible to use Liquid or Dye Penetrant testing. As the name states, this testing method uses very thin coloured liquids that penetrate the surface defect and remain into the flaw when the excess liquid is removed.

[14] Yuan, F., et al. (2021), Investigation of DC electromagnetic-based motion induced eddy current on NDT for crack detection, *IEEE Sensors Journal*, Vol. 21:6, pp. 7449-7457, ISSN 1530-437X.

[15] Aguila-Muñoz, J., et al. (2016), A magnetic perturbation GMR-based probe for the nondestructive evaluation of surface cracks in ferromagnetic steels, *NDT & E International*, Vol. 79, pp. 132-141, ISSN 0963-8695.

[16] Dadouche, A., et al. (2008), Sensitivity of air-coupled ultrasound and eddy current sensors to bearing fault detection, *Tribology Transactions*, Vol. 51:3, pp. 310-323, ISSN 1547-397X.

The cleaning procedure is vital in this test, both before and after the inspection. Before applying the liquid, the surface of the sample must be clean and polished to avoid obtaining erroneous results. After the inspection, the product must be thoroughly removed to avoid deterioration such as corrosion. This is a time-consuming process than can be manual or automated. This method is very popular, since it is non-destructive, very versatile, and very low-cost. Nonetheless, the use of this technique is restricted to surface flaw detection and can only be done in non-porous materials.

TABLE 14. INSIGHTS OF LIQUID PENETRANT INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	Just suited for surface testing
Inspectable features	Surface structural integrity	Cracks, pores
Detection depth	Surface	
Minimum detectable damage	Depends on visual methodology implemented	
Testing scale range	Very High	Implementation from development to operation
Assessment scale range	Low	Independent components
Materials suitable to inspection	Non-porous	
Real-time	No	
Rate of inspection	Low	
In-process or post-process	Post-process	
Automation	Medium	
Human interaction/supervision	Low	
Harsh Environment	No	High temperatures can evaporate the liquid. The operator needs direct access to the component

Funded by the European Union

4.2.3 Summary of the Benchmarks

TABLE 15. COMPARISON BETWEEN ACOUSTIC EMISSION INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	AE TRANSIENT MEASUREMENT	AE CONTINUOUS MEASUREMENT	VIBRATIONS	ULTRASOUND TESTING	EDDY CURRENT	LIQUID PENETRANT
Precision (accuracy and detection efficiency)	High (signal-noise ratio dependent)	High (signal-noise ratio dependent)	High	High	High	High (surface restricted)
Inspectable features	Cracks, manufacturing defects, fibre breakages	Corrosion sites, friction cycles	Machinery structural integrity	Cracks, manufacturing defects	Cracks, manufacturing defects	Surface pores or cracks
Detection depth	TBA	TBA	Surface	~1-2mm	Surface	Surface
Minimum detectable damage	TBA	TBA	<100µm	~200µm	<1mm	Depends on visual methodology
Testing scale range	Very wide	Very wide	Very wide	Very wide	Wide	Very wide
Assessment scale range	Very wide	Very wide	Low	Very wide	Low	Low
Materials suitable to inspection	All kinds	All kinds	All kinds	All kinds, except wood or paper	Only conductive materials	Non-porous metals
Real-time	No (Yes for data acquisition)	Yes	Yes	Yes	No	No
Rate of inspection	Very low	Medium	Medium	Very low	Low	Low
In-process or post-process	Post-process	In-process	In-process	Post-process	Post-process	Post-process
Automation	Low	High	High	High	Low	No
Human interaction/supervision	High	Medium-Low	High	High	Medium-Low	Low
Harsh Environment	Yes	Yes	Yes	Yes	No	No

4.3 MIR-OCT Sub-surface Anomaly Detection

4.3.1 Description

OCT (Optical Coherence Tomography) in general is a low coherence interferometer 3-D imaging technique where a light source is used with a low temporal coherence. It is an interferometric imaging technique based on backscattered laser light from internal microstructures and material interfaces. It was developed in 1991 for biomedical imaging and is widely used today as a diagnostic tool within ophthalmology, dermatology, and cardiology. In recent years, the technology has also found applications within NDT due to the possibility of high resolution, non-contact 3D imaging, including cultural heritage preservation (paintings), inspection of industrial and pharmaceutical coatings, paper, and textile inspection.

OCT inspection solution proposed by NORBLIS benefits from use of a Mid-Infrared (MIR) broadband source: a super-continuum laser source which has a wide wavelength band. Categorically NORBLIS OCT falls into Fourier-domain OCT, which is one type of OCT system as shown in below Figure 3.

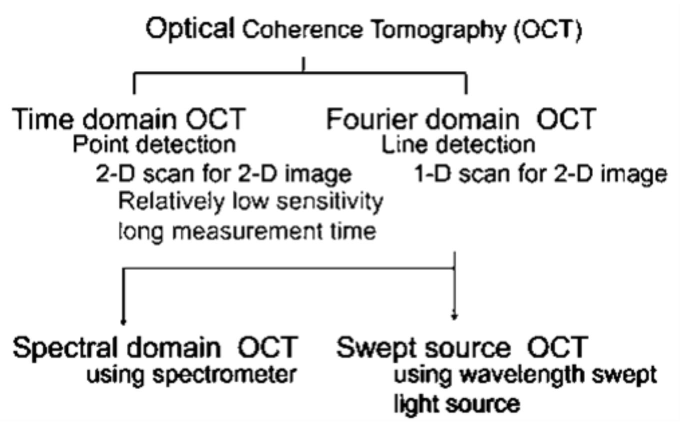

FIGURE 3. TYPES OF OCT AND SUBCATEGORIES.

In Fourier-domain OCT, the mirror arm is fixed and the interference, as a function of wavelength, is recorded as shown in the Figure 4.

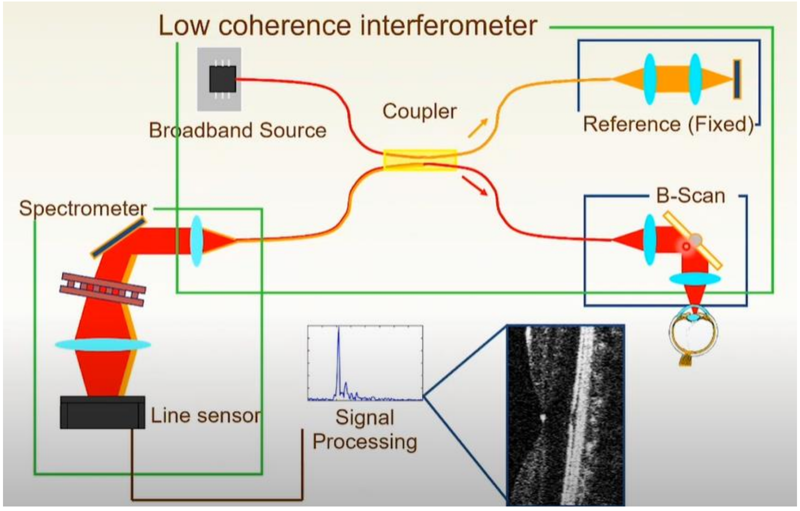

FIGURE 4. OPTICAL SCHEME OF FD-OCT.

As a type of Fourier-domain OCT, the proposed MIR-OCT by NORBLIS, is an SD-OCT (Spectral Domain OCT) which uses a spectrometer. The core of an SD-OCT is a Michelson-type interferometer with a stationary reference mirror. The interference signal from the two returning beams recombined on the beam splitter is recorded as spectrum. A result of the light beam spread out or dispersed with a diffraction grating and detected by a high-speed CCD line camera. A Fourier transform is performed on the spectrally resolved interference pattern detected by the camera array thus obtaining the reflectivity as a function of depth, i.e., the A-scan. An overview of a MIR SD-OCT system is shown in Figure 5, it consists of five parts that are connected via optical fibre, namely a broadband mid-infrared supercontinuum source based on a master-oscillator power amplifier pump laser and fluoride fibre, a free-space Michelson interferometer, a scanning x, y translation stage, a frequency up-conversion module and a silicon CMOS-based spectrometer.

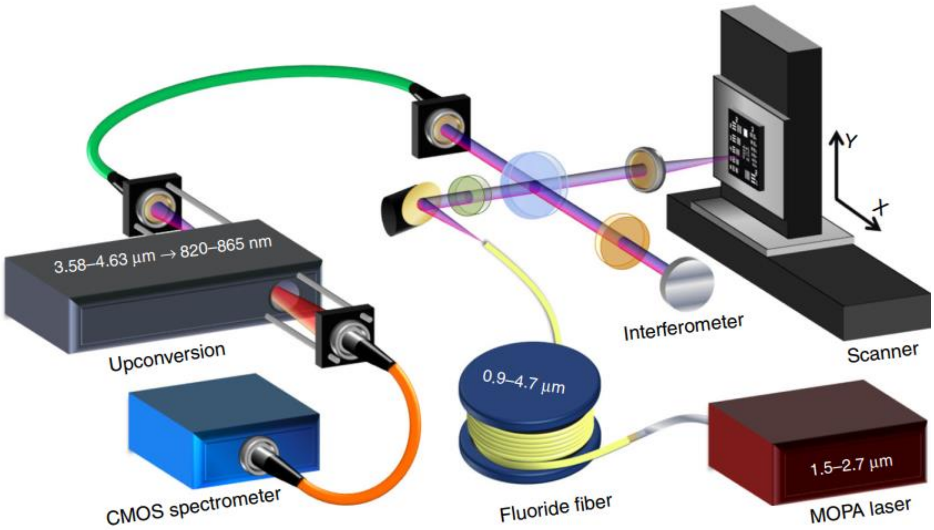

FIGURE 5. ILLUSTRATION OF A MIR SD-OCT SYSTEM.[1]

[1] Israelsen, N. M., et al. (2019), Real-time high-resolution mid-infrared optical coherence tomography, *Light: Science & Applications*, Vol. 8, 11, ISSN 2095-5545.

Applying MIR-OCT imaging for defect detection involves probing changes of a sample's refractive index. This is done non-destructively and without a contact medium providing a 3D volume containing microscopic sub-surface scattering information. Probing with mid-infrared light at 4 µm wavelength enables deep penetration into alumina based industrial ceramics in contrast to the traditionally utilized near-infrared counterpart going up to 1.5 µm wavelength. By scanning industrial ceramics with the MIR-OCT, defects such as cracks, unwanted particles and bubbles seen in the layer-to-layer transitions of the prints can be identified and linked to the quality and the performance of the printed component.[2]

4.3.1.1 State, Maturity and Relevance

As a specific type of SD-OCT, the NORBLIS aims to manufacture the first commercial MIR-OCT in the market. Right now, the development of the first prototype is undergoing. Other SD-OCT systems so far employ NIR-OCT. As a technology, Fourier-domain OCT in general allows for a fast imaging in contrast to scanning of the reference arm mirror in the interferometer, as all the back-reflections from the sample are being measured simultaneously. This speed increment introduced by Fourier-domain OCT has opened a whole new area of applications for the technology. Figure 6 shows the following information about the technical readiness of the SD-OCT system along with others.[3]

FIGURE 6. DISTRIBUTION OF KEY OCT SPECIFICATIONS WITHIN THE 59 INCLUDED SYSTEMS.

[2] Zorin, I. et al. (2022), Mid-infrared optical coherence tomography as a method for inspection and quality assurance in ceramics additive manufacturing, *Open Ceramics*, Volume 12, 100311, ISSN 2666-5395.

[3] Rank, E. A., et al. (2022), Miniaturizing optical coherence tomography, *Translational Biophotonics*, Vol. 4, 1-2, ISSN 2627-1850.

4.3.1.2 Flexibility and Level of Integration

In terms of flexibility, scanning head of MIR-OCT by NORBLIS will provide flexibility by for instance being attached on a robot arm. Regarding level of integration, at the moment the prototype is not really integrated, and this is planned to be improved as part of the project.

4.3.1.3 Industrial applications and References

Apart from MIR-OCT system by NORBLIS, Figure 7 and Figure 8 show the increasing interest and usage of OCT technology in general in different industrial applications since 1991.[4]

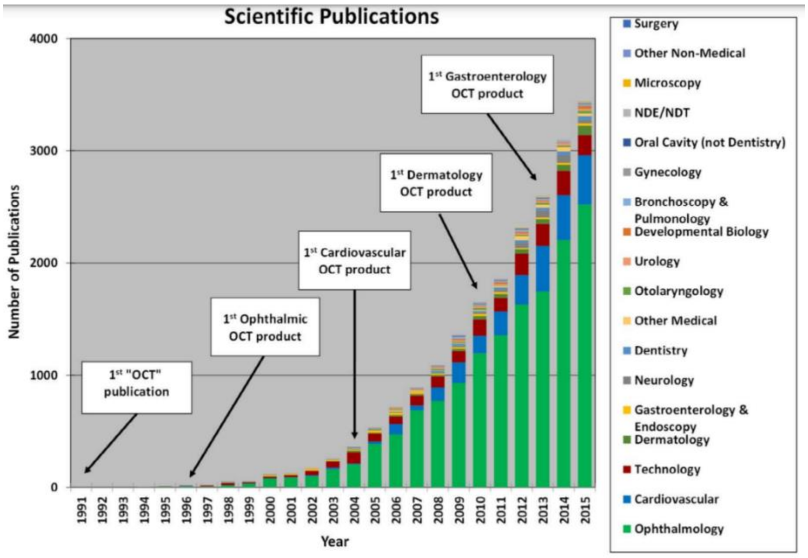

FIGURE 7. SCIENTIFIC PUBLICATIONS SHOWING THE USE OF OCT.

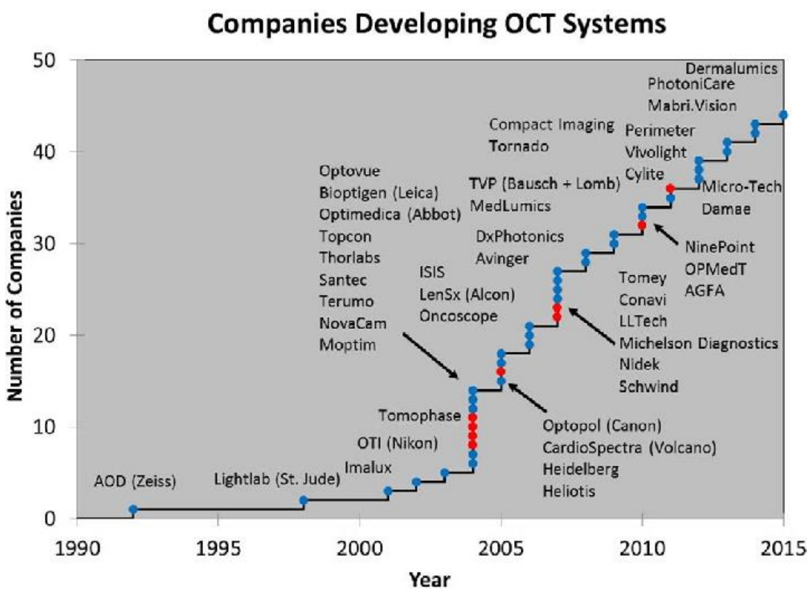

FIGURE 8. STUDY SHOWING INCREASING NUMBER OF COMPANIES IN RECENT DECADES.

[4] Fujimoto, J., Swanson, E. (2016), The Development, Commercialization, and Impact of Optical Coherence Tomography, *Investigative Ophthalmology & Visual Science*, Vol. 57:9, pp. OCT1-OCT13, ISSN 0146-0404.

4.3.1.4 Competitive destructive or non-destructive inspection technologies

A wide-spread technique is Ultrasonic inspection because it is sensitive to defects, such as de-bonding and delamination, and can inspect thick samples (>1 cm). US paint thickness gauges are available from several manufacturers at a cost of €2k/gauge. However, they are limited to contact-based spot checks on dry coatings because they require physical contact through a contact medium. The technology may be used for scanning, such as in ultrasonic phased arrays, but the requirement of physical contact will cause noisy and faulty data unless complex analysis algorithms are used. First 1mm will be invisible. Such scanning systems are provided by companies such as Olympus, Zetec, and FORCE at prices from about €70k and up and would still only provide information about the total thickness and lack of bonding to the substrate.

THz imaging is an emerging NDT technique, which shares many similarities with OCT. Companies like TeraSense and Lytid, are marketing high speed imaging systems for scanning e.g., conveyor belts. However, while the penetration is significantly better, the resolution is similar to UT and thus insufficient for imaging of small defects. THz imaging can achieve resolutions similar to that of high-frequency UT without the need for a contact medium, but the technology is limited by long acquisition times and more complex data processing and instrumentation.

X-ray CT is also commonly used in NDT on smaller coating samples. This technique gives high-definition 3D images of smaller objects (up to 30 cm). However, it is not appropriate for in-line or field applications. Apart from being expensive and hazardous, the sample or source/detector must be rotated which means that the systems are large, and scanning is slow (30-60 min). Other non-imaging technologies for NDT of coatings, such as thermography, Eddy currents, etc., are not considered competing. X-ray based techniques can offer sub-micron imaging resolution but are largely avoided in the field due to the hazards of ionizing radiation. X-ray systems are also challenged by its transmission modality that requires a detector-array on the backside of the sample or a rotating system for 3D scanning.

Thermographic imaging methods infer the presence of subsurface defects from the surface thermal radiation, and as such it is difficult to detect small or vertically stacked defects, and the results are highly dependent on the thermal properties of the sample.

4.3.1.5 Advantages and Limitations of supplied technology

MIR-OCT provides the following major advantages:

- Very high depth resolution (axial resolution) of the sample being inspected.
- By the use of a super-continuum source, it will be able to resolve the reflectivity at a certain depth and wavelength inside a sample. This is also one of the crucial advantages, since one may manufacture an MIR-OCT system, but with a different light source technology, one will never have the speed or the depth resolution (scales inversely to the source bandwidth, which is enormous for the MIR-OCT SC source) that the NORBLIS system has.
- MIR-OCT can employ a non-invasive optical scanner for sub-surface coating inspection unlike many other techniques.

Funded by the European Union

Disadvantages:

- Water absorption in the MIR range makes it difficult to resolve for some materials
- Depending on the material the penetration depth is <1mm

TABLE 16. INSIGHTS OF MIR-OCT INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Non-contact	Yes	
Non-destructive	Yes	
High sensitivity	Yes	
Industry-ready	Yes	
Penetration depth	Very low	Depends on the material (absorption and scattering properties) – water has high absorption and large particles will scatter light.
Depth resolution	Very high	
Lateral resolution	High	
Real-time inspection	Yes	
Inspection speed	Very high	
Inspection in motion	Yes	
Reflection modality	Yes	

4.3.2 Benchmarking Technologies/Solutions

4.3.2.1 Ultrasonic Inspection

TABLE 17. INSIGHTS OF ULTRASONIC INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Non-contact	No	Couplant needed (e.g., ultrasonic gel)
Non-destructive	Yes	
High sensitivity	Yes	
Industry-ready	Yes	
Penetration depth	Very high	
Depth resolution	Low	Due to large wavelength of acoustic waves, ultrasound cannot measure very thin objects or separate very thin layers.
Lateral resolution	Very low	
Real-time inspection	Yes	
Inspection speed	High	
Inspection in motion	Yes	
Reflection modality	Yes	

4.3.2.2 THz Imaging

TABLE 18. INSIGHTS OF THZ IMAGING INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Non-contact	Yes	
Non-destructive	Yes	
High sensitivity	Yes	

Industry-ready	No	High resolution imaging is still being developed
Penetration depth	High	
Depth resolution	Low	Same as ultrasound
Lateral resolution	Very low	
Real-time inspection	No	Post processing and scanning takes long time
Inspection speed	Very low	
Inspection in motion	Yes	
Reflection modality	Yes	

4.3.2.3 X-ray CT

TABLE 19. INSIGHTS OF X-RAY CT INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Non-contact	Yes	Ionizing radiation. Can break chemical bonds etc.
Non-destructive	No	
High sensitivity	Yes	
Industry-ready	Yes	
Penetration depth	Very high	
Depth resolution	Very high	
Lateral resolution	Very high	
Real-time inspection	No	Post processing and scanning takes long time
Inspection speed	Very low	
Inspection in motion	No	Scanners are large and stationary.
Reflection modality	No	Temperature takes time to settle, moving not practically possible

4.3.2.4 Thermographic Imaging

TABLE 20. INSIGHTS OF THERMOGRAPHIC INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Non-contact	Yes	
Non-destructive	Yes	
High sensitivity	No	Low contrast
Industry-ready	Yes	
Penetration depth	Low	
Depth resolution	Very low	Subsurface information inferred from surface temperature profile, i.e., no real depth resolution
Lateral resolution	Very low	
Real-time inspection	Yes	
Inspection speed	Low	Takes time for temperature to settle etc.
Inspection in motion	No	Temperature takes time to settle, moving not practically possible
Reflection modality	Yes	

4.3.3 Summary of the Benchmarks

TABLE 21. COMPARISON BETWEEN MIR-OCT INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	MIR-OCT	ULTRASONIC INSPECTION	TERAHERTZ IMAGING	X-RAY CT	THERMOGRAPHIC IMAGING
Non-contact	Yes	No	Yes	Yes	Yes
Non-destructive	Yes	Yes	Yes	No	Yes
High sensitivity	Yes	Yes	Yes	Yes	No
Industry-ready	Yes	Yes	No	Yes	Yes
Penetration depth	Very low	Very high	High	Very high	Low
Depth resolution	Very high	Low	Low	Very high	Very low
Lateral resolution	High	Very low	Very low	Very high	Very low
Real-time inspection	Yes	Yes	No	No	Yes
Inspection speed	Very high	High	Very low	Very low	Low
Inspection in motion	Yes	Yes	Yes	No	No
Reflection modality	Yes	Yes	Yes	No	Yes

4.4 EMAT Ultrasonic Inspection

4.4.1 Description

The inspection solution proposed by Innerspec involves an EMAT-based system that will be able to monitor the weld quality during the manufacturing process. EMAT references to Electro-Magnetic Acoustic Transducers that generate ultrasonic waves through a combination of two magnetic fields. EMAT technology is widely implemented in different industrial sectors, such as automotive or aerospace. This said, the application of an EMAT-based in-line multi-pass weld inspection system is a novel application with a TRL below 4.

The proposed inspection solution includes the following components:

- The EMAT equipment, which integrates a large number of complex electronic components and is responsible of generating and processing the ultrasonic signal. Also, the equipment can apply several processing steps to the raw signal to improve its quality according to the inspection requirements.
- The sensors, which generate the ultrasonic wave in the element which is going to be inspected and receive it when is reflected due to the presence of a defect.
- The graphic interface, which allows the inspector to set up the inspection's parameters according to the specifications of the element subjected to be inspected and provides a real-time view of the inspection.

The inspection process will be parallel to the manufacturing process. The sensors will be integrated into the welding system at a certain distance from the arc welding head and connected to the EMAT equipment with a protected cable. The proposed solution will inspect the weld pass by pass, evaluate the presence of defects and send a stop signal once a defect is detected. Figure 9 illustrates a process schematic of the EMAT-based inspection solution for multi-pass welding.

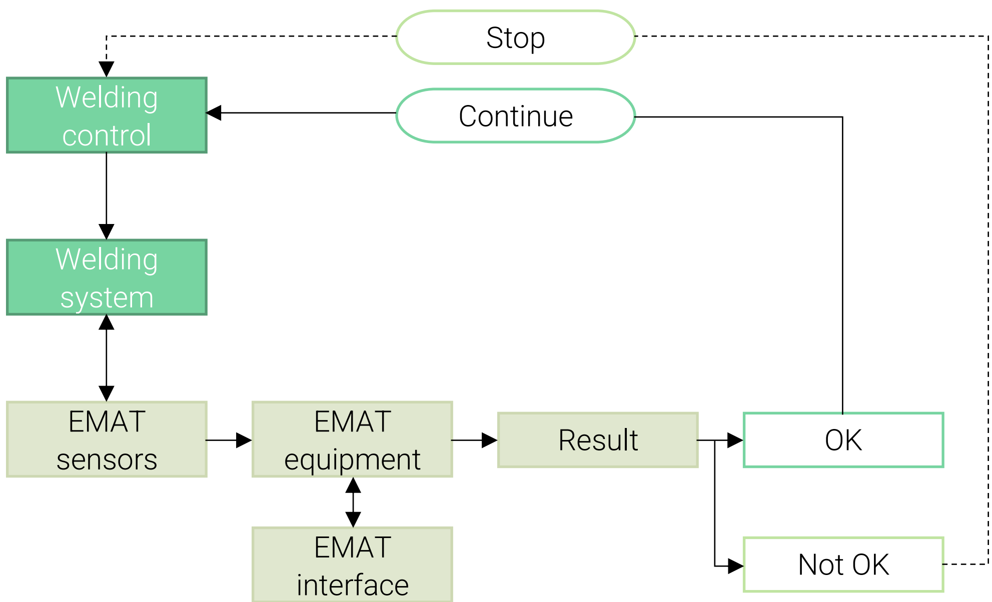

FIGURE 9. SCHEMATIC PROCESS OF THE EMAT-BASED INSPECTION SOLUTION

4.4.1.1 State, Maturity and Relevance

Nowadays the EMAT-based solutions for multi-pass weld inspection are at low TRL (3-4). The use of Rayleigh waves for the inspection of thick welds is not anything new but it was never applied as in-line inspection solution at high temperatures. The proposed solution will further develop this concept in the following ways:

- Inspection process: the ZDZW EMAT-based solution will work during the welding process, as an in-line inspection system, in contrast with any potential alternative that targets the inspection as a post-processing task.
- The high temperature of the welding process environment will be a major challenge, not only for its potential negative effect towards the sensor's integrity, but also for the ability to capture meaningful data. Since the properties of the metals differ at such high temperatures, especially those related to ferromagnetic properties, a comprehensive study is required on both material characterization and potential signal properties in terms of signal to noise ratio and correct definition of the speed of sound in the medium.
- Solution integration: the ZDZW EMAT-based solution must be integrated into the welding system to ensure the weld quality in real-time. While this might be considered a minor problem, the integration is highly dependent on the results from the previous point, and several process parameter optimizations might be required to achieve adequate temperature ranges before the inspection can be carried out.

As part of the project, an EMAT-based solution for the inspection of multi-pass welds will be applied to the construction of wind turbine towers, whose industry has experienced a strong growth in the last few years, boosting the manufacture of more powerful turbines and higher towers (up to 150 m). These improvements have affected structural health requirements turning them more stringent.[1] [2]

Currently, the weld inspection of the wind turbine towers is carried out once the manufacturing process has ended. The presence of defects in the weld means that the weld must be removed and reworked, but in the worst one, the whole part could be entirely scrapped.

The EMAT-based inspection solution will monitor the weld quality during the manufacturing process pass-by-pass, allowing the operators to stop the process once a defect is detected. In this way, defects will be detected and repaired in real-time before adding more weld passes, optimizing resource consumption and reducing waste generation. This solution will significantly improve the current manufacturing process of wind turbine towers.

4.4.1.2 Flexibility and Level of Integration

The proposed EMAT-based solution for multi-pass weld inspection will be optimized to address the integrity of the wind turbine tower sections (pilot 3) in the frame of the ZDZW

[1] Lian, J., et al. (2019), Health Monitoring and Safety Evaluation of the Offshore Wind Turbine Structure: A Review and Discussion of Future Development, *Sustainability*, 11:2, 494. ISSN 2071-1050.

[2] International Renewable Energy Agency, Wind energy (Available, accessed on 2022/11/08).

project. However, this solution can also be extended to other industrial environments whose manufacturing processes include a multi-pass weld stage, like the naval sector.

The solution is going to be developed according to the weld technique requirements for wind turbine towers, namely Submerged Arc Welding (SAW), which is widely used in the manufacture of a large number of products. While the SAW technique is common, the parameters used for each use case can greatly differ, so applying the proposed solution to other use cases require an optimization stage to ensure the highest performance. The proposed EMAT-based solution for multi-pass weld inspection is, therefore, a flexible technique to monitor the weld quality in real time and is easily transferable to other industries with only minor modifications.

In any specific application, the integration requirements need to be initially defined together with the end user: on the one hand, the design, construction and installation of a suitable sensor, including protection elements, can require a close collaboration to ensure that the integration of such elements near the welding head does not represent any harm to the performance of the welding equipment; on the other hand, the EMAT electronics system should include a remote connection and simplified access to the control software, through a graphical user interface.

Once all the EMAT hardware and software equipment is ready, the integration with the welding system should be implemented to cover existing standard PLC protocols, so that it facilitates the future integration in other industries or markets with different PLC hardware and communication protocols.

4.4.1.3 Industrial applications and References

The proposed EMAT-based solution could be easily optimized to cater for other industries that include multi-pass welding in their manufacturing processes such as the ones depicted in Figure 10.

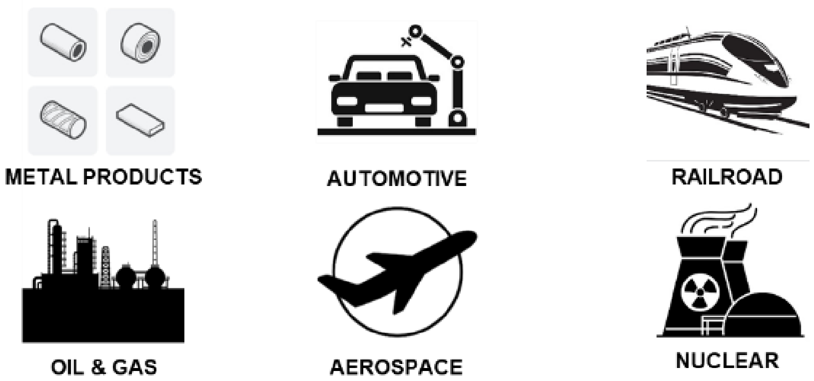

FIGURE 10. INDUSTRIES WHERE EMAT-BASED SOLUTION FOR MULTI-PASS WELD INSPECTION CAN BE APPLIED

4.4.1.4 Competitive destructive or non-destructive inspection technologies

Below there is a description of the other inspection solutions that can compete with the EMAT-based solution proposed by Innerspec, as well as their limitations according to the EMAT-based one.

- The X-ray inspection is used to look for sub-surface. The main limitations are the radiation hazards and the slow inspection speed. Also, in most cases, the results require operator interpretation, and its integration into an automated process is not possible.
- The Eddy Current technique provides surface and limited sub-surface inspection (a few thousandths of an inch) through electromagnetism phenomena. It is commonly used as a complementary technique due to its difficulty in detecting some critical defects and its inability to penetrate the test material.
- Conventional UT uses high-frequency elastic waves to inspect the weld and it covers both surface and internal inspections. This technique is capable of detecting the most common weld defects (lack of penetration, lack of fusion, pinholes, etc.). But inspecting with conventional UT involves the use of a couplant, thus implies important limitations:
    - Unable to inspect at high temperatures
    - Difficult to automate
    - Sensitive to surface conditions such as roughness and contamination

All these potential competitive solutions are post-production inspection methods, in comparison with the proposed EMAT-based solution that enables in-line monitoring during the welding process.

4.4.1.5 Advantages and Limitations of supplied technology

The EMAT-based solution presents a large number of advantages regarding the current inspection solution for multi-pass weld inspection. These are described in the table below:

TABLE 22. INSIGHTS OF EMAT ULTRASONIC INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
High-temperature inspection	Yes	Capable to perform complete inspections at 300°C and 650°C for punctual inspection.
Surface requirements	No	Insensitive to surface conditions.
Dry inspection	Yes	No couplant is needed. UT is generated in the material to be inspected.
Real-time inspection	Yes	-
Automation	Very high	Easy to automate and integrate into production.
Inspection in motion	Yes	-
Inspection speed	Very high	High inspection speeds (over 1 m/s), but it will depend on the welding process speed.
Flexibility	High	Capable of generating several types of UT waves, both Guided Waves (Rayleigh, Lamb, etc.) and Bulk Waves (longitudinal, Shear Vertical, etc.)
Self-calibration	Yes	Sample to sample self-calibration of signals on Guided Waves.
Precision (accuracy and detection efficiency)	Very high	-

Reproducibility	Very high	-
Human interpretation	No	No need for operator interpretation.
Easy to scale	Very high	-

4.4.2 Benchmarking Technologies/Solutions

4.4.2.1 X-ray inspection

TABLE 23. INSIGHTS OF X-RAY INSPECTION TECHNIQUE

CRITERIUM	VALUE/LEVEL	NOTES
High-temperature inspection	No	-
Surface requirements	No	Insensitive to surface conditions.
Dry inspection	Yes	-
Real-time inspection	No	-
Automation	No	Impossible to automate and integrate into production.
Inspection in motion	No	-
Inspection speed	Very low	-
Flexibility	Yes	-
Self-calibration	N/A	-
Precision (accuracy and detection efficiency)	High	-
Reproducibility	Very high	-
Human interpretation	Yes	It needs operator interpretation.
Easy to scale	Yes	-

4.4.2.2 Eddy current

TABLE 24. INSIGHTS OF EDDY CURRENT INSPECTION TECHNIQUE

CRITERIUM	VALUE/LEVEL	NOTES
High-temperature inspection	Yes	Capable to perform complete inspections at 300°C.
Surface requirements	No	Insensitive to surface conditions.
Dry inspection	Yes	No couplant is needed. UT is generated in the material to be inspected.
Real-time inspection	Yes	-
Automation	High	-
Inspection in motion	Yes	-
Inspection speed	Very high	High inspection speeds (over 1 m/s), but it will depend on the welding process speed.
Flexibility	High	-
Self-calibration	No	-
Precision (accuracy and detection efficiency)	Very high	-
Reproducibility	Very high	-
Human interpretation	Yes	It needs for operator interpretation.
Easy to scale	Very high	-

4.4.2.3 Piezoelectric ultrasonic testing

TABLE 25. INSIGHTS OF PIEZOELECTRIC ULTRASONIC TESTING

CRITERIUM	VALUE/LEVEL	NOTES
High-temperature inspection	No	-
Surface requirements	Yes	-
Dry inspection	No	Couplant is needed. UT is generated in the material to be inspected.
Real-time inspection	Yes	-
Automation	Yes	Difficult to automate and integrate into production due to the couplant supply.
Inspection in motion	Yes	-
Inspection speed	High	-
Flexibility	High	-
Self-calibration	Yes	Sample to sample self-calibration of signals on Guided Waves.
Precision (accuracy and detection efficiency)	Very high	-
Reproducibility	Very high	-
Human interpretation	Yes	It needs for operator interpretation.
Easy to scale	Very high	-

4.4.3 Summary of the Benchmarks

TABLE 26. COMPARISON BETWEEN EMAT ULTRASONIC INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	EMAT ULTRASONIC INSPECTION	X-RAY	EDDY CURRENT	PIEZOELECTRIC ULTRASONIC TESTING
High-temperature inspection	Yes	No	Yes	No
Surface requirements	No	No	No	Yes
Dry inspection	Yes	Yes	Yes	No
Real-time inspection	Yes	No	Yes	Yes
Automation	Very high	No	High	Yes
Inspection in motion	Yes	No	Yes	Yes
Inspection speed	Very high	Very low	Very high	High
Flexibility	High	Yes	High	High
Self-calibration	Yes	N/A	No	Yes
Precision (accuracy and detection efficiency)	Very high	High	Very high	Very high
Reproducibility	Very high	Very high	Very high	Very high
Human interpretation	No	Yes	Yes	Yes
Easy to scale	Yes	No	Yes	No

5 ZDZW VISION TECHNOLOGIES FOR SUSTAINABLE MANUFACTURING

Conventionally the Visual Testing (VT) for non-destructive evaluation encompasses a wide range of methodologies that systemize inspector observations in order to provide a thorough and quantitative assessment quickly and with minimal equipment. Typically, humans can identify micrometre-sized features by touch and sight. Simple manipulations of the objects or surroundings, such as shining a light to reflect off a surface, are helpful.

Tools used for visual inspection include dimensional measurement instruments (calibre, weld gauges, inspection blades, etc.), illumination (flashlights, light meters, directional mirrors etc.), magnification (magnifying glass, magnifying mirrors, optical microscopes etc.) and cameras. Techniques that use light sources outside of the visible spectrum are also considered part of the VT family.

Traditionally, offline visual inspection is performed by periodic random sampling, where operators perform an eye-naked inspection to recognize defects. Since this inspection task is not performed online or in process, the time delay incurs an elevated scrap in high-volume production lines. However, it is often too late when defects are identified since the high production rate could incur substantial product wastage. In contrast, automatic machine vision systems are more effective, reliable, and can perform accurate detection automatically and non-destructively at high speed.

ZDZW Vision Technologies for Sustainable Manufacturing, foreseen within WP5 activities, will pursue the development and implementation of automatic machine vision systems in production environments, which finally improve defect detectability avoiding dependence on human factors such as fatigue. A typical machine vision detection system includes image acquisition, image analysis, decision-making, and execution module. The image acquisition part is composed of a CCD camera and an objective lens structure. Then the information is analysed by a computer or an embedded server through a machine vision algorithm optimized for defect detection and identification, or for dimensional measurement.

5.1 Volumetric Inspection

5.1.1 Description

In this context, the term volumetric inspection refers to any procedure or algorithm capable of automatically examining and evaluating the 3D geometric shape of an object assuring its integrity and compliance. In order to do so, vision technologies, such as cameras, are the main source of information that subsequent algorithms will use to inspect target objects. Different methods can be used to acquire 3D for industrial applications[1], however in this section the focus is set in optical methods.

[1] Bi, Z. M., Wang, L. (2010), Advances in 3D data acquisition and processing for industrial applications, *Robotics and Computer-Integrated Manufacturing*, Vol. 26:5, pp. 403-413, ISSN 0736-5845.

The acquired image or 3D information must be compared with an ideal model or reference, usually the engineer design of the produced piece. These references may be a complete 3D specification such as a computer-aided design, or simple guidelines and measures that the object must meet to be considered valid.

Depending on the nature of the final application or industry, different requirements may arise: working volume, hidden surfaces, concavities, speed, accuracy, elastic tolerances, non-rigid geometries and more. As these factors often conflict, the optimal solution may be slightly different for each use case. Actually, there exists no industrial vision system capable of handling all tasks in every application domain.

For instance, for a full inspection without hidden surfaces, carving algorithms with multiple cameras such as ZG3D technology used in WP5 may obtain a good approximation of the object yet they will be more imprecise inspecting concavities in 3D. This technology[2] relies on multiple cameras to capture an object in free fall to obtain a 360º view of the inspected object without stopping the production line.

Although specific solutions are slightly different, pipelines in volumetric inspection include the following generic stages:

- Capture: the first step to conduct any analysis is to acquire image or images of the target that will be inspected.
- Segmentation: after the images are acquired it is necessary to filter noise data and identify the target to be analysed in them.
- Data integration: information may come from different sources, for instance multiple cameras or range sensors, so it is necessary to combine and integrate this data in a unique representation.
- Alignment: in this stage the previously generated unique data representation, that could be but is not limited to a 3D reconstruction, needs to be aligned with the model or reference so they share the same coordinate system.
- Data comparison: finally, the aligned unique representation of the target object is compared with the reference, in order to find differences in its 3D volume shape that will decide if the object meets production design requirements.

FIGURE 11. SCHEMATIC PROCESS OF THE VOLUMETRIC INSPECTION SOLUTION

5.1.1.1 State, Maturity and Relevance

The use of vision systems for quality control in industrial processes has rapidly increased since the last decade.[3] Unfortunately, these solutions are mostly *ad-hoc* for specific problems, for example, camera-based fruit sorting machines capable of rejecting rotted fruit as it moves in a conveyor. Other solutions rely on well-presented targets to measure

[2] Perez-Cortes, J. C., et al. (2018), A System for In-Line 3D Inspection without Hidden Surfaces, *Sensors*, Vol. 18:9, 2993, ISSN 1424-8220.

[3] Psarommatis, F., et al. (2020), Zero defect manufacturing: state-of-the-art review, shortcomings and future directions in research, *International Journal of Production Research*, Vol. 58:1, pp. 1-17, ISSN 0020-7543.

a few critical parameters that ensure the product is valid in the measured dimensions. Comprehensive studies of vision systems functions, techniques and capabilities can be consulted.[4] [5]

Although vision systems are already well established in the industrial quality control processes, complete volumetric inspection is still being introduced in them. This is the next step as precision and tolerance requirements increase in the industry, making the use of traditional inspection processes harder. Furthermore, vision-based automatic metrology systems are based on solid mathematical models and are constantly tested to provide accurate results.

There are different kinds of waste related to a manufacturing process that could stem from inventory management[6]: transportation, motion, waiting, overproduction, over-processing and flawed parts. However, the latter is one of the costliest because it could bleed into the others, especially transportation or over processing. For this reason, an early detection of manufacturing defects has a great impact on the costs and waste of a product.

This solution prevents defects taking a toll, detecting them as they are produced so the faulty product can be reworked, recycled or in the worst case discarded avoiding more waste from transport, integration in the final product or being delivered to the client. Furthermore, this early detection allows tracking down faster the source of flaws allowing to lower the number of defective parts produced.

Moreover, this solution may inspect not only the manufactured product but the raw material in order to assure the inputs to the production line are correct and will not introduce defects in the manufactured product. This input quality assurance can prevent the production of flawed objects even before any item is actually produced.

5.1.1.2 Flexibility and Level of Integration

Visual volumetric inspection may be used in any manufacturing production line and with any kind of product as long as its geometry can be seen from a camera. The capture configuration, such as cameras position, illumination, backgrounds and so forth can be adapted to the specific needs of the inspected target. For instance, light polarization might be required depending on the reflective properties of the surface or backlighting can be the best option with planar geometries.

Furthermore, depending on the required accuracy, it is also possible to adjust inspection costs reducing the number of cameras, their quality, or their resolution.

[4] Semeniuta, O., et al. (2018), Towards increased intelligence and automatic improvement in industrial vision systems, *Procedia CIRP*, Vol. 67, pp. 256-261, ISSN 2212-8271.

[5] Malamas, E. N., et al. (2003), A survey on industrial vision systems, applications and tools, *Image and Vision Computing*, Vol 21:2, pp. 171-188, ISSN 0262-8856.

[6] Shingo, S., Dillon, A. P. (1989), *A study of the Toyota production system: From an Industrial Engineering Viewpoint*, ISBN 978-0915299171.

However, this technology is limited to external geometry. In order to inspect the internal structure or composition of a product other options may be suitable such as ultrasonic, thermal or radiographic inspection.

This technology can be easily integrated in most automated production lines, just after the product is manufactured or before the raw material is introduced, if a previous inspection of the inputs is required. The product is captured by the device and defective pieces can be automatically rejected.

Depending on the requirements and the capture system used, the level of integration in the industry may be different. Volumetric inspection results may automatically discard items, raise alerts or even stop the production line in critical scenarios. These behaviours should be configured depending on the industry needs and requirements.

Additionally, the solution may provide quality production results and statistics that can be analysed in order to find the cause of the defects.

5.1.1.3 Industrial applications and References

Proposed technology can be used in any industry that requires dimensional quality control for its production. For instance, automotive industry[7], automatic PCB inspection[8] or plastic injection[9] are obvious applications of the volumetric vision analysis. However, any process that requires geometry related inspection is suitable as application.

5.1.1.4 Competitive destructive or non-destructive inspection technologies

Nowadays most production quality inspection processes are still carried out by trained personnel that manually checks the product shape with their naked eye, making use of calibrated mechanical gauges or, in the best of cases, with specialized measuring equipment. In the case of high precision requirements, tactile methods are used to periodically measure samples in the production line such as Coordinate Measure Machine (CMM).

In any case, this is a laborious process that requires human intervention making the process slow and therefore impossible to automatically inspect products in a factory production line.

If the geometry meets certain requirements, it is possible to use passive methods such as industrial sieving machines that mechanically classifies produced objects according to their shape. Unfortunately, these methods may only be used with a limited number of products and each solution is designed specifically for a single geometry.

[7] Rio-Torto, I., et al. (2021), Automatic quality inspection in the automotive industry: a hierarchical approach using simulated data, *2021 IEEE 8th International Conference on Industrial Engineering and Applications (ICIEA)*, pp. 342-347.

[8] Mar, N. S. S., et al. (2011), Design and development of automatic visual inspection system for PCB manufacturing, *Robotics and Computer-Integrated Manufacturing*, Vol. 27:5, pp. 949-962, ISSN 0736-5845.

[9] Muresan, M. P., et al. (2020), Automatic vision inspection solution for the manufacturing process of automotive components through plastic injection molding, *2020 IEEE 16th International Conference on Intelligent Computer Communication and Processing (ICCP)*, pp. 423-430.

5.1.1.5 Advantages and Limitations of supplied technology

This technology is capable of inspecting 100% of produced goods in an industrial production line, detecting errors and discarding faulty pieces as soon as possible. This allows to reduce waste, stop production when machine maintenance is required and avoid faulty parts to be integrated in the final product or to be delivered to the client.

It is not possible to achieve this with manual inspections, even in slow production processes of a few pieces per minute. Manual inspections performed by trained operators require to position and align each individual piece in metrology equipment in order to measure it in an operation that takes some minutes in the best case. Volumetric vision inspection can be automatized to inspect multiple objects per second with a single inspection device.

TABLE 27. INSIGHTS OF VOLUMETRIC VISION INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Reproducibility	High	
Real-time inspection	Yes	Often possible
Rate of inspection	High	Often 100% of the products
Inspection in motion	Yes	Low acquisition times allow this
Processing time for a piece	Less than a second	Depending on processing demands of algorithms and computational resources
Multi-object parallel analysis	Yes	Possible with one camera covering more objects or production lines
Automation	Very high	
Human interaction/supervision	Yes	Operators may supervise analysis results through an interface
Harsh Environment	Yes	
Easy to scale	Very high	
Flexibility	High	
Requires human intervention	No	
Complete 3D inspection	Yes	It may require multiple images to actually build a complete 3D, it can be easily done in free fall configurations as in [2]

5.1.2 Benchmarking Technologies/Solutions

5.1.2.1 Non-destructive human visual inspection

It is composed of tedious and repetitive tasks, sometimes off the production line, often limited within a fraction and not all of the products. In some applications it is desirable due to the complexity of the workpiece. The main obvious limitation not reported in the table below is the lack of digitalization in the inspection procedure, with no option to re-consider or re-process the analysis over time.

TABLE 28. INSIGHTS OF NON-DESTRUCTIVE HUMAN VISUAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Low	May be mined by operator's fatigue or point of view. Limited in accuracy
Reproducibility	Limited	Varies between operators or even same operator at different times
Real-time inspection	Yes (limited)	Depends upon accessibility, throughput
Rate of inspection	Low	Often limited within a sample of products
Inspection in motion	No/limited	
Processing time for a piece	Seconds	
Multi-object parallel analysis	No	
Automation	Low	
Human interaction/supervision	n/a	
Harsh Environment	Human-limited	
Easy to scale	High	
Flexibility	Very high	
Requires human intervention	Yes	
Complete 3D inspection	Yes	

5.1.2.2 Human tool-assisted inspection

It is composed by repetitive measuring tasks using any available equipment such as mechanical gauges, angle plates or precision calibre. It is often limited to a tiny fraction of the production and prone to human errors.

TABLE 29. INSIGHTS OF HUMAN TOOL-ASSISTED INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	It may depend on operator and equipment
Reproducibility	High	Slight changes depending on operator
Real-time inspection	Yes (limited)	Depends upon accessibility, throughput
Rate of inspection	Low	Often limited within a sample of products
Inspection in motion	No/limited	
Processing time for a piece	Minutes	
Multi-object parallel analysis	No	
Automation	Low	
Human interaction/supervision	n/a	
Harsh Environment	Human-limited	

Easy to scale	Medium	May depend on availability of equipment
Flexibility	Very high	
Requires human intervention	Yes	
Complete 3D inspection	Yes	

5.1.2.3 Automated coordinate measuring machines (CMMs)

Specially purposed CMMs measure with contact the dimensions of the workpiece in the key points of interest. They may consist in linear-actuated fixed-position prongs or more complex robot-arm driven measuring devices.

TABLE 30. INSIGHTS OF INSPECTION WITH CMMS

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Very high	
Reproducibility	Very high	
Real-time	No	Or in only limited cases
Rate of inspection	Very low	Often limited within a sample of products and depends on the number of key points
Inspection in motion	No	
Processing time for a piece	Minutes	Strongly variable with size
Multi-object parallel analysis	No	
Automation	Low	
Human interaction/supervision	No	
Harsh Environment	Limited	
Easy to scale	Low	
Flexibility	High	
Requires human intervention	Yes	Operator needs to position and align the product
Complete 3D inspection	Yes	It may take more than one object positioning

5.1.2.4 Laser scanners

This equipment exploits the simple physics of light beams and the ease of use of low-cost hardware. They can be very precise and fast in measuring key points of interest but sometimes inapplicable to transparent surfaces. Nowadays, laser scanners can acquire a high number of points in less than a second. Reference[10] can be consulted for more details.

[10] Martínez, S., et al. (2010), Analysis of laser scanning and strategies for dimensional and geometrical control, *The International Journal of Advanced Manufacturing Technology*, Vol. 46:5, pp. 621-629, ISSN 0268-3768.

TABLE 31. INSIGHTS OF LASER SCANNERS

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Reproducibility	High	
Real-time inspection	Yes	
Rate of inspection	Very high	
Inspection in motion	Yes	
Processing time for a piece	< second	Variable with dimensions and number of key points
Multi-object parallel analysis	Yes	
Automation	High	
Human interaction/supervision	No	
Harsh Environment	Yes	
Easy to scale	Medium	Industrial laser scanners are expensive compared with other technologies
Flexibility	High	
Requires human intervention	No	
Complete 3D inspection	No	Without object manipulation only 2.5D is achievable

5.1.2.5 Industrial sieving machines

Industrial sieving machines are capable of automatically sorting manufactured products making use of different physical properties such as size, density or roughness. In order to do so, sieving machines use vibrating machines to separate the objects and automatically classify them. The main issue with this kind of machines is they are only useful in very specific geometries.

TABLE 32. INSIGHTS OF INDUSTRIAL SIEVING MACHINES

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Reproducibility	High	
Real-time inspection	Yes	
Rate of inspection	Very high	
Inspection in motion	Yes	
Processing time for a piece	<< second	It can process a huge number of pieces per second
Multi-object parallel analysis	Yes	
Automation	Very high	
Human interaction/supervision	No	
Harsh Environment	Yes	
Easy to scale	Very high	

Flexibility	Very low	Only suitable objects
Requires human intervention	No	
Complete 3D inspection	No	Depends on object geometry

Funded by the European Union

5.1.3 Summary of the Benchmarks

TABLE 33. COMPARISON BETWEEN VOLUMETRIC INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	VOLUMETRIC VISION INSPECTION	NON-DESTRUCTIVE HUMAN VISION	HUMAN TOOL-ASSISTED INSPECTION	AUTOMATED CMMS	LASER SCANNERS	INDUSTRIAL SIEVING MACHINES
Precision (accuracy and detection efficiency)	High	Low	High	Very high	High	High
Reproducibility	High	Limited	High	Very high	High	High
Real-time inspection	Yes	Yes (limited)	Yes (limited)	No	Yes	Yes
Rate of inspection	High	Low	Low	Very low	Very high	Very high
Inspection in motion	Yes	No/limited	No	No	Yes	Yes
Processing time for a piece	< second	Seconds	Minutes	Minutes	< second	<< second
Multi-object parallel analysis	Yes	No	No	No	Yes	Yes
Automation	Very high	Low	Low	Low	High	Very high
Human interaction/supervision	Yes	N/A	N/A	No	No	No
Harsh Environment	Yes	Human-limited	Human-limited	Limited	Yes	Yes
Easy to scale	Very high	High	Medium	Low	Medium	Very high
Flexibility	High	Very high	Very high	High	High	Very low
Requires human intervention	No	Yes	Yes	Yes	No	No
Complete 3D inspection	Yes	Yes	Yes	Yes	No	No

Funded by the European Union

5.2 Surface Anomaly Detection

5.2.1 Description

Surface anomaly detection is the process of automatically examining an object and finding anything abnormal in its surface. Such anomaly can be defined as any textural characteristic that is not supposed to be found in a valid object: stains, scratches, contamination and so on. In order to find these anomalies automatically, vision technologies, such as cameras, are the main source of information that subsequent algorithms will use to inspect target objects. To inspect the complete surface of the target multiple views will be necessary, these can be easily achieved with a multicamera free fall capture device such as ZG3D[1], which will be used in this work package.

Due to the infinite number of possible irregularities, instead of characterizing the anomalies and compare captured images with them it is necessary to condense the information of any valid object surface into a model or reference – learned from images of valid objects – and measure deviations from it to find the anomalies.

Depending on the inspected surface light properties, different problems such as reflections, shines or translucency may arise, making necessary the use of specific illumination or sensors[2]: this is the reason why there is no generic solution capable of inspecting any manufactured object.

Although specific solutions are slightly different, surface anomaly detection has a generic pipeline with two different purposes: training texture models and evaluating pieces:

- Capture: the first step to conduct any analysis is to acquire image or images of the target to be inspected.
- Segmentation: after the images are acquired it is necessary to filter noise data and identify the target to be analysed in them.
- Data integration: data may come from different sources, for instance multiple cameras, different polarization angles, wavelength filters and more, so it is necessary to combine and integrate this data in a unique representation.
- Training: in this stage a condensed model that represents the accepted visual surface of the object will be created with data from valid objects. These models need to represent the valid range of the object so depending on the complexity of the texture it may be difficult to create and interpret.
- Data comparison: finally, the captured image integrated is compared with the trained reference finding differences in its surface that will decide if the object follows the distribution of the training samples or not.

[1] Perez-Cortes, J. C., et al. (2018), A System for In-Line 3D Inspection without Hidden Surfaces, *Sensors*, Vol. 18:9, 2993, ISSN 1424-8220.

[2] Czimmermann, T., et al. (2020), Visual-Based Defect Detection and Classification Approaches for Industrial Applications—A Survey, *Sensors*, Vol. 20:5, 1459, ISSN 1424-8220.

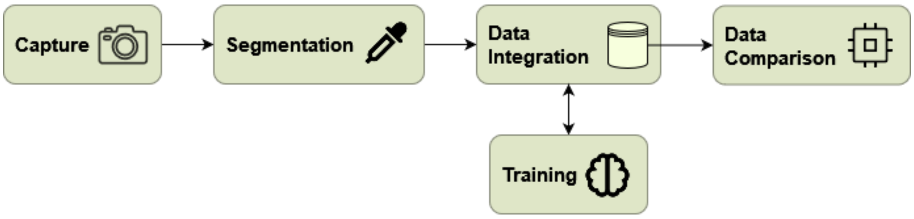

FIGURE 12. SCHEMATIC PROCESS OF THE SURFACE INSPECTION SOLUTION

5.2.1.1 State, Maturity and Relevance

Surface anomaly detection has been introduced in industrial processes in the last decades and its popularity is growing fast with the introduction of deep learning.[3] As previously mentioned, fruit sorting machines capable of automatically sorting fruit depending on its colour or rotten parts as they move in a conveyor are widely used in industrial processes. Unfortunately, these solutions are mostly *ad-hoc* for specific problems, so a generic solution capable of reliably finding anomalies on the surface is not available yet. As an example, in a survey[4] 120 different publications are reviewed only for flat steel surface defects.

Even though vision systems are already well established in the industrial quality control processes, automatic surface analysis is highly demanded in the manufacturing industry. This kind of process will be an important step up in quality, leaving behind the slow and imprecise manual inspection.

As described in volumetric inspection, from the different kinds of waste related to manufacturing flawed parts is one of the costliest because it could bleed into the others, especially transportation or over processing. An early detection of surface anomalies has a great impact on the costs and waste of a product.

5.2.1.2 Flexibility and Level of Integration

Any manufacturing production line is suitable for surface anomaly detection as long as it requires surface quality assurance. Depending on the surface properties and the kind of anomalies to look for, capture configuration, such as cameras position, illumination, backgrounds and so forth might change in order to optimize it. For instance, light polarization might be required in metallic parts, so that scratches and surface imperfections are accurately detected.

As this is camera-based technology, integration in production lines is an easy process since just some cameras, illumination and maybe backgrounds are required. Depending on the specific needs of the products to be analysed, inspection may be required just after the product is manufactured or before the raw material is introduced. The product is captured by the device and pieces with anomalous surfaces can be automatically rejected.

[3] Bhatt, P. M., et al. (2021), Image-Based Surface Defect Detection Using Deep Learning: A Review, *Journal of Computing and Information Science in Engineering*, Vol. 21:4, 040801, ISSN 1530-9827.

[4] Luo, Q., et al. (2020), Automated Visual Defect Detection for Flat Steel Surface: A Survey, *IEEE Transactions on Instrumentation and Measurement*, Vol. 69:3, pp. 626-644, ISSN 0018-9456.

Similarly, to other inspection solutions, surface anomaly detector results may automatically discard items, raise alerts or even stop the production line in critical scenarios. These behaviours should be configured depending on the industry needs and requirements. Additionally, the solution may provide quality production results and statistics that can be analysed in order to find the cause of the defects.

5.2.1.3 Industrial applications and References

Proposed technology can be used in any industry that requires surface quality assessment for its production. For instance, automotive industry[5] or plastic injection[6] are obvious applications of the surface anomaly detector.

5.2.1.4 Competitive destructive or non-destructive inspection technologies

The lack of specialized technology for surface quality inspection capable of finding a wide variety of defects makes this process expensive and tedious. This is the reason why object surface quality inspection processes are still carried out by trained personnel that manually checks the product with their naked eye or in the best of cases, when high precision is required, with specialized equipment such as spectrometers or surface roughness meters.

Obviously, this is a laborious process that requires human intervention making the process slow and therefore impossible to automatically inspect items in a factory production line with high throughput.

Besides human inspection and computer vision, some surface defects such as roughness can be automatically inspected with laser scanners or surface roughness meters . However, these technologies are not able to inspect many other texture defects such as stains.

5.2.1.5 Advantages and Limitations of supplied technology

The main advantage of surface anomaly detection is the capability to inspect 100% of produced goods in an industrial inspection line. This will allow an early rejection of pieces with anomalous surface reducing waste preventing over processing and transport to final client. Furthermore, this early detection also allows to stop production for maintenance when required, avoiding faulty parts to be produced.

It is not possible to achieve this with manual inspections, even in slow production processes of a few pieces per minute. Manual inspections performed by trained operators require to carefully inspect each object looking for any anomaly. Although humans are efficient in this task, it may take a few seconds per piece, and it is prone to fail after short periods of inspection. Surface anomaly detection can be automatized to inspect multiple objects per second with a single inspection device.

[5] Shi, Q., et al. (2005), Development of an automatic optical measurement system for automotive part surface inspection, *Proceedings, 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 1557-1562.

[6] Im, D., et al. (2021), A Data-Centric Approach to Design and Analysis of a Surface-Inspection System Based on Deep Learning in The Plastic Injection Molding Industry, *Processes*, Vol. 9:11, 1895, ISSN 2227-9717.

TABLE 34. INSIGHTS OF SURFACE ANOMALY DETECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Reproducibility	High	
Real-time inspection	Yes	
Rate of inspection	Very high	
Inspection in motion	Yes	
Processing time for a piece	Less than a second	
Multi-object parallel analysis	Yes	
Automation	Very high	
Human interaction/supervision	Yes	
Harsh Environment	Yes	
Easy to scale	Very high	
Flexibility	Very high	
Requires human intervention	No	
Types of defects	Any: stains, roughness, scratches	It may require specific type of illumination/angles to detect any possible defect

5.2.2 Benchmarking Technologies/Solutions

5.2.2.1 Non-destructive human visual inspection

It is composed of tedious and repetitive tasks, sometimes off the production line, often limited within a fraction and not all the products. In some applications it is desirable due to the complexity of the workpiece. The main obvious limitation not reported in the table below is the lack of digitalization in the inspection procedure, with no option to re-consider or re-process the analysis over time.

TABLE 35. INSIGHTS OF NON-DESTRUCTIVE HUMAN VISUAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Low	May be mined by operator's fatigue or point of view. Limited in accuracy
Reproducibility	Limited	Varies between operators or even same operator at different times
Real-time inspection	Yes (limited)	Depends upon accessibility, throughput
Rate of inspection	Low	Often limited within a sample of products
Inspection in motion	No/limited	
Processing time for a piece	Seconds	
Multi-object parallel analysis	No	
Automation	Low	

Human interaction/supervision	N/A	
Harsh Environment	Human-limited	
Easy to scale	High	
Flexibility	Very high	
Requires human intervention	Yes	
Types of defects	Any: stains, roughness, scratches	

5.2.2.2 Human tool-assisted inspection

It is composed by repetitive measuring tasks using any available equipment such as spectrometers, surface roughness meters or any other precision tool. It is often limited to a tiny fraction of the production and prone to human errors.

TABLE 36. INSIGHTS OF HUMAN TOOL-ASSISTED INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	It may depend on operator and equipment
Reproducibility	High	Slight changes depending on operator
Real-time inspection	Yes (limited)	Depends upon accessibility, throughput
Rate of inspection	Low	Often limited within a sample of products
Inspection in motion	No	
Processing time for a piece	Minutes	
Multi-object parallel analysis	No	
Automation	Low	
Human interaction/supervision	N/A	
Harsh Environment	Human-limited	
Easy to scale	Medium	
Flexibility	Very high	
Requires human intervention	Yes	
Types of defects	Any: stains, roughness, scratches	

5.2.2.3 Laser scanners

This equipment exploits the physics of light beams and the ease of use of low-cost hardware. Due to their high precision and point density, they can detect geometric surface defects such as roughness or even scratches.

TABLE 37. INSIGHTS OF LASER SCANNERS

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Reproducibility	High	
Real-time inspection	Yes	
Rate of inspection	Very high	
Inspection in motion	Yes	
Processing time for a piece	Less than a second	Variable with dimensions and number of key points
Multi-object parallel analysis	Yes	
Automation	High	
Human interaction/supervision	No	
Harsh Environment	Yes	
Easy to scale	Medium	Industrial laser scanners are expensive compared with other technologies
Flexibility	Medium	
Requires human intervention	No	
Types of defects	Geometric defects: roughness, scratches	

Funded by the European Union

5.2.3 Summary of the Benchmarks

TABLE 38. COMPARISON BETWEEN SURFACE ANOMALY DETECTION SOLUTION AND DEFINED ALTERNATIVES

CRITERIUM	SURFACE ANOMALY VISION DETECTION	NON-DESTRUCTIVE HUMAN VISION	HUMAN TOOL-ASSISTED INSPECTION	LASER SCANNER
Precision (accuracy and detection efficiency)	High	Low	High	High
Reproducibility	High	Limited	High	High
Real-time inspection	Yes	Yes (limited)	Yes (limited)	Yes
Rate of inspection	Very high	Low	Low	Very high
Inspection in motion	Yes	No/limited	No	Yes
Processing time for a piece	Less than a second	Seconds	Minutes	Less than a second
Multi-object parallel analysis	Yes	No	No	Yes
Automation	Very high	Low	Low	High
Human interaction/supervision	Yes	N/A	N/A	No
Harsh Environment	Yes	Human-limited	Human-limited	Yes
Easy to scale	Very high	High	Medium	Medium
Flexibility	Very high	Very high	Very high	Medium
Requires human intervention	No	Yes	Yes	No
Types of defects	Any: stains, roughness, scratches	Any: stains, roughness, scratches	Any: stains, roughness, scratches	Geometric defects: roughness, scratches

Funded by the European Union

5.3 AI-Enhanced Artificial Vision Inspection

5.3.1 Description

The vast majority of industrial processes rely on continuous inspection of the working material, intermediate and final products: between all five senses, sight is essential to evaluate how well a job is done. Artificial vision solutions allow to extract features of interest from a digital image, so to be processed for further analysis, like dimensional control or defect detection. In industrial applications these controls can be used to assess the quality and conformity of products and eventually automate some related decision (eject, rework, etc.). AI techniques can also be integrated to extend the potential and applicability of AV solutions, enabling supervised or unsupervised classification tasks and quality predictions.

2D Camera based embedded systems located in line will allow to inspect products, extract characteristic features, check their geometry, size, and relative position, measure defined dimensions, all this to finally be able to assess production quality and track relevant parameters in time.

In this project perspective, artificial vision technology can be used to detect defective parts at early stage of manufacturing and improve production-line parameters to achieve the best possible quality, aiming to zero defects, with the least amount of low-quality product waste.

A typical development workflow, as showed in Figure 13, usually starts from the collection of images, also taking into consideration the final acquisition procedure. Depending on the chosen technology, the subsequent paths diverge:

- Classical artificial vision requires the characterization of the images to set common parameters delineating a defect or a feature to be extracted, then the development of the analysis software and its testing.
- AI requires the feature labelling phase, supervised or unsupervised, in which all the sample defects are marked, then a training phase yielding a model and the final validation phase.

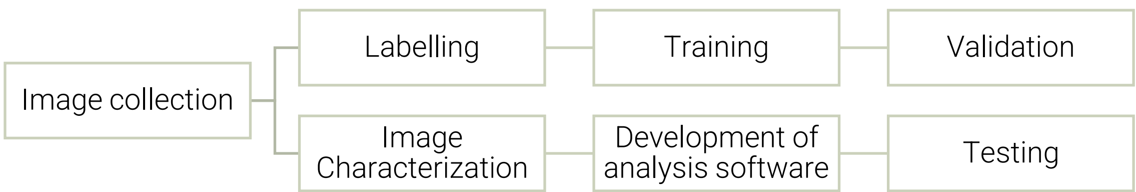

FIGURE 13. DEVELOPMENT WORKFLOW OF VISION INSPECTION SYSTEMS

Both branches of the workflows intertwine with the design of the physical sensors, illumination equipment, processing hardware and their integration in the quality control system.

5.3.1.1 State, Maturity and Relevance

Artificial vision techniques are already well established in the industry with countless applications and plenty available software libraries and research publications.[1] [2]

In the past decades, contextually with lower limitations and skyrocketing performance improvements achieved by consumer and dedicated hardware, AI solutions gained visibility with lots of research papers and became increasingly available in open-source frameworks and online services. In some fields such as object detection or OCR, traditional techniques were wiped out by AI which solved with ease complex and nearly unprogrammable scenarios, especially in the image processing field.

5.3.1.2 Flexibility and Level of Integration

Vision solutions often relieve human workforce from repetitive and error-prone tasks. They can also replace human inspection in dangerous or hazardous environments. Despite AI solutions are usually more resource intensive and require higher end hardware with respect to traditional image processing solutions, they pay back with their improved performance.

Thanks to the miniaturization of the electronics of camera systems, on-line, in-line, off-line embedded artificial vision systems can nowadays be implemented in tight spaces and with small form factors. Traditional or AI solutions can be embedded in the system or exported on standalone hardware, local or remote machines communicating with the latest IoT protocols such as MQTT.

The image processing part of the solution can be separated from the image acquisition task and become a standalone service. Possible locations are unlimited, like the edge of the production line, a data centre facility or a cloud server.

At its apex, such a service may be integrated in a web application suite from which all the AV and AI workflow can be managed, equipped with traditional or AI-based processing tools, performance evaluations, etc.

This is also the approach proposed by Video Systems within the scope of the project, consolidating and extending the results recently developed. Thanks to a web-based graphical programming framework, the solution easily allows the creation of image processing algorithms by experienced quality control operators, facilitating the work also for those who are not skilled in image processing code. The solution integrates the use of classical image processing modules and the use of modules based on AI algorithms, targeting image classification, image annotation for object detection, Generative Adversarial Networks (GAN) for surface anomaly detection, and so on. The solution also integrates IoT communication modules for integration into enterprise automation and information systems and connection to cloud systems.

[1] Zhou, L., et al. (2021), Computer Vision Techniques in Manufacturing, *TechRxiv*, preprint.

[2] Noble, J. A. (1995), From inspection to process understanding and monitoring: a view on computer vision in manufacturing, *Image and Vision Computing*, Vol. 13:3, pp. 197-214, ISSN 0262-8856.

For edge and high-rate applications, to be self-contained and close to production lines, Video Systems proposes embedded platforms integrating NVIDIA GPUs with high computing power for running artificial visions and AI algorithms.

5.3.1.3 Industrial applications and References

Automated Vision Systems enhanced with artificial intelligence can be adapted to a plethora of manufacturing and quality control sight-involving processes with a high degree of specificity. For example, they are used in glass and metallurgical industries to supervise production and assess its qualities along the line, such as presence of superficial defects (excess or lack of materials, creep, cracks and so on), dimensional compliance and real-time tracking of the products on the conveyors.

5.3.1.4 Competitive destructive or non-destructive inspection technologies

Whether destructive or non-destructive, the human inspection of products is interlaced with manufacturing since the beginning of the industrial era. This very general field includes not only visual check-ups but also physical manipulation and testing of the products in the operator's hands.

Among non-destructive inspection technologies, mainly used in dimensional quality assessments, there are:

- Automated coordinate-measuring machines (CMM)
- Laser scanners
- Structured light
- Photogrammetry

On the other hand, alternative destructive tests are difficult to mention due to the variability of possible applications, depending strongly on the product/process to be monitored. As an example, they can encompass the analysis of surface properties (that can alternatively be controlled by AV) such as watertightness of packages in food and beverage sector through submersion tests, which in case of failure would ruin the entire package contents.

Another example taken from Illy's use case within ZDZW project deals with the possibility to check conformity of the punching of the silicone septum in the capsule body by means of AV, as an early-stage alternative to the destructive dispensing tests carried out on the final assembled capsule including coffee. These sample tests at the moment may evidence an incorrect puncture, but with the undesirable side effect of wasting also conforming material (ground coffee, non-defective capsule components) and assembly time/costs.

5.3.1.5 Advantages and Limitations of supplied technology

The generality of artificial vision technologies is one of their primary advantages, rendering them adaptable to almost every sight-involving quality control process. AI solutions add another level of generalization because they can deal with and produce any type of data: for example, using images and/or other sensor information they can figure out production-related parameters and quality indexes, or predict them if needed.

Regarding the technology used in the image processing, it must be said AI can achieve a very high level of precision and data adaptation, but every intermediate calculation remains unintelligible under its model. On the other hand, the traditional processing, although predictable and somewhat straightforward, can quickly become complicated to develop from scratch. The proper thing to do is to find a sweet spot between the two to get a performing solution.

On the long run, automated vision technologies, could reduce the time spent by the workforce in quality control activities leading to a zero waste of human resources in a broad sense.

One of the biggest concerns about AI, ethically speaking, is that it is not enough mature nor regulated to handle life-critical applications, which are beyond the scope of the ZDZW project.

TABLE 39. INSIGHTS OF AI-ENHANCED ARTIFICIAL VISION INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Very high	
Reproducibility	Very high	
Inspectable features	Surface defects, dimensions	
Real-time inspection	Yes	Often possible
Rate of inspection	Very high	Often 100% of the products
Inspection in motion	Yes	Possible up to or more than 1000 parts/min, due to fast image acquisition and processing time
Processing time for a piece	Fractions of a second	Depending on processing demands of algorithms and computational resources
Multi-object parallel analysis	Yes	Possible with one camera covering more objects or production lines
Automation	Very high	
Human interaction/supervision	Yes	Operators may supervise analysis results through check of acquired digital images (becomes a needed process for AI approach)
Harsh Environment	Yes	
Easy to scale	Very high	

5.3.2 Benchmarking Technologies/Solutions

5.3.2.1 Non-destructive human visual inspection

It is composed of tedious and repetitive tasks, sometimes off the production line, often limited within a fraction and not all of the products. In some applications it is desirable due to the complexity of the workpiece. The main obvious limitation not reported in the table below is the lack of digitalization in the inspection procedure, with no option to re-consider or re-process the analysis over time.

TABLE 40. INSIGHTS OF NON-DESTRUCTIVE HUMAN VISUAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Low	May be mined by operator's fatigue or point of view. Limited in accuracy
Reproducibility	Limited	Varies between operators or even same operator at different times
Inspectable features	Surface defects, roughness, dimensions	May be qualitative and not qualitative
Real-time inspection	Yes (limited)	Depends upon accessibility, throughput
Rate of inspection	Low	Often limited within a sample of products
Inspection in motion	No/limited	
Processing time for a piece	> 0.5-1 s	
Multi-object parallel analysis	No	
Automation	Low	
Human interaction/supervision	n/a	
Harsh Environment	Human-limited	
Easy to scale	High	

5.3.2.2 Automated coordinate measuring machines (CMMs)

Specially purposed CMMs measure the dimensions of the workpiece in the key points of interest by sensing the surface of the object with a probe. They may consist in linear-actuated fixed-position prongs or more complex robot-arm driven measuring devices.

TABLE 41. INSIGHTS OF AUTOMATED COORDINATE MEASURING MACHINES INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Very high	
Reproducibility	Very high	
Inspectable features	Dimensions, surface defects	Only surface defects with a volume can be measured
Real-time	No	Or in only limited cases
Rate of inspection	Very slow	Often limited within a sample of products and depends on the number of key points
Inspection in motion	No	
Processing time for a piece	> 0.2-1 min	Strongly variable with size
Multi-object parallel analysis	No	
Automation	High	

Human interaction/supervision	No	
Harsh Environment	Limited	
Easy to scale	Low	

5.3.2.3 Laser scanners

This equipment exploits the simple physics of light beams and the ease of use of low-cost hardware. They can be very precise and fast in measuring key points of interest but sometimes inapplicable to transparent surfaces. More complex machines may enable laser direction change and thus 3D measuring capabilities with a set of mirrors.

TABLE 42. INSIGHTS OF LASER SCANNERS INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Very high	
Reproducibility	Very high	
Inspectable features	Dimensions, roughness, surface defects	Only surface defects with a volume can be measured
Real-time inspection	Yes	
Rate of inspection	Very high	
Inspection in motion	Yes	
Processing time for a piece	Fractions of a second	Variable with dimensions and number of key points
Multi-object parallel analysis	Yes	
Automation	High	
Human interaction/supervision	No	
Harsh Environment	Yes	
Easy to scale	Yes	

5.3.2.4 Structured light

Two sensors can reconstruct the 3D shape of an object by analysing the behaviour of varying pre-determined light patterns which are projected onto itself. They can be excellent with simple shapes, but the performance can be mined when reflectivity changes along the object (for example, when the product is composed by multiple materials).

TABLE 43. INSIGHTS OF STRUCTURED LIGHT INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Very high	
Reproducibility	Very high	
Inspectable features	Dimensions, surface defects	Only surface defects with a volume can be measured
Real-time inspection	Yes	
Rate of inspection	High	

Inspection in motion	No/limited	
Processing time for a piece	> 2 s	Strongly variable with size of object, image resolution and shape complexity
Multi-object parallel analysis	Yes	
Automation	Yes	
Human interaction/supervision	No	
Harsh Environment	Yes	
Easy to scale	Yes	

5.3.2.5 Photogrammetry

A single sensor can be used to capture images of the object from different angles. Then, the acquired images are processed to extract dimensionality. This method is better suited to highly featured, organic and smooth objects, and may show deficiencies and artifacts with planar surfaces.

TABLE 44. INSIGHTS OF PHOTOGRAMMETRY INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	
Reproducibility	High	
Inspectable features	Dimensions, surface defects	Only surface defects with a volume can be measured
Real-time inspection	Yes (limited)	Depends on throughput
Rate of inspection	Low	
Inspection in motion	No/limited	
Processing time for a piece	> 5-10 s	Strongly variable with size of object, image resolution and shape complexity
Multi-object parallel analysis	Yes	
Automation	Yes	
Human interaction/supervision	No	
Harsh Environment	Yes	
Easy to scale	Yes	

5.3.3 Summary of the Benchmarks

TABLE 45. COMPARISON BETWEEN AI-ENHANCED ARTIFICIAL VISION INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	AV + AI INSPECTION	NON-DESTRUCTIVE HUMAN VISION	AUTOMATED CMMS	LASER SCANNERS	STRUCTURED LIGHTS	PHOTOGRAM-METRY
Precision (accuracy and detection efficiency)	Very high	Low	Very high	Very high	Very high	High
Reproducibility	Very high	Limited	Very high	Very high	Very high	High
Inspectable features	Surface defects, dimensions	Surface defects, roughness, dimensions	Dimensions, surface defects	Dimensions, roughness, surface defects	Dimensions, surface defects	Dimensions, surface defects
Real-time inspection	Yes	Yes (limited)	No	Yes	Yes	Yes (limited)
Rate of inspection	Very high	Low	Very slow	Very high	High	Low
Inspection in motion	Yes	No/limited	No	Yes	No/limited	No/limited
Processing time for a piece	Fractions of a second	> 0.5-1 s	> 0.2-1 min	Fractions of a second	> 2 s	> 5-10 s
Multi-object parallel analysis	Yes	No	No	Yes	Yes	Yes
Automation	Very high	Low	High	High	High	High
Human interaction/supervision	Yes	N/A	No	No	No	No
Harsh Environment	Yes	Human-limited	Limited	Yes	Yes	Yes
Easy to scale	Very high	High	Low	Yes	Yes	Yes

5.4 AR-Enhanced Vision Inspection

5.4.1 Description

Augmented Reality is a method to extend the perception of the real-world with digital information. This can include multiple sensory modalities, such as haptic, acoustic and visual. Visual augmented reality is the most used and is currently the only relevant modality for the use-cases at hand, so in this section the term "augmented reality" refers to "visual augmented reality".

The augmentation of the real world is achieved by blending the digital content into the user's field-of-view, using different display technologies, these can be either:

- A combination of a display and a camera: these can be hand-held devices such as tablets or smartphones or fixed displays and separate cameras. This mode of augmented reality is referred to as "video see-through".
- A head-mounted display (HMD): this is the most immersive mode of augmented-reality, as it displays the digital content directly into the user's field-of-view. Devices that offer this kind of augmented reality include Microsoft HoloLens or Google Glass. This is usually referred to as "optical see-through".
- A projector, that allows to visualize the digital content directly onto the target scene. This can be a video-projector, as commonly used in (home) cinema or presentations, or more specialized projector, such as a laser projector. This is referred to as "projected augmented reality".

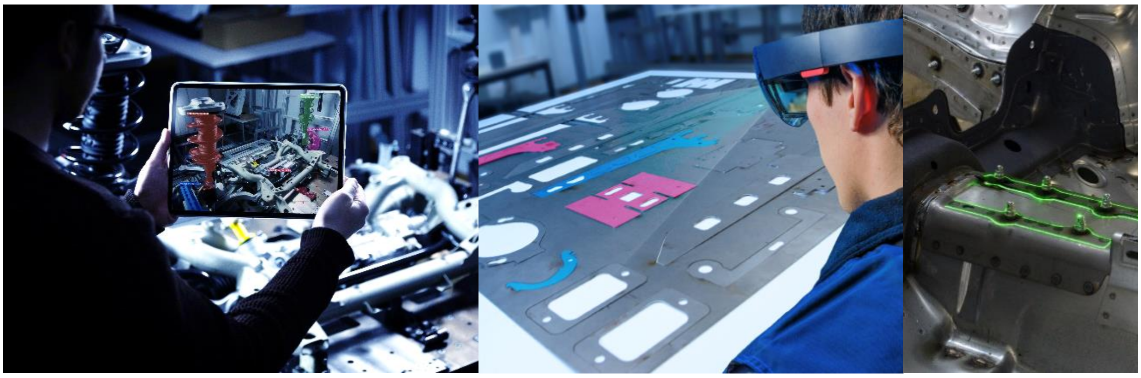

FIGURE 14. THE THREE TYPES OF AUGMENTED REALITY: VIDEO-SEE-THROUGH-, OPTICAL-SEE-THROUGH- AND PROJECTED AUGMENTED REALITY. THE IMAGE FOR PROJECTED AR IS FROM EXTEND3D'S WERKLICHT PRO L[1]

In order to be able to display the digital content with the correct position and orientation in the real world, all these methods of displaying need to be combined with a sensory device, which must be capable of capturing the current state of the real world. If high fidelity is required, this is usually a camera, whose images are then fed into an algorithm that uses them to localize and recognize relevant objects in the scene. The localization

[1] Extend3D GmbH, Werklicht Pro L (Available, accessed on 2022/12/07).

can be supported with other sensory modalities, such as inertial measurement units (IMUs) or a GPS-system.

For industrial quality inspection, augmented reality can be applied in the following ways:

- Display the results of an automated inspection to a user, who is responsible for fixing or evaluating the detected defects.
- Overlay the desired state of the target-object onto the real object, to assist a user in a manual inspection.

This means that augmented reality is not an inspection-solution by itself, but it can be used to assist human beings in tasks that have to be done during the inspection process.

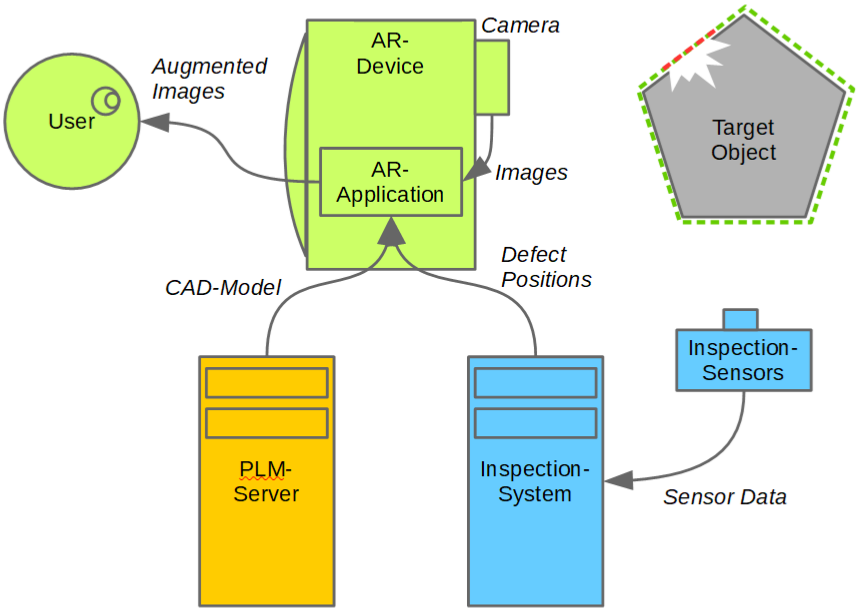

FIGURE 15. SCHEMATIC REPRESENTATION OF AN AR-ENHANCED INSPECTION SYSTEM. THE AR-DEVICE IS USED TO VISUALIZE DEFECTS ON THE TARGET OBJECT. CORRECT POSITIONING OF THE AUGMENTATIONS IS REALIZED BY DETECTING THE TARGET OBJECT IN THE IMAGES BASED ON ITS CAD-MODEL, PROVIDED BY THE PLM-SYSTEM. THIS IS JUST A SAMPLE ARCHITECTURE; THE SPECIFIC ARCHITECTURE OF AN AR-BASED SOLUTION DEPENDS ON THE USE-CASE.

5.4.1.1 State, Maturity and Relevance

With the advent of consumer-grade mobile devices incorporating high-resolution displays, cameras and high computing-power, augmented reality has gained a lot of traction in the last 15 years. Both dominant operating systems for smartphone and tablets, iOS and Android, offer a framework for implementing augmented reality on their devices: ARKit and ARCore, respectively. The success of this technology has furthered the research in this area, leading to even more dedicated augmented-reality hardware being developed, such as Google Glass or Microsoft HoloLens. Standard use-cases these platforms can handle very well include marker-based augmented reality, self-localization by using IMUs or capturing the environment using 2D images or 3D reconstructions. However, a large problem in many augmented reality applications is a fast, accurate and robust markerless scene-understanding, by recognizing and localizing objects of interest. There is currently no one-fits-all solution available on the market for detecting objects in the scene.

The most promising current research direction studies neural networks that have been trained based on CAD-models of the target objects, so they can reliably detect, classify and orient them based on input-images. As an institute for applied science, Fraunhofer IGD tackles this problem by applying current research results in this area into actual industrial use-cases, although not providing an off-the-shelf product enabling augmented reality, but developing custom solutions. These are based on software and hardware building blocks and the employee's expertise, which have been developed throughout the years. Depending on the customers' needs Fraunhofer IGD usually develops solutions with a technology readiness level of 5 to 7, in other words applications that are somewhere between the spectrum of proof of concept and prototypes for mid-term production use.

A scientific survey of the current state of the art of object detection, presenting requirements industrial use cases pose on object detection and an aggregation of current benchmark results of object detectors, is available under [2].

5.4.1.2 Flexibility and Level of Integration

Augmented reality solutions can be integrated in workflows that comprise human action. As it is a technology for assisting human beings, many of the same restrictions apply to its usage as those for manual inspections regarding safety and processing times. Furthermore, the usage of augmented reality as proposed here puts some conditions on the use case. The relevance of each of the following points is highly dependent on the specific requirements, mainly regarding accuracy, robustness and speed. A rough list of conditions that have to be met, so that augmented reality as planned for ZDZW can be a feasible solution for an inspection use case is:

- The CAD-model is available and accurate
- Target objects are neither too occluded, nor transparent, nor too reflective
- Lighting of the target scene is relatively constant and diffuse
- There is enough space to mount cameras and eventually other sensors
- The workplace conditions allow for an AR-device to be integrated. For example, helmets can interfere with head-mounted-displays, hand-held devices can hinder workers, if they need their hands for their tasks, and projectors need to be placed at a certain distance to the target object
- There is enough time to train the neural network with new objects

5.4.1.3 Industrial applications and References

There are several providers that offer augmented-reality-solutions for the industry. Some examples illustrating what can be done with this kind of technology are listed below:

[2] Gorschlüter, F.; et al. (2022), A Survey of 6D Object Detection Based on 3D Models for Industrial Applications, *Journal of Imaging*, Vol. 8:53, ISSN 2313-433X.

- Microsoft's HoloLens [3] is a head-mounted display acting as a platform for augmented reality solutions. The device incorporates a camera and a mobile computer, which take part in object detection and elaborate augmentation for display them in the right places on the display.
- Visometry GmbH[4] is a spin-off based on Fraunhofer IGD's own developments. The main technological basis of VisionLib is an algorithm for model-based tracking. This can be used to track objects in a video feed from frame to frame, after they have been aligned roughly to an initialization pose. Visometry offers two main products: VisionLib as a library for developing custom applications based on model-based tracking. Twyn, an off-the-shelf solution for assisting manual comparison of target and actual state via augmented reality.
- Augment-IT's Inspect AR[5] allows users to record scenes in 3D, annotate them with an authoring tool and then use these annotations in guided processes. However, their technology does not seem to be able to understand scenes in terms of individual objects.
- Extend3D[6] offers solutions for projected augmented reality based on video and laser projectors. The projectors also comprise cameras and their software is capable of detecting object of interest in the captured scene, so that augmentations can projected in the right places.

5.4.1.4 Competitive destructive or non-destructive inspection technologies

Broadly speaking, augmented-reality-based inspection technologies compete with two other inspection methods: manual visual inspection and automated inspection. Here augmented reality falls in between these two, trying to mitigate the disadvantages of manual inspection compared to automated inspection.

The main advantage of manual inspection is flexibility. Human beings are very mobile and adapt much better to unexpected situations than computers. Furthermore, they come with a multitude of moderately accurate sensors (senses) and highly adaptable actuators (hands and feet). Human beings also can be found in most workplaces, so if inspection tasks have to be done occasionally, letting a human perform it can be cheaper than buying highly specialized equipment for automated inspection. Due to the flexibility of human beings, manual inspections in many cases can directly include fixing defects, whereas in fully automated processes finding defects and fixing them usually must be done in two distinct steps, using two specialized machines. To sum up, manual inspection is preferred over automatic inspection in one these two cases:

- The inspection task cannot be automated because it is too complex for a machine to handle
- The inspection task could be automated, but it needs to be done so infrequently that buying a highly specialized machine is not economically viable

[3] Microsoft Corporation, HoloLens (Available, accessed on 2022/12/07).

[4] Visometry GmbH, Homepage (Available, accessed on 2022/12/07).

[5] Augment IT company, Inspect AR (Available, accessed on 2022/12/07).

[6] Extend3D GmbH, Homepage (Available, accessed on 2022/12/07).

As human memory is limited with respect to reliability and space, manual inspection is often supported by documents specifying the inspection process, such as checklists. These can comprise images or textual information and come on paper or in digital form.

Computers, on the other hand, shine when it comes to accuracy and speed. Compared to machines, human beings are very prone to errors and offer a very inconsistent performance, which depends on factors like concentration and motivation. Computers also can perform complex calculations with a high count of variables in fractions of seconds, whereas most humans struggle to keep seven things in their mind at a time.

5.4.1.5 Advantages and Limitations of supplied technology

In contrast to pure manual inspection, augmented reality can assist human beings in inspection processes, by making information more intuitively available and reducing the cognitive load required. As an example, workers having to inspect certain positions of a complex machine do not need to search and transfer textual or schematic descriptions of where and what to inspect on a target object, but they can get the position and additional information directly blended into their field of view. In this way manual inspection can become more accurate and faster.

Compared to non-assisted manual inspection, using augmented reality is limiting regarding mobility and flexibility. Adding one or more devices to a workflow always brings along certain restrictions, which have to be kept in mind when evaluating the feasibility of these solutions. For example, hand-held devices can hinder processes that require workers to use their hands, wearing head-mounted devices for long times can be tiring and all mobile devices are limited by their battery capacity. Stationary setups on the other hand have restrictions regarding the available space and have a decreased mobility compared to just a human being walking around.

Compared to automated inspection, all advantages of manual inspections presented above still apply to manual inspection assisted by augmented reality.

Drawbacks of manual inspection in contrast to automated inspection are mitigated by augmented reality, but generally not fully eliminated. Overlaying the positions to inspect into a worker's field of view mitigates the risk of him or her forgetting inspection steps, but still cannot guarantee that the inspection happens and that it is performed as accurately as an automated system would do the task.

TABLE 46. INSIGHTS OF AR-ENHANCED VISION INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Intermediate	AR can increase the reliability of manual inspection.
Reproducibility	Intermediate	AR can increase the reliability of manual inspection.
Rate of inspection	Intermediate	Workers do not have to refer to documents anymore.
Flexibility	High	Workers can still think and act as in non-assisted inspections.
Mobility	Intermediate	Depends on the use-case. Mobile setups only limit workers a little, stationary setups a lot.

Cost (one-off)	Intermediate	Depends on the use-case. In particular mobile devices are usually comparably cheap.
Cost (ongoing)	Intermediate	In addition to human labour, the maintenance of the AR-system must be paid.

5.4.2 Benchmarking Technologies/Solutions

5.4.2.1 Manual Inspection

Manual inspection means letting a human being perform the inspection, usually assisted by some kind of checklist.

TABLE 47. INSIGHTS OF MANUAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	Low	Human beings are not as reliable as machines.
Reproducibility	Low	Human beings are not as reliable as machines.
Rate of inspection	Low	Compared to computers human beings think and act slowly.
Flexibility	High	Human beings are highly adaptable and equipped for a multitude of purposes.
Mobility	High	Human beings can usually move freely around.
Cost (one-off)	Low	Human beings are usually available in most workplaces.
Cost (ongoing)	High	Salaries are one of the main cost-factors for every company.

5.4.2.2 Automated Inspection

Automated inspection relies fully on machines, for example sensory devices to capture the target object, computers to assess the quality and eventually actuators to react to the result.

TABLE 48. INSIGHTS OF AUTOMATED INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Precision (accuracy and detection efficiency)	High	Machines do not tire and deliver a constant performance.
Reproducibility	High	Machines do not tire and deliver a constant performance.
Rate of inspection	High	Computers can perform complex calculations in fractions of seconds.
Flexibility	Low	Unlike human beings, automated solutions are designed for very specific tasks only.

Funded by the European Union

Mobility	Low	Most machines do not have legs and thus are less mobile than human beings.
Cost (one-off)	High	Specialized inspection-equipment is costly.
Cost (ongoing)	Low	Machines need to be maintained, but these costs are usually negligible compared to salaries.

5.4.3 Summary of the Benchmarks

TABLE 49. COMPARISON BETWEEN AR-ENHANCED VISION INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	MANUAL INSPECTION	AUGMENTED REALITY AIDED INSPECTION	AUTOMATED INSPECTION
Precision (accuracy and detection efficiency)	Low	Intermediate	High
Reproducibility	Low	Intermediate	High
Rate of inspection	Low	Intermediate	High
Flexibility	High	High	Low
Mobility	High	Intermediate	Low
Cost (one-off)	Low	Intermediate	High
Cost (ongoing)	High	Intermediate	Low

Funded by the European Union

6 ZDZW THERMAL INSPECTION TECHNOLOGIES FOR SUSTAINABLE MANUFACTURING

Infrared thermography technology is divided into passive and active (with external stimulation such as pulsed laser, eddy current, etc.) modes. Passive infrared thermography is a detection method based on the relationship between the surface temperature of an object and the intensity of infrared thermal radiation energy generated by the object. In active infrared thermography, the surface temperature of the component is increased briefly with the help of a uniform optical excitation source: infrared lamps, halogen lamps, and hot air guns are used to generate one (or more) thermal pulse(s) on the surface of the components within 2-10 ms.

In IR thermography, an IR camera controlled by a computer (PC) records the surface temperature response due to thermal energy. In a homogeneous material, the transient heat flow from the surface into the component will be uninterrupted. As soon as a thermal discontinuity appears, there is a break in the transient heat flow characteristics, which shows on the surface as a hot or a cold spot, indicating the presence of a foreign body in the bulk of the material or defect. This inhomogeneous heat diffusion on the surface of the part caused by existing defects inside the material is recorded via an infrared (IR) camera. The IR camera receives the emitted infrared waves from the material's surface and converts them into electrical signals and, subsequently, into IR images. Then, the defects can be visualized by analyzing the images through AI algorithms for defect detection and identification. Expansions, voids, inclusions, material loss, and other geometric mistakes can be detected with thermography. Recent improvements in thermal imaging sensors have significantly impacted the minimum size of detectable defects as well as the ability to identify additional deeper features of defects.

ZDZW Thermal Inspection Technologies for Sustainable Manufacturing, foreseen within WP6 activities, will allow to automate the quality control of industrial heat transfer based industrial processes, like plastic thermoforming, package heat-sealing, and metallic tube welding. In this way, the post-production inspection to identify defects, often carried out by human operators through visual or tool-assisted inspection, will be substituted partly or completely by in-line automated thermal inspection AI-enhanced solutions, resulting into 100% reproducible ND controls and recommendations for correction of process parameters, finally reducing waste, repair, and re-working.

6.1 Thermoforming Digital Twin Inspection

6.1.1 Description

Thermoforming is a process in which a heater plastic sheet is converted into a desired shape with a mould. In order to soften the plastic material, a two-level heating operation is executed. Depending on the form of the final product, zonal heating is applied on the piece. Hence, a non-uniform temperature map is created on the surface. This is affecting the material behaviour of the plastic sheet while deforming under the action of the mould. This process can create defects on the final product if the temperature distribution is not properly set during the heating process.

The proposed solution performs an inspection for the defect prediction with the insight from the heating system. Heat transfer calculations performed with FEM (Finite Element Method) and the sensor data collected from the machine are combined with each other to create a tuned Digital Twin of the process. Based on the data of the heating elements, the system offers warnings if there is a possibility of a defect on the final product.

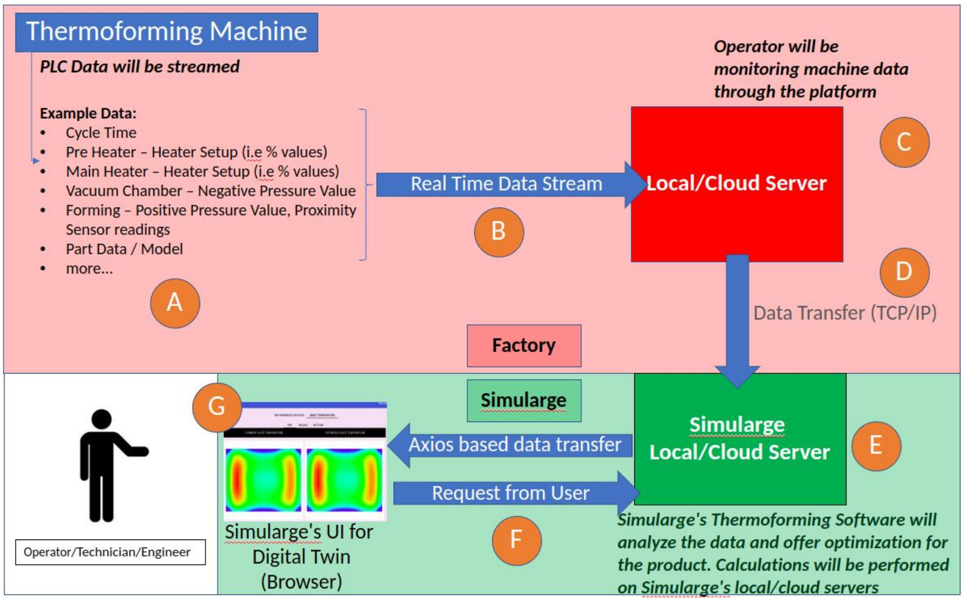

FIGURE 16. HIGH-LEVEL WORKFLOW OF HEAT TRANSFER DIGITAL TWIN

6.1.1.1 State, Maturity and Relevance

For a typical application, representative tests on manually collected data from the thermoforming machine are calibrated into a mathematical model that resolve the radiative heating pattern on the plastic sheet. Heating element array thermal outputs are characterized by their power levels which are set as percentages. These settings are then correlated to temperature values as boundary conditions on the machine. Plastic material's properties are also embedded into the Digital Twin. Geometric setup is arranged dynamically, in other words, if the bounding box for critical components are given, then the mathematical model is automatically adapted to new product or machine.

The mathematical formulations used in the development of Digital Twin are also based on a well-accepted modelling technique. Finite Element Method is a systematic approximation method where partial differential equations are solved in generic shapes. Both steady and time-dependent (i.e., transient) solutions are possible in dimensions ranging from 1D to 3D. Plastic materials exhibit hyper-elastic behaviour under deformation. Several methods including Neo-Hookean or Mooney-Rivlin models are also in use to estimate non-linear deflections.

Main motivation of this system is to reduce the plastic consumption and prevent wastes before happening. This is especially critical for factories where vast amounts of raw materials are consumed. With nearly 50000 tons of plastic material use in its Refrigerator Factory, Arcelik (Pilot 2) is a very good fit for such an inspection system, as 5% of defective amounts cost over 2 million euros every year. On top of that, rework efforts and energy losses due to wasted heating operations should also be included. Hence, a system that prevents the defects and identifies problematic areas before moving to next station on the shopfloor would improve the efficiency significantly. Consequently, it will support the drive into zero defect zero waste movement.

FIGURE 17. A VIEW OF THE HEATING ELEMENT ARRAY AND THE PLASTIC SHEETS

6.1.1.2 Flexibility and Level of Integration

The solution is composed of multiple sub-systems that communicates with each other. These items include the HMI that transmits/gets the action to/from the end users, i.e., the operators. A backend system is used to serve the requests into the main software that performs the real calculations. The backend also collects the data from a middleware. Middle-ware sole purpose is to collect the PLC and sensor data (including the sensors on the machine as well as extra components like thermal camera) and transfer it to the backend. Here, since the systems are separated and working in harmony, adding new sub-modules and extending the capabilities is possible.

Basic level of connectivity to the PLC and data gathering from the external devices, i.e., sensors and thermal camera, is essential for the accuracy of the solution. PLC data is mainly required to understand the heating capacity of the thermal elements on the machine. Safety sensor data is also essential to make sure the system operates within the margins. Thermal camera data will capture a temperature map of the heated plastic surface which will be fed into the main calculator of the Digital Twin. This data will be used to tune the heat transfer parameters. After several test cases and updates, the system will be ready to make predictions on the defect conditions once data from the PLC and thermal camera continue to be monitored.

6.1.1.3 Industrial applications and References

Whenever there is a heating operation, this technology could be leveraged. For instance, industrial furnaces are heavily used to heat/cure ceramics materials, glasses, or metals. Once the mathematical model and geometry definitions of the target equipment is set, then getting the data and training the Digital Twin will not be too much of a deviation from the solution applied here.

FIGURE 18. THE TECHNOLOGY COULD BE ADAPTED FOR INDUSTRIAL FURNACES

6.1.1.4 Competitive destructive or non-destructive inspection technologies

As of now, there are no real automated technologies to detect the defects on the final products for heavy gauge thermoforming. Typical inspection methods include manual checks on the final shape. The visual inspections are performed under the ambient lighting of the factory or behind a light source to guesstimate opaquer (or more transparent) regions if the piece is small. In both scenarios, the accuracy of the inspection is based on the experience of the technician or the machine operator. This is still a laborious process.

Even if some defects on the final form, like tears or holes, are easier to detect with naked eye, their locations might vary. Hence, an operator must look around the part and verify the faulty sections. In this scenario, the detection of the wall thickness is still not possible. To overcome this problem, another manual operation is carried out. With a special device, the predefined critical locations on the shaped form are identified. Then local measurements are performed to estimate the wall thicknesses. The values are compared to best practices for that particular product in respective factory. If the measurements are within the limits on various locations of the part, then the inspection is complete, and the part is released. Since the whole process is manual and time consuming, the inspections are not applied for all products. Typically start and end of a batch is favoured for sampling.

6.1.1.5 Advantages and Limitations of supplied technology

This solution is relatively easy to integrate. It is based on engineering physics so the system can start generating solution even if there is not enough data collection on the behalf of the machine in interest. It is based on several submodules rather than a monolithic solution. Hence, pieces can be updated or extended independently which would increase the capacity of the Digital Twin. The solution can also be further enhanced for new Digital Transformation solution. For instance, what-if scenarios can be run without interfering the production line. That new software could also help the operator to optimize the working parameters, on top of preventing and identifying the defects.

TABLE 50. INSIGHTS OF THERMOFORMING DIGITAL TWIN INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Detection or Prediction	Prediction (Detection)	Defects and thickness can be predicted. Heat transfer anomalies can be detected and used as an input to correct the operation
Simulation capabilities	Yes	Design new product/adjust process parameters (what-if scenarios). If the product dimensions or material properties vary, simulation can still be adapted.
Real-time inspection	Yes	
Reproducibility	High	
Precision (accuracy and detection efficiency)	High	Precision is based both on FEM mesh and on the Thermal Camera resolution. Number of heaters in the machine array is a guideline for lower bound of the granularity
Inspectable features	Surface defects, thickness	
Rate of inspection	High	
Processing time for a piece	30-60 s	Pre-heating, Main heating and Forming stages separately.
Automation	High	
Human interpretation	Yes	
Harsh Environment	Yes	Inside the thermoforming station, temperature values are as high as 500 °C and above
Easy to scale	Yes	Product variants might need some fine tuning of FEM models

6.1.2 Benchmarking Technologies/Solutions

6.1.2.1 Human visual inspection

TABLE 51. INSIGHTS OF HUMAN VISUAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Detection or Prediction	Detection	Visual inspection for holes, tears
Simulation capabilities	No	
Real-time inspection	Medium	For smaller parts, testing can be done for all parts. Light source works with manual labour. For large parts, it is done with sampling
Reproducibility	Medium	Large defects are easier to be detected by different operators. Thickness inspection requires experienced technicians
Precision (accuracy and detection efficiency)	Low	May be mined by operator's fatigue or point of view. Limited in accuracy

Inspectable features	Surface defects, thickness (rough)	Thickness is only roughly estimated through transparency check
Rate of inspection	Limited	
Processing time for a piece	Variable	<1 min for small parts
Automation	No	
Human interpretation	Yes	Would require experience on the operation. New technicians need guidance.
Harsh Environment	Human-limited	Performed after the piece Is produced
Easy to scale	Low	With additional workers

6.1.2.2 Human tool- assisted inspection: Thickness Measurement

TABLE 52. INSIGHTS OF HUMAN TOOL-ASSISTED INSPECTION FOR THICKNESS MEASUREMENT

CRITERIUM	VALUE/LEVEL	NOTES
Detection or Prediction	Detection	Manual measurement for wall thickness.
Simulation capabilities	No	
Real-time inspection	No	
Reproducibility	Limited	If the measurement locations are not fixed, the readings vary
Precision (accuracy and detection efficiency)	Medium	Accuracy is acceptable in measured locations. It is only valid locally, not a global view of the part. Limits based on mm. 0.8, 1.2, 1.4 mm are general limits for different locations.
Inspectable features	Wall thickness	
Rate of inspection	Limited	Select product are tested with sampling. First and last parts produced within a batch are typically selected.
Processing time for a piece	3-5 min	
Automation	Medium	Measurement is performed manually. However, robots can be installed with additional expense to automate the process.
Human interpretation	No	
Harsh Environment	Human-limited	Performed after the piece Is produced
Easy to scale	No	Measurement time is longer than production time

Funded by the European Union

Pepper, D. W., Heinrich, J. C. (2017), *The Finite Element Method*, 3rd edition, ISBN 978-1498738606.

Zienkiewicz, O. C., et al. (2013), *The Finite Element Method: Its Basis and Fundamentals*, 7th edition, ISBN 978-0750663205.

Tshai, K. Y., et al. (2014), Performance of Hyperelastic Material Laws in Simulating Biaxial Deformation Response of Polypropylene and High Impact Polystyrene, *Numerical Modeling of Materials Under Extreme Conditions*, pp. 199-230, ISBN 978-3642542589.

Throne, J. L. (2008), Understanding Thermoforming, 2nd edition, ISBN 978-3446407961.

6.1.3 Summary of the Benchmarks

TABLE 53. COMPARISON BETWEEN THERMOFORMING HEAT TRANSFER DIGITAL TWIN INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	THERMOFORMING HEAT TRANSFER DIGITAL TWIN	HUMAN VISUAL INSPECTION	HUMAN THICKNESS MEASUREMENT
Detection or Prediction	Prediction (Detection)	Detection	Detection
Simulation capabilities	Very high	No	No
Real-time inspection	High	Medium	No
Reproducibility	Very high	Medium	Limited
Precision (accuracy and detection efficiency)	Very high	Medium	Medium
Inspectable features	Surface defects, thickness	Surface defects, thickness (rough estimation)	Wall thickness
Rate of inspection	High	Limited	Limited
Processing time for a piece	30-60 s	Variable	3-5 minutes
Automation	High	No	Medium
Human interpretation	No	Yes	No
Harsh Environment	Yes	Human-limited	Human-limited
Easy to scale	Yes	Low	No

6.2 Thermal Imaging Inspector

6.2.1 Description

Thermal imaging technology uses infrared radiation due to the thermal energy of objects to gather information through images, even in low visibility environments. This technology is based upon the science of infrared energy (heat) which is emitted from all objects. Thermography is the process of converting the infrared (IR) radiation emitted by the surface of bodies as a function of their temperature, according to the black body radiation law, into images depicting the spatial distribution of temperature differences in a scene observed by a thermal imaging camera.

Thermal inspection systems or thermal inspectors using thermal images captured by thermal cameras become the most efficient systems which are used to detect the defects and anomalies in industrial processes such as thermoforming, heat-sealing, chemicals, plastics, etc. In ZDZW project, AI-based thermal imaging inspecting solutions focusing respectively on thermoforming process and heat-sealing process will be developed as different inspection solutions proposed by two distinct technical partners (SIE and SIM). For this reason and also for having a different scope of application (thermoforming control vs heat-sealing control), which means for example that alternative technologies to compare with are significantly different, it was chosen to keep them separate in the content of all sub-sections, introducing each by the solution name in bold, as below.

Thermal Imaging Anomaly Detector for Thermoforming Inspection (Thermoforming Thermal Inspection)

Thermoforming, as the name implies, is the forming of a plastics part by the application of heat and pressure. The thermoforming process involves heating plastic sheets and forming pre-heated flexible materials against a mould’s contours by mechanical and pneumatic tools. After holding a mould’s shape with negative air pressure, the material cools down in the intended form. Due to the high plasticity, curing, and heat allowances of the material, the technique applies only to thermoplastic components, such as the refrigerator's interior body of Arcelor's use case within ZDZW project. The finished surfaces and dimensional precision of a refrigerator's interior body are critical parameters for the product quality. Problems in the thermoforming lead to visible defects in the final product and directly affect customer satisfaction.

The solution proposed by Siemens provides a thermal imaging and anomaly inspector which combines the advanced image acquisition techniques on thermal images and deep learning models to detect anomaly status on the plastic sheet surfaces for thermoforming process. The anomaly detector solution which will be developed during the project will be designed a stand-alone solution and then it will be integrated to Digital Twin application for thermoforming process.

The high-level architecture of thermal anomaly inspector for thermoforming are given in Figure 19.

Funded by the European Union

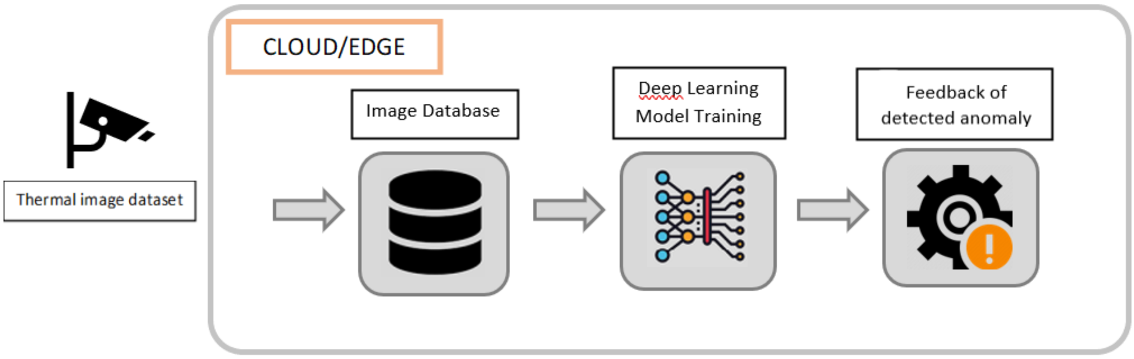

FIGURE 19. HIGH-LEVEL ARCHITECTURE OF AI-BASED THERMAL ANOMALY DETECTION FOR THERMOFORMING

Input data of thermal anomaly detector consists of the real thermal images provided by the thermal cameras and sensors, which will be placed into the thermoforming manufacturing line. The system will generate a notification when the anomaly on the plastic sheet surface is detected. This feedback will feed the Digital Twin application to reconfigure the thermoforming process parameters.

Thermal Imaging for Heat-Sealing Inspection (Heat-Sealing Thermal Inspection)

More than 99% of the heat-sealed products, including food packages and cosmetic cases, are not tested for pack seal integrity. The integrity of the primary package seal is mainly verified by destructive off-line sample testing with no in-line data for process improvement and failure prevention. This approach generates waste and might even be an obstacle when the industry moves towards sustainable packaging (a desired goal for 2025).

In order to enable in-line and real-time control, there is a need for a technology like thermal imaging to monitor the heat-sealing process in a passive manner without slowing the production lines. Monitoring the heat pattern and combining the information with AI technologies allows rejecting unsealed products and raise alerts of processes deteriorations, and by these actions, improving the digitalization of the production line. This is the solution proposed by YORAN within the ZDZW project.

An example of a heat-sealing product is the cosmetic case, filled by a cold cream, and sealed on the top of the tube. The thermal imaging produces a very clear inspection of the sealed strips. Therefore, it is possible to see even invisible defects in the sealing process as well as monitoring the cream filling level. The cream is cold (darker areas), and the seal is hot (lighter areas).

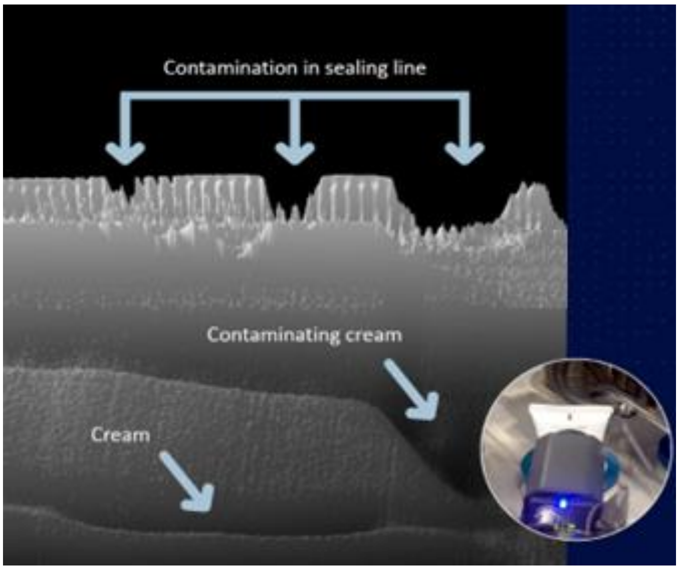

FIGURE 20. THERMAL IMAGING OF A HEAT-SEALED COSMETIC TUBE

Another common case is the flow-pack pouch. In the flow-pack process, the pouch is sealed in multiple areas. A common approach to check the sealing quality is to drain the pouch in a water bath.

With thermal imaging cameras, the 3D profile of the heat-sealing lines can be monitored in detail. The data produced by thermography can be visualised in tables, graphs and dashboards: this analysis can help to signal a trend of process instability in the production line. Detecting and acting on such a trend at an early stage is crucial to reduce waste.

In this way, the combination of thermal imaging with the AI and big data analysis, enables a preventive approach, and allows managers, operators, or other users to prevent failures in the processes and increase the production lines productiveness.

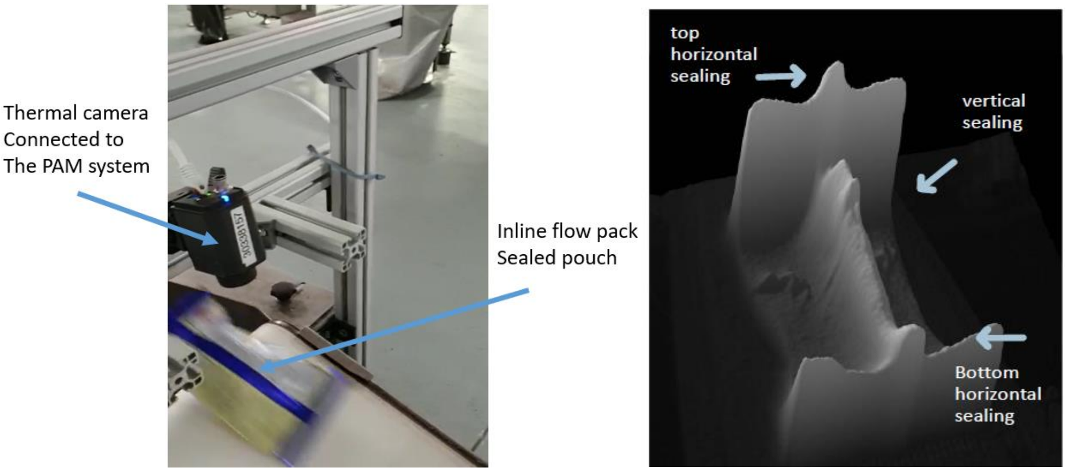

FIGURE 21. THERMAL INSPECTION OF A FLOW PACK POUCH WITH 3D VISUALIZATION

6.2.1.1 State, Maturity and Relevance

Thermoforming Thermal Inspection

Thermography is not a new control system in industrial processes. However, there is no complete inspection solution that integrates a thermography system with the use of artificial intelligence techniques for the detection of anomalies on the surfaces of plastic sheets produced during the thermoforming process.

In recent years, AI-based approaches have been successfully applied in industrial processes, such as quality inspection, fault diagnosis and anomaly detection on manufactured parts. The integration of AI and thermal imaging has great potential to achieve quality inspection and anomaly detection for manufactured hot parts and end products in plastic manufacturing. In this project, the Thermal Anomaly Detector solution combining thermography and AI approaches for thermoforming inspection will be developed to detect defects on manufactured plastic sheets using real thermal image data collected in the thermoforming production line of the Arcelik's refrigerator factory (pilot 2), with the objective to reduce plastic consumption and prevent waste.

Heat-Sealing Thermal Inspection

Products are sealed by heat all over the world for many years already. In the area of human food, animals' food, medications, cosmetics and others, consumers encounter a lot of failures in the heat-sealing process: for these products, open bags can mean bad food taste, defective pills, oxidized or deteriorated material, etc., with all the risks involved. However, due to limitations of human resources, time, money, and other problems, it is impossible to check every product before it is delivered to the customer. These reasons, but not only, point to the relevance of application of thermal imaging to monitor the quality, the level, and every aspect of the heat-sealing process.

During the last few years, considering the impact reported on the monitored lines, together with the growth of AI and classification models abilities, thermal imaging seems to be a promising technology for controlling heat-sealing production lines. The technology provides sufficient amount and type of data to analyse and help preventing waste and defects.

6.2.1.2 *Flexibility and Level of Integration*

Thermoforming Thermal Inspection

Thermal Anomaly Detector solution for Thermoforming inspection is composed of the image acquisition modules utilizing the real thermal image data collected in thermoforming production line, AI models and the interfaces which provide the interoperability with other modules and systems. Image dataset will gather from the external devices such as thermal cameras and sensors which are placed in thermoforming line. The system will monitor the thermal images on the heated and vacuum-formed plastic sheets to detect the defects, identify the anomaly on the produced plastic sheets. The system will also provide the feedback to Digital Twin application when anomaly started to achieve the semantic interoperability with Digital Twin solution which will be implemented for thermoforming process monitoring.

Heat-Sealing Thermal Inspection

Thermal Imaging solution to control heat sealing integrity is very flexible. Integrating a thermal camera on existing lines is a flexible procedure. Thermal imaging systems can integrate to the following filling and sealing machines: Flow pack (horizontal and vertical), sachet (horizontal and vertical), tubes, cups, trays, blisters, induction sealed bottles (through the plastic cap). The laminates can be made of aluminium/plastic, aluminium, plastic, plastic /paper, paper, bio – plastic.

The integration of the proposed solution is very simple and already done as Plug-And-Play with a few of the most common manufacturers to the lines today, such as:

- Mespack
- Ishida
- Bosch
- Wolf
- Tna
- Rovema
- Mediseal
- Volpack
- Thiele

6.2.1.3 *Industrial applications and References*

Thermoforming Thermal Inspection

Thermal imaging plays a key role in medical, military and industry applications. Therefore, thermal image processing combined AI-based approaches is considered as very essential research area to analyse and interpret thermal images with high-accuracy for automation in industry. In this project, Siemens will develop an AI-based thermal imaging and anomaly detection solution with the integration of the thermal camera, image processing techniques and AI approaches detect the defects and anomalies of the produced parts. The system will also provide the feedback when anomaly detected by APIs and interfaces to Digital Twin to reconfigure the thermoforming process parameters.

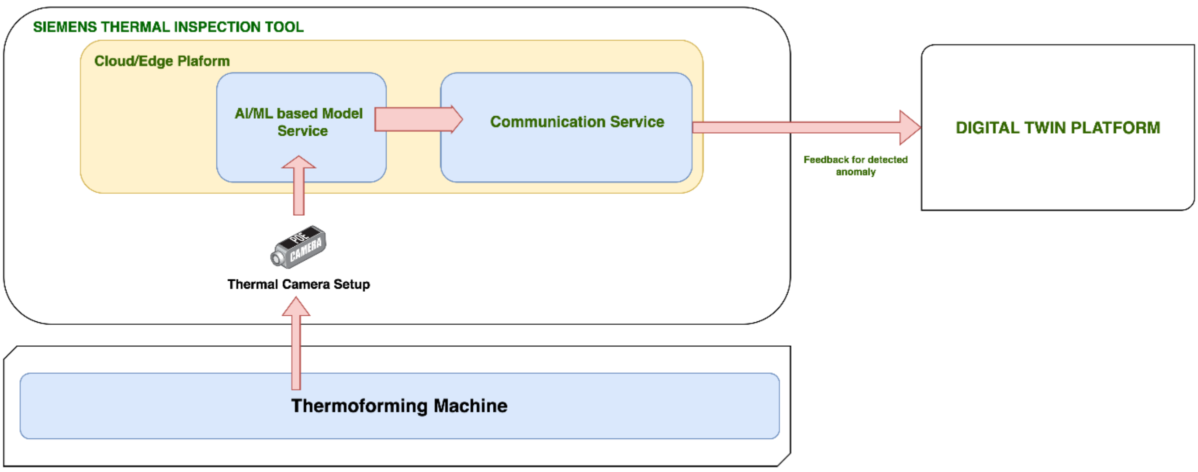

FIGURE 22. AI-BASED THERMOFORMING INSPECTION TOOL

Heat-Sealing Thermal Inspection

Thermal imaging enables to visualize the heat-sealing process, generate digitized data, apply inline algorithms, including AI models. This enables to reject in real time unsealed products, to raise alerts monitoring real time process trends in the process and to prevent future failures by applying AI technologies.

This technology for heat-sealing control is already under use in different industrial sectors like of human food, animals' food, medications, cosmetics and wherever it is necessary to perfectly seal a good to prevent its deterioration.

6.2.1.4 Competitive destructive or non-destructive inspection technologies

Thermoforming Thermal Inspection

There are currently not available thermal inspection automation solutions to detect the defects on the shaped product during thermoforming process. The only inspection method is manual check of the plastic sheets by machine operator in the production line after the process has been completed. Visual inspections or manual inspections based on the experience of the operator are performed to inspect the defects on the plastic sheets surfaces. Due to the inability to detect defects with high accuracy, it causes production stoppage and scraping of formed plastic sheets. The competitive advantages with SIEMENS thermal inspection solution can be listed as: ensuring 100% inline inspection, absence of slowdowns in continuous production, integration of advanced thermal image processing, analysis of detects and detection of anomaly on plastic sheets in real-time, communication services supporting feedback mechanism to Digital Twin implementation in case of anomaly detection.

Heat-Sealing Thermal Inspection

Currently, in the packaging industry, to perform quality control procedures to ensure packages are sealed, the first step is sampling: only a small fraction of a batch is taken. Valid conclusions overall cannot be based on tests which have been carried out on non-representative samples. Correct sampling is thus an essential part of a system of Quality Assurance.

Most sampling procedures involve the selection of a random sample (or samples) from a multitude of items, the inspection or analysis of the sample, and the classification of the batch (as 'acceptable' or 'not acceptable') based upon the result of the inspection or analysis of said sample.

Once the samples are chosen, the operators perform different tests on them depending on the sample's materials:

- Sachets and pouches containing gas: The residual oxygen test of small volume package is performed with headspace gas analysis method. The oxygen inside the package is tested with a headspace gas analyser equipped with oxygen sensor. This method requires a minimum quantity of 5 ml for the sampling volume of test gas at standard atmospheric pressure so more than one package is needed to meet such requirement. It is not passive; force is applied, and the product might be damaged. There is also no feedback how to improve the process to overcome the leakage problem and no big data analysis.
- Water bath: The package is pressurised under water, either by squeezing the package by hand or by establishing a vacuum in the water container. A leak can then be detected by bubbles escaping through the leak due to overpressure in the package. The test is often performed with the same frequency as the head space test. The problem with the water bath method for industrial use is that it is manual and thus it is difficult to repeat the testing conditions. Bubbles being detected during one test might not be discovered during the next test, even if the leaks are the same. Another problem is the discovery of the leak as bubbles from small leaks

can be difficult to see. In other words, the quality of the water bath method highly depends on the person performing it and tested packages are difficult to reuse. There is also no feedback how to improve the process to overcome the leakage problem and no big data analysis.

- Tracer gas into modified atmosphere packs to detect leaks: this test can be performed with Hydrogen or Carbon dioxide. The pack needs to contain around 3% hydrogen, and this can then be reliably detected down to around 10 parts per million in the atmosphere around the pack to indicate a leak. Carbon dioxide has also been used to detect leaks because it is already a part of many modified atmospheres, but as it is always present in the air it can lead to false positives. There is also no feedback how to improve the process to overcome the leakage problem and no big data analysis.
- Carbon dioxide-sensitive labels: These labels create a colour change in a pigment when it is in the presence of carbon dioxide. A correctly packaged modified atmosphere package will have a label of a certain colour, if the package is leaking and the modified atmosphere escapes, the colour will change to indicate that the pack is leaking. There is also no feedback how to improve the process to overcome the leakage problem and no big data analysis. While these procedures are enough to identify defects in the selected packages, they cannot identify the defects of packets that were not included in the sample. Therefore, it is assumed the patterns hold across a larger range of products.

Nonetheless, these assumptions are made intuitively rather than based on data. There is no way for the quality control procedure to understand root causes of packaging failure or analyse the heat-sealing process.

6.2.1.5 Advantages and Limitations of supplied technology

Thermoforming Thermal Inspection

Thermal anomaly detector for Thermoforming inspection solution presents many advantages to control the quality defects on the produced plastic parts and to monitor Thermoforming manufacturing process.

Currently, quality checks on the product are performed as manual controls by operators in the Thermoforming production line. These controls have already been described in Section 6.1.1.4 with their tables in 6.1.2. For this reason, the content of the table below is summarized in 6.1.3 rather than in the Summary of Benchmarks of this 6.2 section, where only the Thermal Heat-Sealing inspection and its related alternative inspections will be reported.

TABLE 54. INSIGHTS OF THERMOFORMING THERMAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Detection or Prediction	Detection	Classification of surface defects
Simulations capabilities	No	
Real-time inspection	Yes	
Reproducibility	High	
Precision (accuracy and detection efficiency)	Very High	High accuracy detection of defects

Inspectable features	Surface defects	
Rate of inspection	High	
Processing time for a piece	< second	Variable with thermal image resolution, shape complexity and angle of thermal cameras
Automation	Yes	
Harsh Environment	Yes	Inside of thermoforming station, temperature values are as high as 500°C and above. The space that thermal cameras will place is narrow.
Easy to scale	Yes	

Heat-Sealing Thermal Inspection

Thermal Imaging has is the most advanced and disruptive system and method to assess the quality of the heat seal for different kinds of packaging by using thermal images and machine learning algorithms. It enables to evaluate the quality of the heat-sealing process by applying advanced real time image processing algorithms on the sealing pattern, performing a 100% inline inspection. The system can also detect whether there is a trend so the user can reset the sealing parameters before a defective package is produced. This predictive maintenance can reduce cost and reduce waste to the packaging site.

The main added value is the passive approach of the method, without any slowdown of the production rate and the ability to give feedback to the sealing machine to control and optimize the heat-sealing process.

TABLE 55. INSIGHTS OF HEAT-SEALING THERMAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Detection or Prediction	Detection and prediction	Can detect unsealed products, alert on real time trends in the process and predict process failures
Real-time inspection	Yes	Easy to connect to existing lines, and existing rejectors
Reproducibility	High	
Precision (accuracy and detection efficiency)	High	Thermal imaging monitors the heat-sealing process. it is not a leakage detector. The correlation between these two is high but not perfect.
Inspectable features	Sealing defects, process failures	If there is a direct line of sight to a sealing line about 2 seconds from the sealing process the thermal and spatial resolutions are high
Rate of inspection	High	Up to 120 products per minute and potentially targeting up to 350 sealing phases per minute.
Processing time for a piece	< second	About 0.1 second
Automation	Yes	This is one of the main advantages since it replaces the manual process of sampling water bath tests with no inline automated procedure.

Funded by the European Union

Harsh Environment	Yes	The thermal camera can be equipped for IP67 requirements, and the control cabinet can be located few meters from the production line.
Easy to scale	Yes	Since the system is added on existing lines it is easy to scale up

6.2.2 Benchmarking Technologies/Solutions

6.2.2.1 Water bath immersion testing

TABLE 56. INSIGHTS OF WATER BATH TESTING SOLUTION

CRITERIUM	VALUE/LEVEL	NOTES
Detection or Prediction	Detection	Detects offline by sampling, no prediction
Real-time inspection	No	Offline inspection
Reproducibility	High	
Precision (accuracy and detection efficiency)	High	High accuracy of sealing issues but is based on Offline sampling
Inspectable features	Sealing defects	It is a direct sealing integrity test but cannot detect weak sealing and cannot work with paper-based laminates
Rate of inspection	Low	Offline sampling, less than 1% from the production line
Processing time for a piece	About one minute	
Automation	No	Manual process
Harsh Environment	Yes	
Easy to scale	No	It is impossible to calibrate air bubbles

6.2.2.2 Gas leak test

TABLE 57. INSIGHTS OF GAS LEAK TESTING SOLUTION

CRITERIUM	VALUE/LEVEL	NOTES
Detection or Prediction	Detection	Requires gas in the package
Real-time inspection	No	Offline inspection
Reproducibility	High	
Precision (accuracy and detection efficiency)	High	
Inspectable features	Sealing defects	It is a direct sealing integrity test but cannot detect weak sealing and cannot work with paper-based laminates
Rate of inspection	Low	Offline inspection
Processing time for a piece	Few minutes	
Automation	No	
Harsh Environment	No	Needs sterile environment

Funded by the European Union

Easy to scale	Yes	

Banús, N., et al. (2021), Deep learning for the quality control of thermoforming food packages, *Scientific Reports*, Vol. 11, 21887, ISSN 2045-2322.

Leite, W.D.O., et al. (2018), Vacuum-Thermoforming Process: An approach to modeling and optimization using artificial neural networks, *Polymers*, Vol. 10:2, ISSN 2073-4360.

Li, Y., et al. (2019), Rotating machinery fault diagnosis based on convolutional neural network and infrared thermal imaging, *Chinese Journal of Aeronautics*, Vol. 33:2, Pages 427-438, ISSN 1000-9361.

6.2.3 Summary of the Benchmarks

TABLE 58. COMPARISON BETWEEN HEAT-SEALING THERMAL INSPECTION AND DEFINED ALTERNATIVES

CRITERIUM	HEAT-SEALING THERMAL INSPECTION	WATER BATH IMMERSION TESTING	GAS LEAK TEST
Detection or Prediction	Detection and prediction	Detection	Detection
Real-time inspection	Yes	No	No
Reproducibility	High	High	High
Precision (accuracy and detection efficiency)	High	High	High
Inspectable features	Process failures	Sealing defects	Sealing defects
Rate of inspection	High	Low	Low
Processing time for a piece	< second	About one minute	Few minutes
Automation	Yes	No	No
Harsh Environment	Yes	Yes	No
Easy to scale	Yes	No	Yes

Funded by the European Union

6.3 Welding Process Inspector

6.3.1 Description

The final objective of the Welding Process Inspector is to reduce the costs of inspecting metal joint welds by monitoring the process and warning about the possible presence of defects during the welding process itself. In addition, it also aims to contribute to the Digital Twin of a welded component by providing information from the actual manufacturing process, i.e., digitising the monitored welding parameters. To that ends, it is necessary to implement an online monitoring system capable of collecting real data during the welding process. The system must merge and synchronize (temporally and spatially) data from heterogeneous sensors integrated in the welding cell, giving information on the actual values of relevant parameters such as current and voltage on the welding point or wire feed speeds. The result is an accurate digital representation of the actual welding process.

The aforementioned "real-process" Digital Twin enables the cross-comparison between the real parameters of the welding and the results from any other inspection techniques (Destructive Testing and NDT) or even simulations (e.g., FEM). The new knowledge generated after this correlation is useful to implement online analysis algorithms on the process monitoring system to launch early warnings when the process is not running as expected, resulting in early defect detections or even preventing the appearance of those defects by detecting the wear of any element of the welding infrastructure, for instance[1].

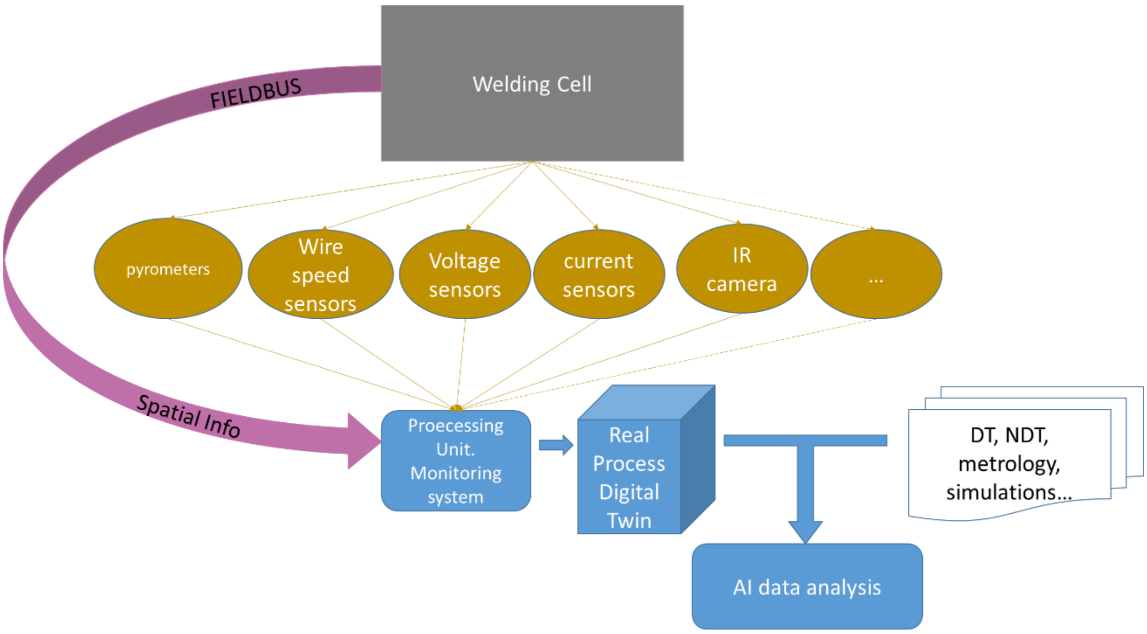

FIGURE 23. SCHEMATIC REPRESENTATION OF PROPOSED WELDING PROCESS MONITORING SYSTEM AS NDI TECHNOLOGY

[1] Fernández, A., et al. (2020), Embedded vision system for monitoring arc welding with thermal imaging and deep learning, *2020 International Conference on Omni-layer Intelligent Systems (COINS)*, pp.1-6 (Available, accessed on 2022/12/07).

6.3.1.1 State, Maturity and Relevance

Online process monitoring on welding is not an innovative idea, however generally welding machine OEMs do not share process information, or they do it partially. So, if it is needed to take a deep insight on the welding process, usually a manufacturing company must envision and deploy its own data acquisition system, which involves sensor integration, interface, connectors to fieldbuses or other networks, a reliable synchronization procedure and HW selection. Furthermore, the challenge also resides in data storage, handling and, especially, processing, since the lack of standardization on file formats, for instance, usually leads to in-house SW developments to visualize and process the monitored data. After the implementation of the monitoring system, an extensive work must be carried out, first gathering data from the sensors and then analysing it together with the manufacturing results (quality inspections), before getting a deep knowledge about the process and start optimizing the process based on the new data

Regarding a production point of view, real-time process monitoring is relevant since the occurrence of a defect during welding, which usually remains undetected until required inspections, leads to a high time-consuming rework stage. In some cases, reworking is a situation under arduous and complex conditions for the operator, especially for big welds on huge parts, like in wind turbine towers of pilot 3 of ZDZW project. A welding process monitoring system can be used to early detect abnormal behaviour during the welding that could lead to the appearance of defects on the welded seam. Early detection of possible defects enables an early reaction, contributing to a reduction of rework time and extra inspection iterations and therefore, reducing considerably the manufacturing costs.

FIGURE 24. THE TIME NEEDED TO REPAIR A SECTION WITH A REFERENCE LENGTH OF 1 M AND 20 MM DEPTH IS ESTIMATED TO BE BETWEEN 6-12 HOURS IN GRI USE CASE

6.3.1.2 Flexibility and Level of Integration

Monitoring hardware must be interoperable with the existing welding machine and positioner by integrating communication capabilities (Fieldbuses, digital/analogue input-outputs) to read data from machine controllers and sensors. External sensors (e.g., high-current probes, high-speed oscilloscope) have to be integrated into the welding cell to monitor process parameters (current, voltage, wire speed…). Devices like IR thermal cameras and pyrometers can be useful to capture the thermal distribution in the affected area. Finally, the monitoring SW must be scalable enabling an easy integration of any new possible sensor installed on the welding cell.

In a holistic perspective, it seems important to point out that online monitoring systems also contribute to the digitalization of industry, being the first step and a fundamental pillar towards getting a digital representation of the industrial process[2]. After a deep analysis and proper processing, data coming from a process-monitoring infrastructure can be useful not only for welding or product inspection and quality control tasks, but for many other different aspects and purposes, such as predictive maintenance, process optimization, adoption of advanced closed-loop control strategies, etc.

6.3.1.3 Industrial applications and References

The proposed monitoring system is multi-modal, so it is able to synchronize data from different sensors, fieldbuses or communication protocols, which may differ in data format, size and sampling frequency. This feature makes it easily adaptable for different industrial processes. For instance, this technology can be applied to any metallic and non-metallic welding process, cladding or even Additive Manufacturing (AM) processes in a relative straightforward way, but could also fit any other manufacturing process where the temporal and/or spatial synchronization of data from heterogeneous sensors is required.

FIGURE 25. AM IS A CLEAR EXAMPLE OF INDUSTRIAL APPLICATION WHERE THE PROCESS MONITORING APPROACH IS INTERESTING[3].

6.3.1.4 Competitive destructive or non-destructive inspection technologies

The most common inspection techniques in welding processes are classic and phased-array Ultrasonic Testing, eddy current testing, X-rays testing, penetrant liquids and human visual inspection. However, it is important to point out that process monitoring is not a proper inspection technology and cannot substitute them. Detection of defects using monitored data is an indirect and predictive way to do the task, since a relevant amount of monitored data and data resulting from the respective inspections is needed to find the correlations between the monitored data and the defects appearance.

[2] Natesha, B. V., Guddeti, R. M. R., Fog-Based Intelligent Machine Malfunction Monitoring System for Industry 4.0, *IEEE Transactions on Industrial Informatics*, Vol 17, 12, pp. 7923-7932, ISSN 1551-3203

[3] INTEGRADDE project introduces virtual and digital twins of DED process (Available, accessed on 2022/12/07).

6.3.1.5 Advantages and Limitations of supplied technology

The proposed online process monitoring system cannot substitute any traditional destructive nor non-destructive inspection method, such as UT, eddy current, penetrant liquids, metallographic images, because it is not an inspection method in the strict sense. As aforementioned, the detection of anomalies is achieved indirectly by correlating the monitored data and data from actual inspection procedures. In this sense, the welding process inspector is highly dependent on the specific welding process (materials, process parameters, etc.) and on the monitoring setup (specific sensors, data collection infrastructure, etc.).

On the other hand, the approach of the proposed system seeks to reduce the number of required inspections and decrease repairing time. Once there is enough monitored and inspected data, data models or detection algorithms can be developed and implemented on the online Welding Process Inspector system. This SW will allow warning operators about abnormal behaviour during the welding process, anticipating the possible appearance of defects and enabling the early application of corrective measures to avoid or fix those defects. This way, the reworking/repairing time, the number of required inspections and, eventually, the manufacturing costs are reduced considerably.

TABLE 59. INSIGHTS ON WELDING PROCESS INSPECTOR

CRITERIUM	VALUE/LEVEL	NOTES
Real time	Yes	Possibility of alert about the presence of defects **during** the welding process.
Time consumption	Very low	Results are obtained just after welding.
Automatable	Yes	
Flexibility	Very High	Suitable for different welding techniques. New sensors can be added to monitor different process parameters.
Precision	Low/Medium	To be specified during project. Possibly not such good as traditional NDT techniques.
Scalability	High	-
Digital output	Yes	Contributes to the industrial digitalization (e.g., generates inputs for product Digital Twin)
Human interpretation	No	A skilled operator can interpret the data, but the goal is to automate the defect detection.
Self-calibration	No	Sensors must be adjusted once and checked periodically.

Funded by the European Union

6.3.2 Benchmarking Technologies/Solutions

6.3.2.1 Ultrasonic Testing

TABLE 60. INSIGHTS ON ULTRASONIC TESTING

CRITERIUM	VALUE/LEVEL	NOTES
Real time	No	Takes place after the welding process and results must be interpreted.
Time consumption	High	High inspection speed, off-line inspection, human-interpreted results.
Automatable	Yes	Automated solutions are very specific and require relevant investment.
Flexibility	High	
Precision	Very high	
Scalability	Very high	-
Digital output	Yes	
Human interpretation	Yes	A skilled operator is needed.
Self-calibration	Yes	Sample to sample self-calibration of signals on Guided Waves.

6.3.2.2 Eddy Current

TABLE 61. INSIGHTS ON EDDY CURRENT INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Real time	No	Takes place after the welding process and results must be interpreted.
Time consumption	High	High inspection speed, off-line inspection, human-interpreted results.
automatable	Yes	
Flexibility	Medium	
Precision	Very high	
Scalability	Very high	
Digital output	Yes	
Human interpretation	Yes	A skilled operator is needed.
Self-calibration	No	

6.3.2.3 X Ray

TABLE 62. INSIGHTS ON X-RAY INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Real time	No	Takes place after the welding process and results must be interpreted.
Time consumption	Very high	High inspection speed, off-line inspection, human-interpreted results.
Automatable	No	
Flexibility	Very high	Suitable for a great variety of welding techniques, materials, geometries, defects…
Precision	High	
Scalability	Low	

Funded by the European Union

Digital output	Yes	
Human interpretation	Yes	A skilled operator is needed.
Self-calibration	N/A	

6.3.2.4 Penetrant Liquids

TABLE 63. INSIGHTS ON PENETRANT LIQUIDS INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Real time	No	Takes place after the welding process and results must be interpreted.
Time consumption	Medium	High inspection speed, off-line inspection, human-interpreted results.
Automatable	No	
Flexibility	Medium	Suitable welding techniques, geometries… Detects superficial defects.
Precision	Medium	
Scalability	N/A	-
Digital output	No	
Human interpretation	Yes	
Self-calibration	N/A	

6.3.2.5 Human Visual Inspection

TABLE 64. INSIGHTS ON HUMAN VISUAL INSPECTION

CRITERIUM	VALUE/LEVEL	NOTES
Real time	No	Takes place after the welding process and results must be interpreted.
Time consumption	Medium	
Automatable	No	
Flexibility	High	
Precision	Medium	Depends on the inspector, some defects cannot be identified
Scalability	N/A	-
Digital output	No	Contributes to the industrial digitalization (e.g., generates inputs for product Digital Twin)
Human interpretation	Yes	
Self-calibration	N/A	

6.3.3 Summary of the Benchmarks

TABLE 65. COMPARISON BETWEEN WELDING PROCESS INSPECTOR AND DEFINED ALTERNATIVES

CRITERIUM	PROCESS MONITORING	ULTRASONIC TESTING	EDDY CURRENT	X-RAYS	PENETRANT LIQUIDS	HUMAN VISUAL INSPECTION
Real time	Yes	No	No	No	No	No
Time consumption	Very low	High	High	Very high	Medium	Medium
Automatable	Yes	Yes	Yes	No	No	No
Flexibility	Very high	High	Medium	Very high	Medium	High
Precision	Low/Medium	Very high	Very high	High	Medium	Medium
Scalability	Very high	Very high	Very high	Low	N/A	N/A
Digital output	Yes	Yes	Yes	Yes	No	No
Human interpretation	No	Yes	Yes	Yes	Yes	Yes
Self-calibration	No	Yes	Yes	N/A	N/A	N/A

Funded by the
European Union

7 CONCLUSIONS

An all-round analysis of all ND inspection technologies involved in the ZDZW project along with their competitive ones was completed, enhancing the knowledge and awareness of partners which will take place in the three work packages of Part Integrity Evaluation, Visual Inspection and Thermal Process Monitoring.

The inspection technologies developed and integrated during the project proved to be sustainable, innovative and aligned with ZDZW philosophy: they will improve process monitoring with the added bonus of reducing the number of flawed products and wasted resources.

Information sourced from academic and professional literature and gathered from partners' experience was then used for establishing benchmarks between the proposed inspection technologies and their alternatives in the same field.

Most of the technologies which will be implemented are automatable and enable the inspection of the total fraction of the items running on the production lines, improving in terms of ZD and ZW the results of the sampling and/or off-line tests, to which the alternative technologies identified are often limited. This aspect, which also makes possible to avoid or reduce the use of human resources (hired for direct human inspection or for the handling of destructive sampling techniques), is confirmed by the analysis of the industrial scenarios for the project pilot cases carried out in depth in deliverable D2.3.

The following table summarizes all the alternative technologies taken into consideration and highlights the commonalities or contamination between the different partners' proposed inspection techniques, even between different work packages.

Funded by the
European Union

TABLE 66. ZDZW INSPECTION TECHNOLOGIES AND ALTERNATIVES ANALYSED

	WP4: INTEGRITY				WP5: VISION				WP6: THERMAL		
Benchmark technologies	Mechanical Hardness DT	Acoustic Emission	MIR-OCT System	EMAT Ultrasonic	Volumetric Inspection	Surface Anomaly Det.	AI-enhanced Artificial Vis.	Augmented Reality Insp.	Thermo-forming DT	Thermal Inspection	Welding Process DT
Barkhausen Emission	x										
Ultrasonic Testing	x	x	x								x
Eddy Current	x	x		x							x
Leeb rebound	x										
Vibration testing		x									
Liquid Penetrant		x									x
THz Imaging			x								
X-ray (CT)			x	x							x
Thermographic Imaging			x								
Piezo Ultrasonic Test				x							
ND Human Visual Insp.					x	x	x		x		x
Human tool-assisted I.					x	x			x		
Automated CMM					x		x				
Laser Scanners					x	x	x				
Industrial Sieving I.					x						
Structured Light							x				
Photogrammetry							x				
Manual Inspection								x			
Automated Inspection								x			
Water Immersion										x	
Gas Leak test										x	

Funded by the
European Union

CHANGE LOG

VERSION	DESCRIPTION OF CHANGE
V0.0.0	First table of contents provided by VSYS
V0.0.1	Complete draft for internal Reviewer 1
V0.0.2	Complete draft for internal Reviewer 2, after reaction to comments from Reviewer 1
V0.0.3	Complete draft for final check before submission, after reaction to comments from Reviewer 2
V1.0.0	Submitted version

Funded by the
European Union