



Electrification of industrial processes using induction and microwaves technologies

D4.5

Health and Safety Requirements – update M18

ISQ, K-FLEX and ARTIGO

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Abbreviations

AC	Alternating Current
ALs	Action Levels
DC	Direct Current
ELF	Extremely low-frequency
EMC	Electromagnetic compatibility
EMF	Electromagnetic fields
ELVs	Exposure limit values
H&S	Health and Safety
HVAC	Heating, Ventilation, and Air Conditioning
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IPT	Inductive Power Transfer
OEL	Occupational Exposure Limits
PPE	Personal protective equipment
PWM	Pulse Width Modulation
RMS	Root Mean Square
SOPs	Standard Operational Procedures
VFDs	Variable-frequency drives

Executive Summary

The JOULIA project (ID 101192555) aims to demonstrate advanced electric heating solutions to support industrial decarbonisation through the design and development of induction- and microwave-based heating systems. The demonstration campaign will validate their technical feasibility and assess their environmental, health, safety and economic impacts. The upscaling activities focus on two industrial processes: rubber flooring vulcanisation and adhesive gluing.

Task 4.3 – Health and Safety Requirements (WP4) purposes to identify the health and safety (H&S) requirements for the induction and microwave heating systems, based on the analysis of relevant standards, regulations and guidelines; H&S good practices for the safe design, installation, operation and maintenance of the equipment; and the H&S challenges, critical factors, perceptions and needs associated with the adoption of the innovative technologies developed within JOULIA. This task is structured into two deliverables:

- **D4.3 – Health and Safety Requirements – Preliminary Report** (M12), which provides an initial analysis of each heating technology, describing their operating principles, associated hazards and risks, and potential prevention measures. It also reviews applicable standards, regulations, guidelines and recommendations, with particular emphasis on electromagnetic fields (EMF), which are relevant to both technologies.
- **D4.5 – Health and Safety Requirements – Final Report** (M18), which focuses on the conceptual and design aspects of the induction and microwave heating systems for the two demonstrators (ARTIGO and K-FLEX). It considers the technical specifications of both technologies under development in JOULIA to deliver the final health and safety requirements for the rubber flooring vulcanisation and adhesive gluing case studies.

The submission of this deliverable is done in accordance with the description in the Grant Agreement Annex 1 Part A with no time and no content deviation from the original plan.

1 Introduction

1.1 Purpose and scope of D4.5

This deliverable (**D4.5**) builds upon the preliminary assessment presented in **D4.3**, which analysed the operating principles of induction and microwave heating systems, identified associated hazards and risks, and reviewed relevant standards, regulations and guidelines, including those related to electromagnetic fields (EMF).

D4.3 established the technical and regulatory foundation for understanding the health and safety implications of these technologies, providing a detailed examination of their physical principles, operational characteristics, and the factors influencing heating efficiency, penetration depth, dielectric behaviour and process stability. It also highlighted the advantages and limitations of each technology in the context of industrial electrification, as well as the main occupational hazards—EMF exposure, electrical shock and burns, fire and explosion risks, and exposure to fumes and airborne particulates—emphasising the influence of workplace layout, operator proximity and task duration.

The preliminary deliverable further included a comprehensive review of Directive 2013/35/EU [1], ICNIRP recommendations [2], IEEE C95.1-2019 [3] and relevant IEC standards, clarifying applicable exposure limits and the predominance of short-term thermal and neuromuscular effects in the regulatory landscape. It also summarised good practices for EMF assessment, including measurement strategies, workstation design considerations, scenario-based exposure modelling and mitigation measures such as workplace reorganisation, procedural redesign and targeted training. Overall, D4.3 concluded that general exposure limits alone are insufficient, and that realistic, scenario-specific assessments are essential to characterise worker exposure and implement effective preventive measures.

Building on this foundation, the present deliverable (**D4.5**) advances the analysis by focusing on the real industrial environments of the JOULIA demonstrators (ARTIGO and K-FLEX). Its objective is to assess worker exposure to EMF in the current production lines, prior to the integration of the new induction and microwave systems, to establish a baseline risk profile and evaluate the potential impact of the technologies developed within the project.

To support this assessment, a monitoring methodology was developed based on the standards and regulatory frameworks reviewed in D4.3, ensuring compliance with Directive 2013/35/EU, ICNIRP guidelines and IEC/IEEE technical standards. The methodology integrates:

- Analysis of questionnaires completed by operators and supervisors to capture perceptions, practices and operational constraints.
- Qualitative and quantitative EMF measurements in the demonstrators' facilities.
- Field observations to characterise realistic exposure scenarios.

This deliverable consolidates these findings and translates them into the final health and safety requirements for the JOULIA technologies, providing the baseline necessary for a future before-and-after comparison of EMF exposure. This comparison will be carried out once the induction and microwave heating systems are installed and demonstrated in Task 13.3 – Regulatory and standardization barriers (WP 13), supporting safe system design, installation and operation in the two industrial case studies.

In addition to its analytical scope, this deliverable incorporates a preliminary Health & Safety implications analysis of the conceptual designs for the induction and microwave systems that are currently available. This includes the initial inputs from D5.1, D5.2 and D5.3 for the induction system, and from D6.1 and D6.2 for the microwave system. As several of these technical deliverables are still under preparation or pending submission, the integration of their complete design information will be carried out in a subsequent update of D4.5, ensuring full alignment with the final system specifications.

1.2 Relation to other project activity

Table 1.1: Relation to other project activities.

Work Package (WP) or Task	Relation to other project activities
WP4 – Baseline assessment and requirements definition	In this Deliverable, the main outputs of the tasks carried out in this WP serve as a basis for expanding the knowledge on the demonstrators, particularly from T4.1 and T4.4.
WP5 – Design and engineering of induction system	WP5 develops the conceptual and final designs for the induction heating system, which D4.5 analyses through a preliminary H&S assessment of the available conceptual designs.
WP6 – Design and engineering of microwave system	The design and engineering of the solutions for the microwave heating system will take place in WP6. D4.5 assesses the preliminary H&S implications of the conceptual designs for the microwave heating system under development.
T13.3 – Regulatory and standardization barriers	The findings of the deliverables D4.3 and D4.5 will serve as a key input to Task 13.3, providing the baseline H&S and EMF exposure information required for the regulatory and standardisation analysis that will be performed once the JOULIA heating systems are installed and demonstrated later in the project.

2 Principal findings of D4.3

Deliverable D4.3 established the technical, regulatory, and safety foundations required to assess the health and safety implications of induction and microwave heating technologies in industrial environments. The main findings are summarised below.

2.1 Technical characteristics of induction and microwave heating

D4.3 provided a detailed description of the physical principles governing both technologies. For induction heating, the report highlighted the role of alternating magnetic fields, eddy current generation, the skin effect, and the dependence of penetration depth on frequency, magnetic permeability, and electrical conductivity. For microwave heating, the analysis focused on dielectric heating mechanisms, dipole rotation and ionic conduction, operating frequencies (typically 915 MHz and 2.45 GHz), and the influence of dielectric properties on heating uniformity and process stability.

2.2 Occupational hazards and risks

The preliminary assessment identified several hazards associated with the industrial use of induction and microwave systems, including:

- **Exposure to electromagnetic fields (EMF)**, with typical industrial values reaching several millitesla (mT) near induction furnaces.
- **Risks of electrical shock and thermal burns** from live parts, hot components or energised electrodes.
- **Fire and explosion hazards** due to overheated components or flammable atmospheres.
- **Exposure to fumes, gases and airborne particulates** generated when heating coated or chemically treated materials.

The report also noted that certain worker groups, such as those with implanted medical devices or pregnant workers, may be particularly sensitive to EMF exposure.

2.3 Regulatory and standards framework

D4.3 reviewed the main standards and regulations governing occupational EMF exposure, including Directive 2013/35/EU [1], ICNIRP guidelines [2], IEEE C95.1-2019 [3] and relevant IEC standards (e.g., IEC 60519-3 [4], IEC 60519-6 [5], IEC 62311 [6]). The analysis clarified:

- Applicable exposure limits for induction and microwave frequencies.
- Differences between magnetic-field-based and electric-field-based assessment frameworks.
- The predominance of short-term thermal and neuromuscular effects in the regulatory landscape.

- The absence of exposure limits dedicated exclusively to induction or microwave technologies, reinforcing the need for scenario-specific assessments.

2.4 Good practices and recommendations

The deliverable summarised good practices for EMF assessment and risk mitigation, including:

- Spatial, spectral and exposimetric measurements across the working area.
- Consideration of workstation design, surrounding structures and operator movement.
- Scenario-based exposure modelling.
- Mitigation measures such as workplace reorganisation, procedural redesign, ventilation strategies and targeted training.

2.5 Overall conclusion

D4.3 concluded that general exposure limits alone are insufficient to ensure adequate protection. Realistic and scenario-specific assessments are essential to characterise worker exposure and implement effective preventive measures. These findings directly motivate the demonstrator-focused analysis developed in D4.5, including baseline EMF measurements, questionnaire analysis and field observations.

3 Demonstrators & Current EMF Hazards

3.1 ARTIGO

ARTIGO S.p.A., settled in Cairo Montenotte (Savona, Liguria) since 1996, is an Italian industrial manufacturer specialised in high-performance rubber flooring solutions for commercial, industrial, and architectural applications. With decades of experience in elastomer processing, the company is recognised for its technical expertise in rubber compounding, calendaring, vulcanisation and surface finishing. ARTIGO's products are widely used in sectors such as transportation, healthcare, education, public buildings, sports facilities and clean-room environments, where durability, hygiene, acoustic comfort and slip resistance are critical requirements.

The company operates modern production facilities equipped with advanced mixing, extrusion and vulcanisation lines, enabling consistent quality and high production capacity. ARTIGO places strong emphasis on innovation, sustainability and product certification, integrating recycled materials into its formulations and ensuring compliance with international standards for indoor air quality, fire performance and environmental impact.

Within the JOULIA project, ARTIGO serves as one of the two industrial demonstrators, providing the real-world context for evaluating the integration of electrified heating technologies. The selected use case focuses on rubber flooring vulcanisation, a process traditionally dependent on thermal oil or steam-based heating systems. ARTIGO's participation enables the assessment of induction and microwave heating technologies in a demanding industrial environment, supporting the project's objectives of decarbonisation, energy efficiency and improved process control.

In this context, the project explores the feasibility of introducing an induction-based heating module as an innovative alternative to ARTIGO's traditional rotocure vulcanisation process. The expectation is that induction heating will streamline the workflow for materials destined for granulation, improve thermal efficiency and process control, and support more sustainable material use. The following section provides a detailed description of ARTIGO's current vulcanisation process to contextualise this comparison.

The core of rubber flooring production at ARTIGO is the continuous vulcanisation stage, carried out using a rotocure (shortened name of Rotary Curing Press), a machine specifically designed for the continuous vulcanization of rubber products (see the scheme in Figure 3.1).

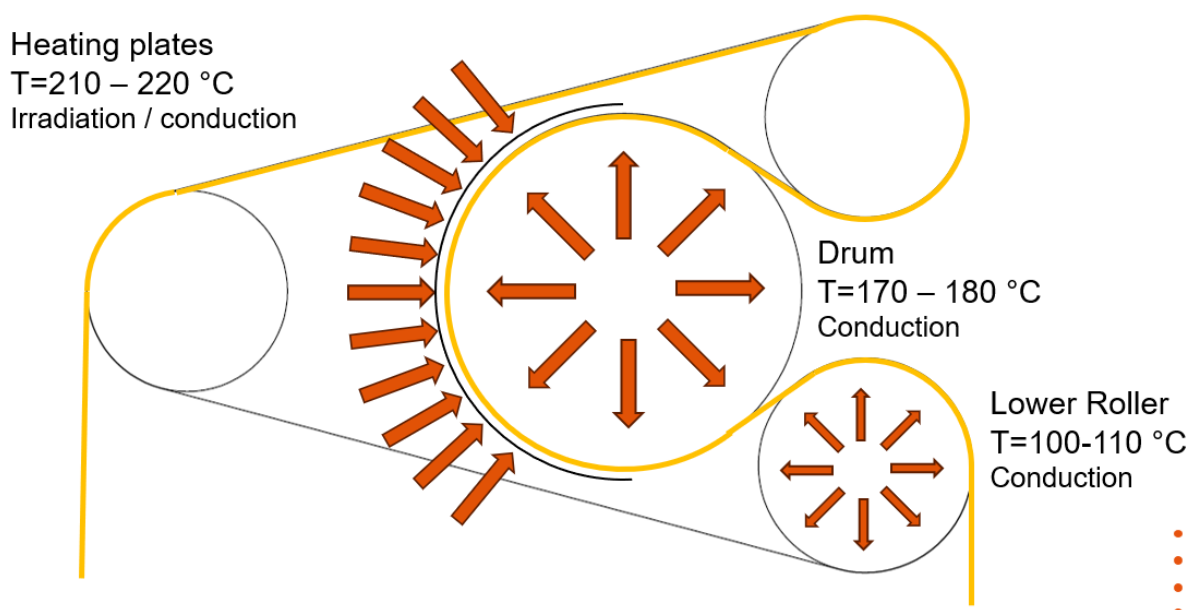


Figure 3.1: Scheme of the rotocure of the production line 1.

In detail, vulcanisation is a continuous curing process in which the rubber sheet is pressed and heated as it wraps around approximately two-thirds of the circumference of the main heated drum. In this zone, heat, pressure and residence time act simultaneously to promote the formation of cross-links between polymer chains, transforming the uncured rubber into an elastic, dimensionally stable material. These three parameters (temperature, pressure and time) are universally recognised as the critical variables governing vulcanisation quality, as highlighted in technical literature on elastomer curing. In the JOULIA demonstrator, the main drum and lower drum are heated by diathermic oil, ensuring uniform thermal transfer, while the heating elements may be electrically heated (ceramic resistors) or supplied with diathermic oil. The flooring thickness, typically between 2 and 5 mm for ARTIGO productions, directly influences the curing conditions: thicker materials require longer residence times or slightly higher temperatures to ensure complete heat penetration and uniform cross-linking, a behaviour consistent with continuous vulcanisation principles described for rotocure systems. Both the working temperatures (measured at the exit of each component) and the absorbed power vary with material thickness, reflecting the increased thermal demand associated with curing thicker rubber sheets. This dependency aligns with established industrial practice, where continuous vulcanisation equipment must maintain stable and homogeneous heat and pressure conditions to avoid under- or over-curing, defects also noted in assessments of rotocure precision and thermal control.

3.1.1 EMF Hazard Identification

Occupational exposure to EMF in vulcanisation systems arises primarily from the high electrical currents used to heat the equipment and from the motors and power-electronics that drive the continuous curing line. In rotocure systems, the main contributors are the electrically heated elements (when present), the high-power drive motors, and variable-frequency drives (VFDs), all of which generate low-frequency magnetic fields typically centred around 50 Hz, with additional harmonic components associated with power-conversion equipment. These sources can create localised EMF hotspots, particularly in areas where operators must work in close proximity, such as the infeed and outfeed zones, during sheet alignment, inspection, cleaning or maintenance. The scientific literature identifies industrial equipment operating with high currents, such as heating systems, motors and VFD-controlled machinery, as relevant contributors to occupational EMF exposure, with low-frequency magnetic fields capable of inducing neuromuscular stimulation at sufficiently high intensities ([2] [7]). Although EMF is a physical agent inherently present in industrial environments, the mere presence of the hazard does not imply risk; risk emerges only when workers perform tasks in close proximity to high-current components or power-electronics where exposure levels can increase significantly.

Exposure assessment studies in industrial environments consistently show that magnetic field levels can become elevated in the immediate vicinity of large motors, transformers and heating circuits, particularly in confined technical rooms or when workers must approach components carrying high currents. Measurements reported in occupational settings document localised magnetic flux densities reaching the millitesla range, depending on equipment load and distance, reinforcing that proximity is the dominant determinant of exposure ([2]; [8]). Importantly, these studies characterise exposure levels but do not establish causal links to adverse health effects.

Regarding potential health impacts, the broader evidence base on Extremely Low-Frequency (ELF) (up to 300 Hz according to the IEEE [3] and ICNIRP [2]) EMF remains inconclusive [9]. Systematic reviews and international risk assessments highlight that, although associations have been suggested between prolonged ELF-EMF exposure and outcomes such as childhood leukaemia, neurodegenerative disorders, oxidative stress or alterations in gene expression, the findings lack consistency across studies and do not demonstrate causality. Proposed biological mechanisms, including oxidative stress induction, intracellular calcium disruption and gene-expression changes, remain plausible but unconfirmed across experimental conditions. This position is reiterated by WHO [8] and ICNIRP [2], which conclude that uncertainties persist and that current exposure limits are designed to prevent established acute effects, such as peripheral nerve stimulation.

The regulatory framework, including Directive 2013/35/EU [1] and IEEE C95.1-2019 [10], emphasises that exposure is strongly dependent on distance and current load, meaning that operational conditions such as heating demand, equipment layout and maintenance state can significantly influence worker exposure. For these reasons, EMF assessment in vulcanisation systems must focus on proximity-based tasks, current-intensive components and the presence of power-electronics that may introduce additional frequency components.

In vulcanisation systems, the combination of continuous operation, high thermal loads and operator interventions at short distances makes EMF a relevant physical agent to be characterised at baseline. The presence of harmonic components generated by VFDs and power-conversion equipment is particularly relevant because exposure limits vary with frequency, requiring broadband measurements and spectral analysis when non-sinusoidal fields are present.

In this context, measuring ELF-EMFs is essential across various contexts of occupational exposure, residential environments and environmental monitoring. In occupational exposure, workers in industries using high-power electrical equipment are routinely exposed to ELF-EMFs, necessitating accurate exposure monitoring for health and safety compliance [11].

3.2 K_FLEX

K-FLEX, located in Uniejów (Łódź region, Poland), is part of a multinational group specialising in the production of flexible elastomeric insulation materials for thermal and acoustic applications. The company operates several production lines dedicated to polymer processing, extrusion, foaming and multilayer insulation technologies, supplying the construction, HVAC (Heating, Ventilation, and Air Conditioning), industrial and energy sectors. The Uniejów facility integrates high-capacity extrusion systems, automated handling equipment and quality-control stations designed for continuous, high-throughput manufacturing.

Within the JOULIA project, the demonstrator focuses specifically on the production of multilayered PERT II insulation pipes, a process that involves the controlled heating, extrusion and shaping of polyethylene of raised temperature resistance (PERT II). This material, capable of operating at temperatures up to 95 °C, combines mechanical robustness with flexibility due to its molecular structure, often described as analogous to a “woven collar”. The production line includes sequential stages of polymer melting, multilayer co-extrusion, dimensional stabilisation and surface finishing, requiring precise thermal management and stable process conditions.

The demonstrator integrates an induction-based heating system used to pre-heat or thermally condition the PERT II tube during processing. The system comprises (see Figure 3.2):

- **Generator cabinet (1)** mounted on a **dedicated stand (2)**, housing the power-electronics, control circuits and cooling infrastructure.
- **Roller with encoder (3)** installed on the stand to measure tube speed and synchronise heating power with line throughput.
- **External exciter (4)** responsible for generating the alternating magnetic field that induces heating in the material.

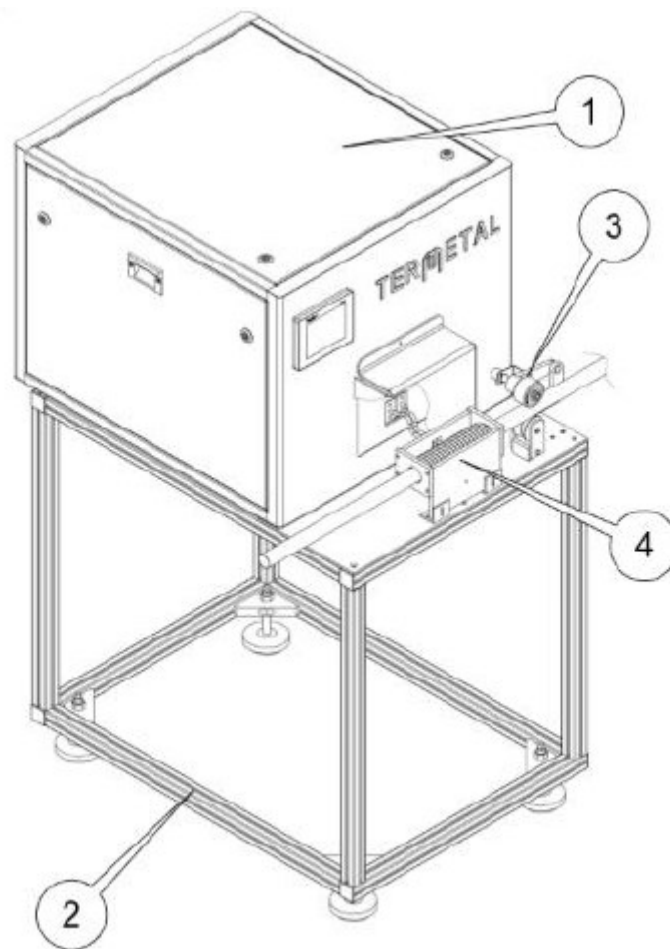


Figure 3.2: Heating induction system in the K_FLEX facilities.

On the other hand, the generator architecture includes:

- A three-phase six-pulse diode rectifier with LC filtering (a passive inductor–capacitor filter used to smooth the rectified DC (direct current) voltage and reduce ripple before the inverter stage), protected by a circuit breaker with overcurrent release.
- A capacitor bank fed through a smoothing choke and a resistor–contactor circuit enabling controlled charging.
- A single-phase resonant transistor inverter, where half-bridge transistors switch alternately to generate the AC voltage supplied to the exciter.
- A matching transformer and capacitor network forming a resonant circuit tuned close to the exciter’s natural frequency.
- An EMC (electromagnetic compatibility) filter in the main supply line to limit electromagnetic interference from inverter switching.
- Electronic control circuits implemented on printed circuit boards inside the cabinet.
- A closed-loop cooling system comprising inlet/outlet manifolds, coolers for semiconductor devices and rectifier diodes, a water-air heat exchanger, and external hose connections with filtration.

During operation, the inverter starts at a frequency several kHz above resonance and gradually decreases until it stabilises slightly above the resonant point, ensuring a smooth and controlled increase in the delivered power. Power modulation is achieved by adjusting the output current via the programmable controller.

The K-FLEX demonstrator operates as a continuous, high-throughput extrusion line, where operators periodically intervene for: i) tube alignment and quality checks; ii) adjustments to line speed or heating parameters; iii) cleaning and maintenance of the exciter area; and iv) monitoring of the generator cabinet and cooling system. These tasks often require short-distance interaction with components carrying high currents or containing power-electronics.

In the context of the JOULIA project, K-FLEX plans to replace this induction-based heating stage with a microwave-based solution in future iterations of the production line, enabling a more efficient and controllable thermal conditioning process for multilayer PERT II pipes.

3.2.1 EMF Hazard Identification

Occupational exposure to EMF in the K-FLEX demonstrator arises primarily from the induction heating system integrated into the PERT II multilayer pipe production line. Unlike the broader hazard characterisation already presented in D4.3, the present section focuses specifically on the equipment, operating conditions and worker interactions relevant to the Uniejów facility.

The induction system comprises a high-power generator cabinet, a single-phase resonant inverter, a matching transformer and an external exciter positioned around the moving PERT II tube. In this configuration, magnetic field generation results from the high currents circulating in the resonant circuit and from the switching behaviour of the power-electronics that regulate heating along the extrusion line. The presence of a six-pulse rectifier, LC filtering stages and a high-frequency inverter contributes to a magnetic field spectrum that includes the 50 Hz fundamental component as well as harmonics associated with power conversion and load modulation.

In the K-FLEX line, EMF-related hazards become relevant when operators perform tasks that require approaching the exciter or the generator cabinet. These include visual inspection and alignment of the PERT II tube, adjustments to line speed or heating parameters, routine checks of the generator cabinet and cooling system, and cleaning or maintenance activities requiring access to the exciter or cabinet interior. Such tasks may place workers within short distances of high-current conductors, power-electronics assemblies and resonant circuits, where localised EMF hotspots are most likely to occur. Industrial EMF studies consistently show that magnetic field levels can increase sharply near transformers, inverters and conductors carrying elevated currents, with distance being the dominant determinant of exposure.

The K-FLEX demonstrator therefore presents two main categories of EMF sources:

- Static or cabinet-integrated sources, including the rectifier, choke, capacitor bank, inverter and cooling system components.

- Process-integrated sources, primarily the exciter and matching transformer, which operate in close proximity to the moving tube and to operator intervention points.

Given that exposure limits vary with frequency, the presence of non-sinusoidal waveforms and harmonic components generated by the inverter and power-conversion stages requires broadband measurements and spectral analysis to characterise the field accurately.

In summary, EMF hazard identification at K-FLEX must focus on proximity-dependent exposure, current-intensive components, and resonant power-electronics, ensuring that subsequent measurements capture both the fundamental and harmonic contributions relevant to worker tasks along the PERT II production line.

4 EMF Assessment Methodology

This section describes a structured methodology for assessing occupational EMF exposure in industrial environments using induction and microwave heating. The approach was designed to be compatible with the requirements and relevant technical standards, ensuring that the assessment is both scientifically robust and aligned with regulatory expectations. The methodology consists of three main phases: (i) preparatory analysis and planning, (ii) field measurements, and (iii) results and data interpretation.

4.1 Preparatory analysis and planning

The assessment began with a detailed characterisation of each industrial demonstrator, providing the operational and technical basis required to define representative exposure scenarios and plan the measurement campaign. This phase includes:

- **Technical questionnaires:** structured questionnaires were distributed to the industrial partners to collect information on equipment characteristics, operating conditions, perceived EMF-related risks, number of workers involved, and identification of the most critical stages of the production process. The responses were analysed to understand the operational context, typical workflows and potential exposure scenarios.
- **Identification of EMF sources:** based on the information collected, preliminary EMF sources were identified. This list is indicative and may be refined or expanded during the on-site assessment.
- **Definition of workstations and exposed tasks:** workstations, worker positions and task sequences were mapped to identify situations where operators may be exposed to elevated EMF levels. Particular attention was given to tasks involving close proximity to the heating equipment, manual adjustments, loading/unloading operations and maintenance activities.
- **Selection of measurement instruments:** appropriate instrumentation was selected according to the frequency range and field type associated with each technology. All instruments comply with EN 50413 [12] and relevant calibration standards.

This preparatory phase ensures that the subsequent on-site measurements are targeted, representative and aligned with the real operational conditions of each demonstrator.

4.2 Regulatory and Standards Framework

The EMF assessment methodology applied in this deliverable is fully aligned with the regulatory requirements of Directive 2013/35/EU [1] and with the technical procedures defined in the relevant international standards, including EN 50413 [12], IEC 60519-6 [5], IEC 60519-1 [13] and IEEE C95.3.1 [10]. These documents provide the scientific and procedural basis for identifying EMF sources, defining exposure scenarios, selecting appropriate instrumentation and interpreting measurement results.

The standards converge on a common sequence of steps for occupational EMF assessment, which is reflected in the methodology adopted in this work. As summarised in Figure 4.1, which includes the following recommended process, i.e.:

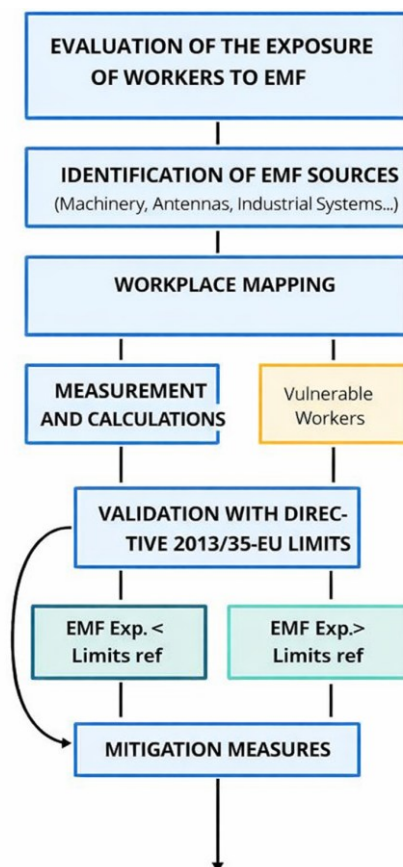


Figure 4.1: The recommended methodology of EMF measurement based on EN 50413 [12].

This structured approach ensures that the assessment is representative of real working conditions and that the results can be directly compared with the Action Levels (ALs) and Exposure Limit Values (ELVs) defined in the Directive.

The initial step requires determining operating frequencies, nominal power, modulation characteristics and the influence of secondary structures, as highlighted in the standards, which note that secondary metallic or reflective elements may increase field levels and create localised EMF hotspots. This principle informed the preparatory phase of the JOULIA assessment, ensuring that both primary and secondary contributors to exposure were considered when defining realistic exposure scenarios.

The standards also specify the technical requirements for measurement instrumentation, including the use of isotropic probes, true-RMS response, adequate bandwidth and calibration traceable to recognised standards, with EN 50413 [12] serving as the reference for instrument performance. These requirements emphasise that instruments must be properly calibrated and technically compatible with the type and frequency range of the field, which guided the selection

of probes for ELF magnetic fields in induction systems, electric and magnetic (E/H) field probes for radiofrequency (RF) and microwave systems, and personal exposimeters when appropriate.

Regarding measurement procedures, the standards emphasise that fields must be assessed under normal operating conditions, covering representative worker positions such as head, torso and hands. Both spot measurements and spatial scans may be required, and temporal variability must be captured when emissions are pulsed or intermittent. This aligns with the protocol's guidance that measurements should be performed at different times and positions to capture operational variability, which directly shaped the measurement strategy adopted in Section 4.3.

When direct measurements are not feasible, standards such as IEEE C95.3.1 [10] and IEC 60519-6 [5] allow the use of computational modelling to estimate induced currents, SAR and thermal effects, particularly in microwave systems or complex geometries.

Finally, all standards converge on the requirement to compare measured or calculated values with the exposure limits defined in Directive 2013/35/EU, including ALs for external fields and ELVs for internal quantities, as well as criteria for thermal and non-thermal effects specified in IEC 60519-6 and IEC 60519-1. The protocol reinforces that measured values must be converted into quantities directly comparable with the ALs or ELVs, which forms the basis for the interpretation criteria presented in Section 4.6 and ensures that the assessment is fully aligned with regulatory expectations.

4.3 Measurement Strategy and Procedures

The measurement strategy was designed to ensure that the EMF assessment captured representative worker exposure under realistic operating conditions. The procedures followed the principles established in the standards mentioned above and were adapted to the specific characteristics of the induction heating system in K-Flex and the existing equipment in both demonstrators (K-FLEX and ARTIGO).

Measurements were carried out under normal production conditions, focusing on the equipment that will be replaced within the project in order to characterise the baseline exposure and understand the potential impact of the future technological upgrade. Fixed-point measurements were performed at different distances along the full length of the line, with measurements taken on both sides of the equipment and at a height representative of the operator's head, reflecting typical working postures. The selected positions corresponded to locations where workers spend the most time during routine operation, ensuring that the assessment captured realistic exposure conditions.

Both spot measurements and spatial scans were conducted. Spot measurements were used to quantify field levels at predefined positions of interest, while spatial scans were performed to identify local maxima and characterise field gradients around the equipment's. Temporal variability was addressed by repeating measurements at different moments during normal production, ensuring that typical fluctuations in operating conditions were captured.

The selection of measurement distances followed the recommendations of the standards and the practical constraints of each demonstrator. Measurements were taken at positions corresponding to typical worker proximity, including near-field locations when accessible and safe. For induction systems, the assessment focused on ELF magnetic fields generated by the high-current resonant circuits and associated power-electronics. For the rotocure and other equipment operating with motors, resistive heating or variable-frequency drives, measurements also targeted ELF magnetic fields, as no microwave or RF sources were present in the current demonstrators. Microwave measurements were not performed because the new heating technologies have not yet been installed, and the assessment therefore reflects the baseline exposure conditions of the existing equipment.

All measurements were performed using calibrated instruments with characteristics compatible with the type and frequency of the field, including isotropic probes with true-RMS response and adequate bandwidth.

The overall strategy ensured that the collected data reflected realistic exposure scenarios, captured spatial and temporal variability, and provided a robust basis for comparison with the ALs and ELVs defined in Directive 2013/35/EU [1].

4.4 Instrumentation

The electromagnetic field measurements were performed using a Wavecontrol SMP2 [14] broadband EMF meter equipped with isotropic probes suitable for low-frequency magnetic field assessment (Figure 4.2). This instrument is widely used in occupational EMF evaluations and complies with the performance requirements of the standards referenced in this deliverable, including true-RMS detection, adequate dynamic range, and appropriate bandwidth for ELF magnetic fields.



Figure 4.2: Equipment used in the monitoring campaigns.

The SMP2 is particularly well suited for the demonstrators assessed in this project, as both the induction heating system (K-Flex) and the rotocure and associated equipment (ARTIGO) operate predominantly in the extremely low-frequency (ELF) range. The ELF magnetic field probes used

with the SMP2 provide true-RMS acquisition, isotropic response and adequate bandwidth to accurately characterise magnetic fields generated by high-current induction circuits, motors, resistive heating elements and variable-frequency drives, ensuring full compatibility with the physical characteristics of the fields present. The instrument and its probes comply with the performance requirements of the relevant standards for occupational EMF assessment, including IEC 61786-1 and the measurement principles referenced in Directive 2013/35/EU, ensuring that the collected data is technically robust and suitable for comparison with the applicable exposure limits.

A tripod was used to support the probe during fixed-point measurements, ensuring stable positioning at the required height and improving repeatability when assessing worker-relevant exposure locations.

All instruments were calibrated and met the accuracy and response criteria required for occupational EMF assessments, ensuring that the collected data reliably reflects the exposure conditions in the demonstrators.

4.5 Demonstrators Perception and Operational Practices (Questionnaire Analysis)

4.5.1 Questionnaire Analysis

The analysis began with the structured questionnaires completed by the demonstrators, which collected detailed information on operational practices, process characteristics and potential sources of electromagnetic fields. The questionnaire covered six thematic areas: general process information, heating technologies used, operational routines, worker proximity and tasks, chemical use, and technical controls. Respondents were asked to describe the heating systems involved, the degree of enclosure, the presence of other EMF-generating equipment, ventilation conditions, power ratings, and any visible emissions or sparks. Operational questions addressed the duration and frequency of worker presence near the equipment, typical distances to the heating systems, manual interventions performed during operation, personal protective equipment (PPE) use, bypassing of interlocks, handling of hot materials, and any symptoms experienced during work. Additional sections captured the availability of Standard Operating Procedures (SOPs), maintenance routines, shielding measures, EMF signage, previous exposure measurements and the presence of workers with implanted medical devices.

This structured information provided a factual basis for identifying the tasks, distances and operational conditions most relevant for EMF exposure, and for understanding how workers interact with induction and microwave systems during routine production. It also highlighted gaps in procedures, variability in safety practices and differences in familiarity with the technologies, which are essential for defining realistic exposure scenarios and guiding the measurement strategy.

The following subsections present the detailed information provided by the two demonstrators.

4.5.1.1 ARTIGO

The questionnaire provided a comprehensive overview of the ARTIGO demonstrator, clarifying the operational characteristics of the vulcanisation process and the functioning of the rotocure, which is the central technology of interest. As previously described, the rotocure (Rotary Curing Press) is a continuous vulcanisation system composed of four revolving steel drums enclosed by an endless steel band. The lower drum and the larger central drum are heated, through a combination of resistive heating and induction coupling, while an additional heating plate, bent around approximately half of the central drum, provides supplementary thermal input via diathermic oil at 210–220 °C. During normal operation, the lower drum reaches 100–110 °C and the central drum 170–180 °C, ensuring the required thermal conditions for rubber flooring vulcanisation.

The questionnaire clarified the operational routines associated with the rotocure, including weekly start-up procedures, continuous production tasks and worker proximity patterns. The equipment is switched off during weekends, and on Monday mornings a single operator initiates the heating sequence from the control cabinet at approximately 4:00 AM. This task lasts a few hours and is performed locally, with the operator positioned close to the control system. During production start-up, three or four workers are involved in feeding the uncured rubber sheet into the rotocure and coordinating material insertion across upstream and downstream machines. This activity is continuous and lasts several hours, with workers remaining in close proximity to the heated drums and steel band. In addition, structural paper is used to protect (or emboss) the surface the floor. Workers may be required to change the paper roll. This activity may require short time.

The questionnaire also confirmed the presence of process-related emissions. Vulcanisation gases, mainly sulphur compounds, are released during operation, although mechanical ventilation is installed in the area. Electricity is used primarily for traction of the steel belt, hydraulic systems and the control system. According to the demonstrator, the highest potential sources of EMF in the factory are the high-frequency AC (alternating current) conductors, although shielding solutions are being evaluated if necessary. Power electronics (AC/DC and DC/AC converters) are enclosed and insulated, and therefore not considered a significant source of operator exposure. The induction components operate in the 70–110 kHz range. Preliminary simulations indicate that the magnetic field generated by the induction system is largely confined within metallic components, which act as an effective shield. At 100 mm from the system boundary, the simulated field drops to approximately 6 μ T, and this value is expected to be even lower once the aluminium enclosure is included in the model.

Workers operate across the production lines on a continuous schedule (24 hours per day, five days per week) due to the central role of the rotocure within the process. Despite this, respondents did not report safety concerns related to EMF. High voltages within the power electronics were acknowledged, but these components are fully enclosed and insulated. The questionnaire also confirmed that equipment inspections and maintenance routines are performed regularly, and no workers with implanted medical devices were identified.

Overall, the structured information provided by ARTIGO enabled a clear mapping of the tasks, distances and operational conditions most relevant for EMF exposure in the rotocure area. It also

highlighted the importance of start-up activities, continuous material handling and the presence of high-frequency induction components as key elements for defining realistic exposure scenarios and guiding the measurement strategy.

4.5.1.2 K-FLEX

The questionnaire responses provided a more detailed characterisation of the K-FLEX production environment, the adhesive activation process, and the operational context relevant to potential EMF exposure. As previously described, the process of interest in this demonstrator corresponds specifically to adhesive activation within the multilayer pipe (MLP) production line. The facility has a total area of approximately 500 m², employs 10 workers and operates on a 24/7 schedule, with full mechanical ventilation installed across the factory.

The technology that will be replaced by the microwave demonstrator is the current adhesive activation system, which uses electromagnetic induction to heat and melt the adhesive applied to the PERT II multilayer structure. Although the induction coils generate ELF magnetic fields during operation, the unit is fully enclosed, which is expected to reduce direct operator exposure.

The questionnaire enabled a clearer mapping of the production sequence, including the number of machines positioned upstream and downstream of the adhesive activation stage, the duration and frequency of operator tasks, and typical proximity distances. Four workers are assigned to this area. Their tasks near the induction system generally last less than 30 minutes, and operators typically remain 0.5 m to 1 m from the equipment during adjustments, inspection or routine handling.

Despite this proximity, workers reported no concerns or suggestions regarding safety during these operations. Only basic PPE is used (heat-resistant gloves, safety goggles, hearing protection and standard workwear). No workers with pacemakers were identified, and no SOPs related to EMF or induction-based equipment are implemented at the facility.

Several knowledge gaps were identified. Workers were unable to provide information on:

- The electrical power of the induction system.
- The magnetic field strength or operating frequency generated by the equipment.

When asked how many systems in the facility could potentially generate EMFs, respondents estimated more than 50, reflecting the presence of multiple electrical and electromechanical units across the production line.

Finally, for all questions directly related to potential electromagnetic field exposure (e.g., monitoring, signage, training, EMF-specific PPE), the responses were consistently “No”, indicating an absence of EMF-specific controls, awareness measures or monitoring practices.

4.5.2 Demonstrators' perceptions

This section combines the findings from the demonstrators' questionnaires with perceptions reported by project partners, creating a coherent understanding of operational practices, perceived risks and worker interactions with induction and microwave systems. This integrated perspective directly informs the definition of exposure scenarios and the design of the EMF measurement strategy.

Additional insights from the stakeholder interviews conducted in T4.4 (and reported in D4.4) further clarify how operators differentiate between induction and microwave technologies in terms of perceived safety. For microwave systems, concerns are strongly shaped by the association with “radiation”, leading to discomfort when working in close proximity to the equipment. Low familiarity and limited hands-on experience amplify these concerns, particularly when safety measures are not clearly communicated. Operators consistently emphasised the need for a dedicated safety expert and for transparent explanations of shielding, interlocks and operational limits to build trust in the technology.

In contrast, induction heating is perceived as a more familiar and controllable technology. Operators highlighted its precision, reduced fire risk compared with flame-based methods, and the fact that most hazards, such as burns or electric shock, are considered manageable with appropriate PPE, training and routine maintenance. Expectations regarding emergency readiness, such as accessible shut-off mechanisms and regular equipment checks, were also recurrent themes.

Across both technologies, the interviews underline that perceived risk is strongly influenced by communication quality, clarity of procedures and the degree of operator involvement during commissioning and training. These perceptions directly inform the definition of realistic exposure scenarios and reinforce the need for clear, practical and well-structured safety protocols in future deployments.

4.6 EMF Interpretation Criteria

The collected data will be interpreted by comparing measured values with the Action Levels (ALs) and ELVs defined in Directive 2013/35/EU [1] and the reference levels established by ICNIRP [2]. Results will be analysed per task, workstation and operational condition to identify situations of elevated exposure or proximity to regulatory thresholds.

The present assessment establishes the baseline exposure profile of the demonstrators prior to the installation of the new induction and microwave systems. This baseline will enable a before-and-after comparison in Task 13.3, supporting the evaluation of the impact of the JOULIA technologies on worker exposure and informing the final health and safety requirements.

5 Baseline EMF Results

The EMF baseline was assessed in the ARTIGO and K-FLEX demonstrators. The analysis integrates quantitative measurements of magnetic and electric fields with qualitative insights into operational practices and worker interaction. The results are evaluated against the Occupational Exposure Limits (OEL) defined in Directive 2013/35/EU [1], providing a comprehensive characterisation of current exposure conditions. This baseline establishes a reference framework for identifying potential risks and supports the assessment of health and safety implications associated with the future integration of induction and microwave technologies.

5.1 ARTIGO EMF results

Figure 5.1 shows the ARTIGO plant with three production lines equipped with advanced mixing, extrusion, and vulcanisation steps (pre-rotocure and rotocure) for the production of rubber flooring. EMF measurements were performed on 3rd March 2026 under normal operating conditions, near the control panels in the areas between lines 1 and 2, and between lines 2 and 3, where operators spend more time and therefore have higher exposure. The distances between the lines are approximately 10 m and 11 m. Note that production lines 1 and 3 follow the same sequence of steps, while line 2 also includes a pre-rotocure (step 3). Only the steps related to pre-rotocure and rotocure were identified for confidentiality reasons. EMF measurements were concentrated mainly near the pre-rotocure and rotocure steps of all the three lines, since these steps will be adapted to receive the new induction-heating technology. Additionally, EMF measurements were performed at all steps of line 1 as a baseline assessment. All three lines and the general ventilation system were operating during the EMF measurements. Indoor environmental conditions were stable, with a temperature of 28.1 °C and a relative humidity of 33.8 %.

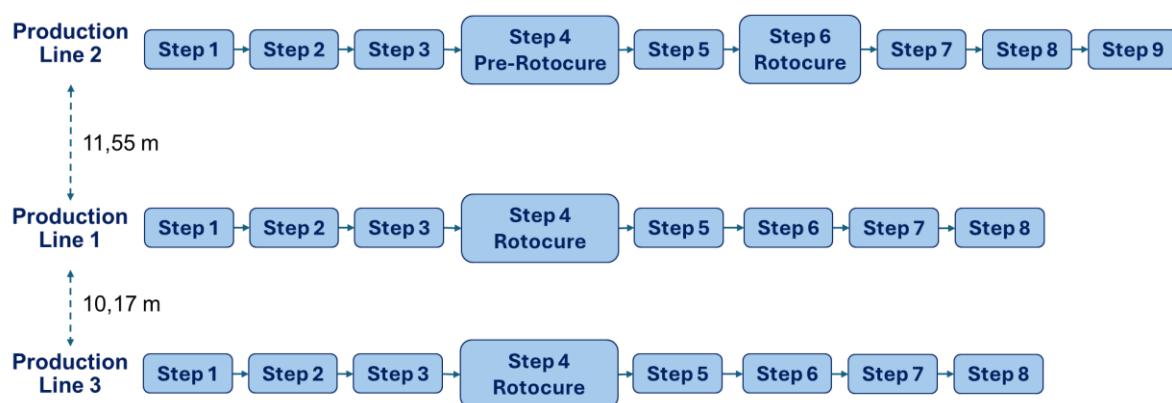


Figure 5.1. Plant of ARTIGO with the production lines 1, 2, and 3.

Figure 5.2 shows the magnetic field levels (peak and RMS (Root Mean Square - time-averaged)) in the rotocure of ARTIGO line 1 at 400 Hz and 4 kHz.

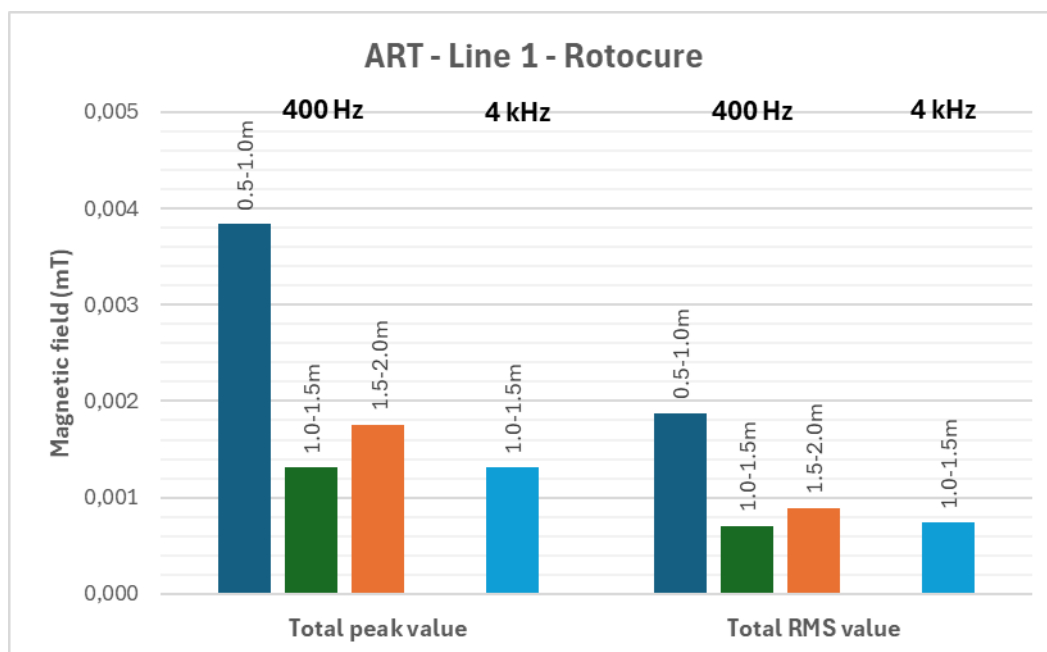


Figure 5.2. Magnetic field measurements at ARTIGO line 1: total peak and total RMS values for the rotocure at 400 Hz and 4 kHz for several measurement distances (0.5-1.0, 1.0-1.5, 1.5-2.0 m).

The magnetic field levels decrease consistently with distance (0.5–2.0 m), confirming a strong spatial attenuation. The highest values are observed at 0.5–1.0 m (≈ 0.004 mT), with significantly lower levels beyond 1.5 m. This pattern reflects typical operator positioning during inspection tasks, where proximity varies dynamically. It confirms that exposure is task-dependent and proximity-driven. Therefore, localised exposure hotspots exist near the rotocure, particularly during close-range interventions. However, measured values remain well below the OEL of 6 mT, indicating compliance under normal operation.

Higher-frequency components (above 400 Hz) were also observed in the rotocure, including peaks around 4 kHz. These components originate from switching electronics such as variable-frequency drives and PWM (Pulse-Width Modulation) controllers, rather than from the 50 Hz mains supply. Their presence is therefore equipment-specific and depends on the type of power-electronics architecture and its switching frequency.

Figure 5.3 shows that elevated magnetic field levels are concentrated at specific steps (notably step 4 – rotocure for lower distances), with lower levels elsewhere. However, all values remain significantly below regulatory thresholds.

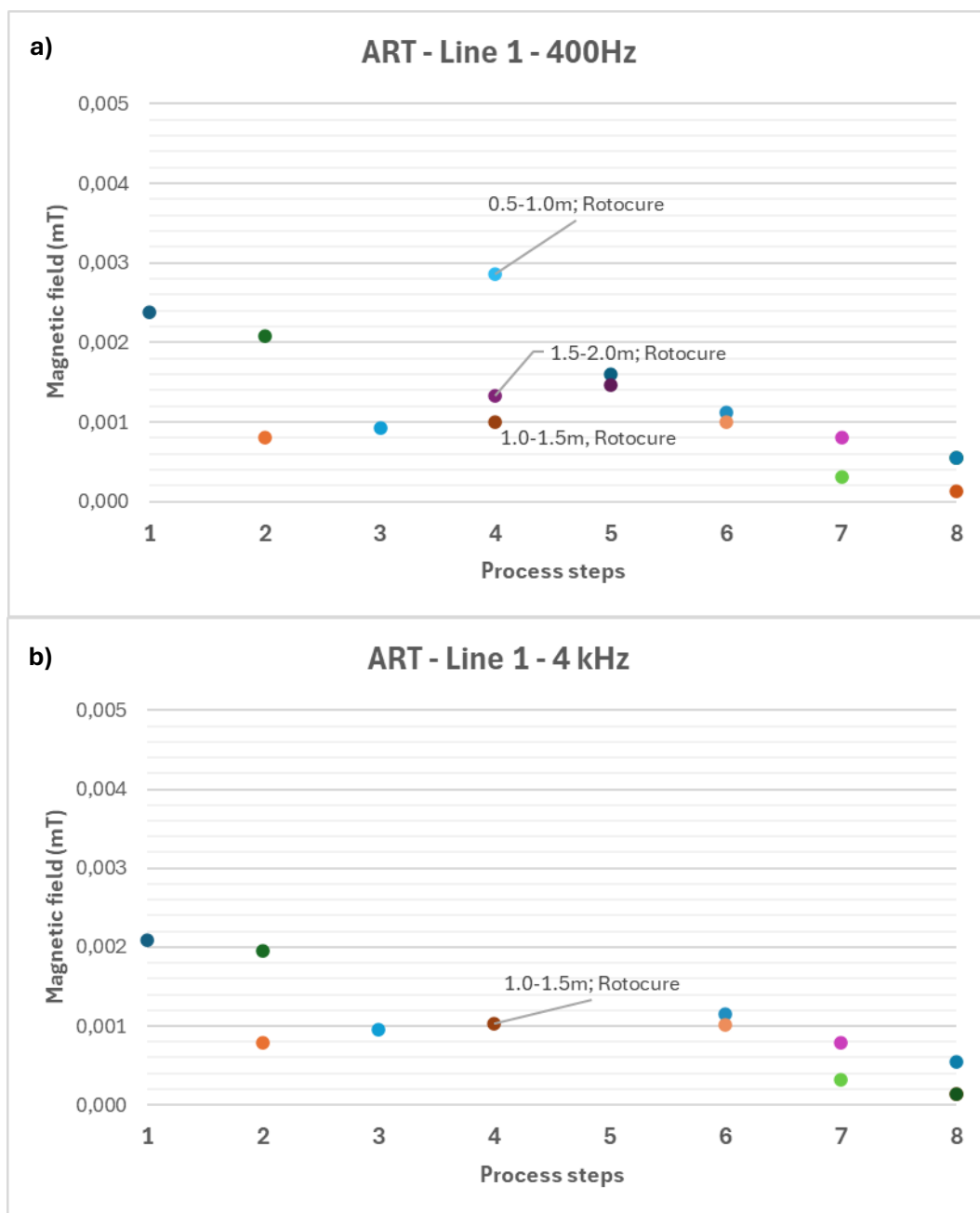


Figure 5.3. Magnetic field measurements at ARTIGO production line 1 – steps 1-8: (a) measurements at 400 Hz; (b) measurements at 4 kHz.

Figure 5.4 presents the electric field levels at 400 Hz and 40 kHz for the rotocure in ARTIGO line 1, as well as the corresponding measurements across all process steps in line 1 (steps 1–8).

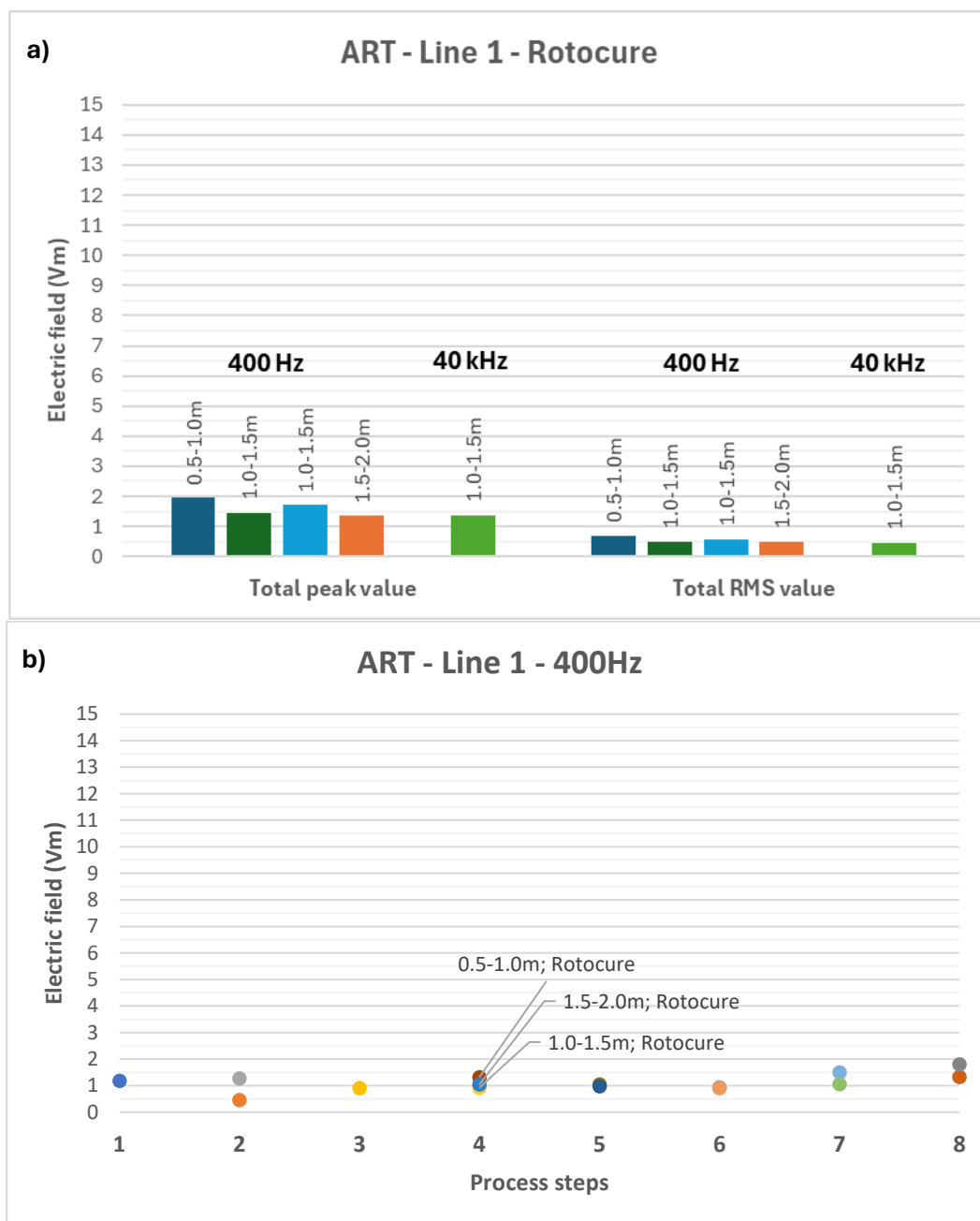


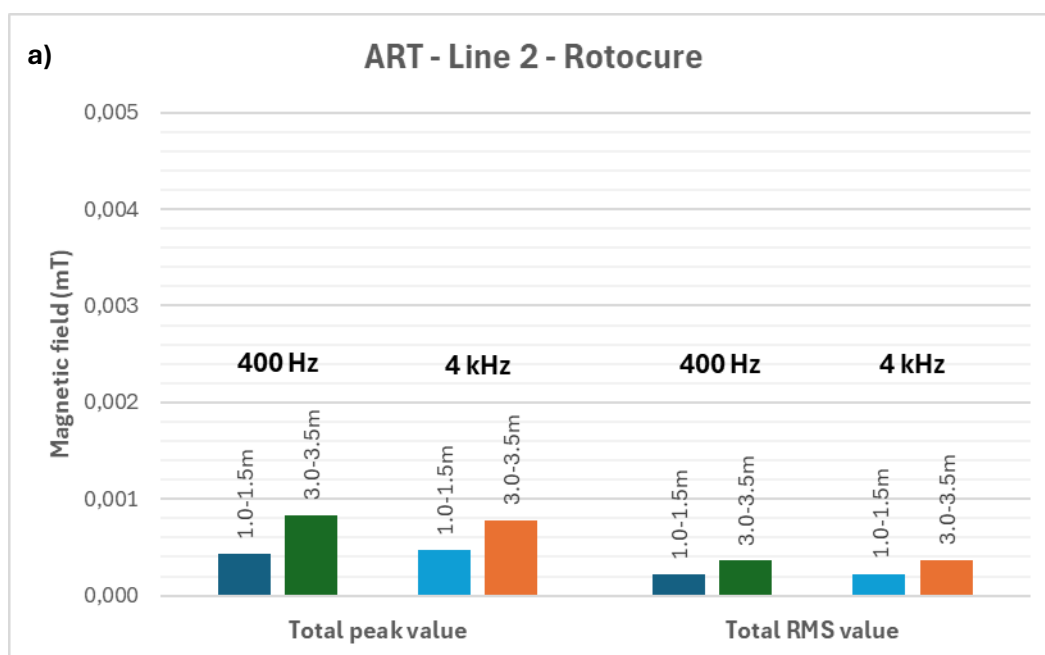
Figure 5.4. Electric field measurements at ARTIGO production line 1: (a) total peak and total RMS values for the rotocure measured at 400 Hz and 40 kHz for several measurement distances (0.5-1.0, 1.0-1.5, 1.5-2.0 m); (b) process steps 1-8 (with identification of rotocure – step 4).

The electric field levels remain far below the OEL of 20 000 V/m and decrease with distance, confirming a clear spatial attenuation pattern. At the rotocure, the measurements taken at 0.5–1.0 m, 1.0–1.5 m and 1.5–2.0 m show no meaningful differences and no visible increases with distance, indicating a stable field distribution.

The comparison between 400 Hz and 40 kHz shows that the higher-frequency components follow the same distance-dependent trend, although with slightly elevated peak values at shorter distances. This behaviour is consistent with emissions from switching electronics, particularly variable-frequency drives and PWM-based controllers, which generate electric-field components in the kHz range. These components are equipment-specific and do not indicate any deviation from normal operation.

Across process steps 1–8, the rotocure (step 4) is the only stage where a consistent increase is observed, confirming it as the main contributor to electric-field exposure within this production line. Even so, all measured values remain orders of magnitude below the regulatory limits.

Figure 5.5 shows the magnetic field levels of rotocure and pre-rotocure in line 2 of ARTIGO for 400 Hz and 4 kHz. Slightly higher magnetic field levels are observed at the pre-rotocure compared to the rotocure, increasing at greater distances (up to 3.5 m). This may result from the interference from the rotocure of line 1, as lines 1 and 2 are approximately 11 m apart. However, all measurements remain well below 6 mT (OEL). In addition, the analysis of the magnetic field levels for other steps of line 2 does not show significant differences (Figure 5.6).



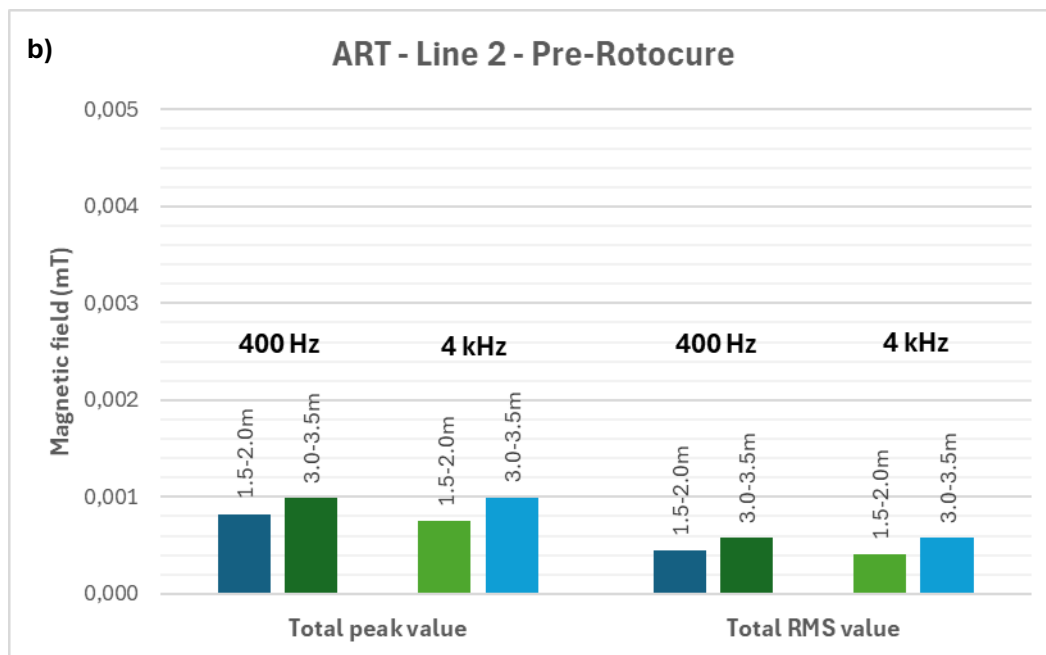


Figure 5.5. Magnetic field measurements at ARTIGO production line 2 - Total peak and total RMS values for 400 Hz and 4 kHz for several measurement distances (1.0-1.5, 3.0-3.5 m): (a) rotocure; (b) pre-rotocure.

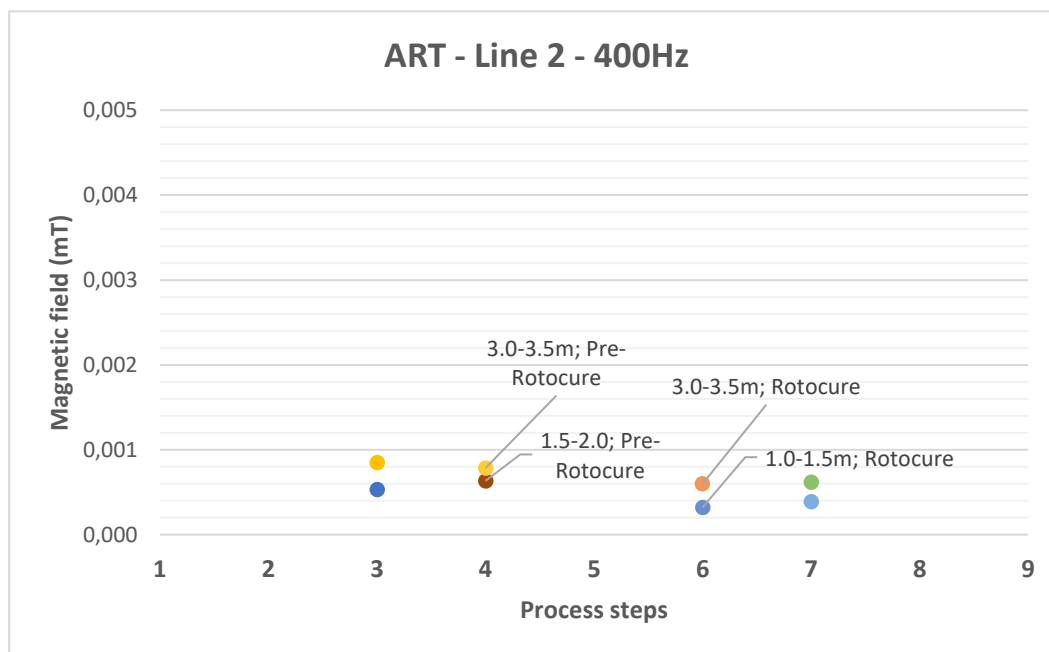


Figure 5.6. Magnetic field measurements at ARTIGO production line 2: measurements at 400 Hz at several distances (1.0-1.5, 1.5-2.0, 3.0-3.5 m) for process steps 1-9 (with identification of pre-rotocure – step 4 and rotocure – steps 6).

Figure 5.7 and Figure 5.8 show that the electric field levels remain low across distances and process steps in line 2 of ARTIGO, with levels substantially below of 20 000 V/m.

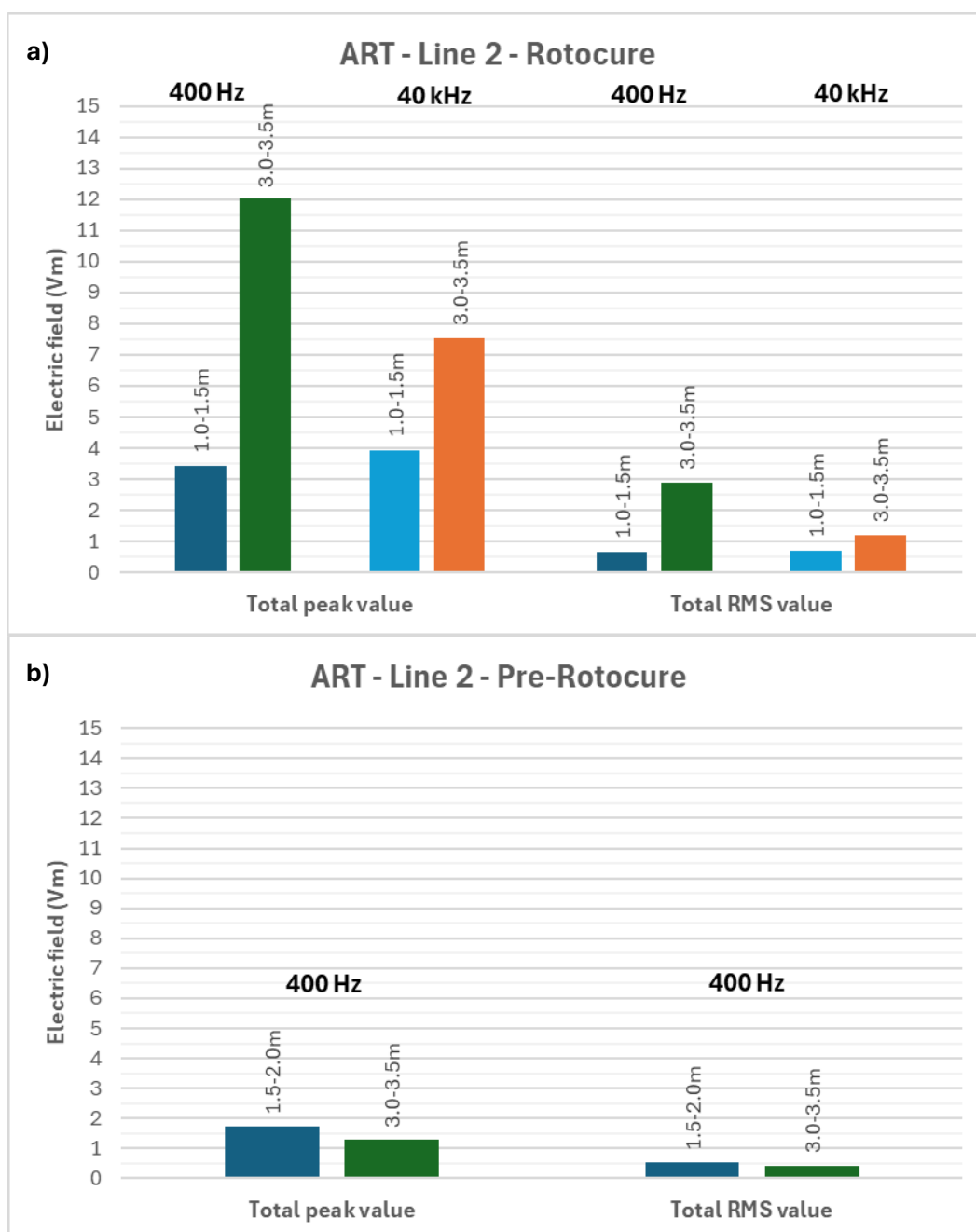


Figure 5.7. Electric field measurements at ARTIGO production line 2 - Total peak and total RMS values for 400 Hz and 40 kHz for several measurement distances (1.0-1.5, 3.0-3.5 m): (a) rotocure; (b) pre-rotocure.

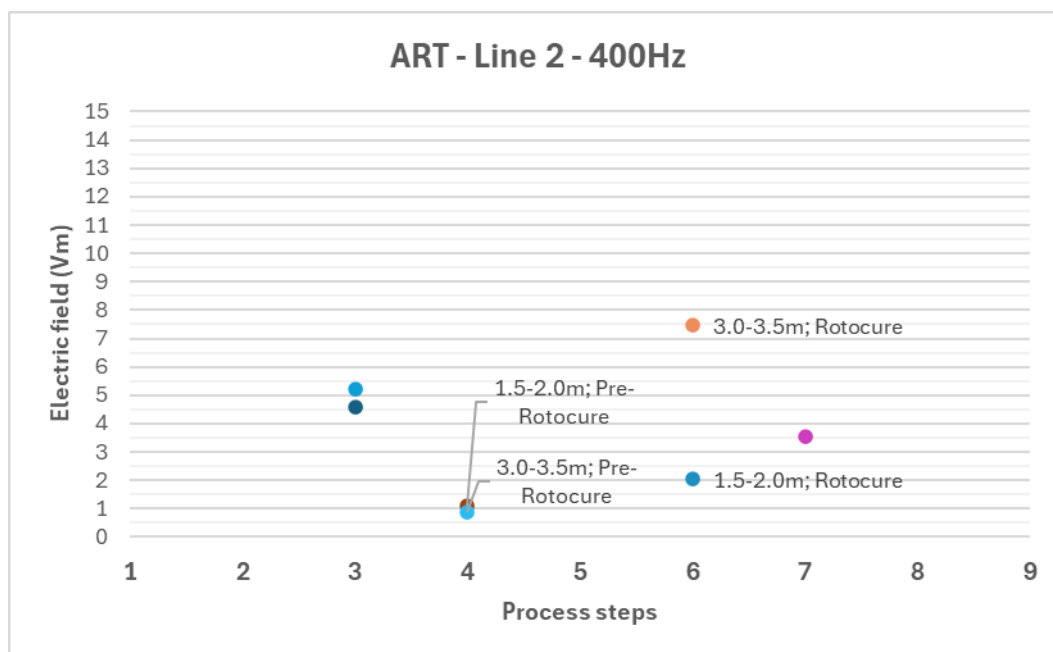


Figure 5.8. Electric field measurements at ARTIGO production line 2: measurements at 400 Hz at several distances (1.5-2.0, 3.0-3.5 m) for process steps 1-9 (with identification of pre-rotocure – step 4 and rotocure – steps 6).

The electric field levels show a slight increase at larger distances (up to 3.5 m), a pattern also observed for the magnetic field (Figure 5.5 and Figure 5.6). This behaviour is consistent with interference from adjacent equipment in line 1, which contributes to the background field when measurements are taken further away from the rotocure or pre-rotocure. At shorter distances, the measurements reflect the local source, whereas at larger distances the influence of neighbouring equipment becomes proportionally more relevant.

Additionally, in line 2, minimal variation is observed across the process steps, despite this being the only production line containing both a rotocure and a pre-rotocure. The electric-field contribution remains low and stable, indicating limited relevance of electric fields in worker exposure scenarios and suggesting effective shielding and low electromagnetic coupling between equipment.

Figure 5.9 and Figure 5.10 shows the magnetic and electric fields measured in line 3 of ARTIGO for 400 Hz and 4 kHz. The magnetic field and electric field trends are consistent with previous lines, i.e., all values remain low and are compliant with Directive 2013/35/EU [1].

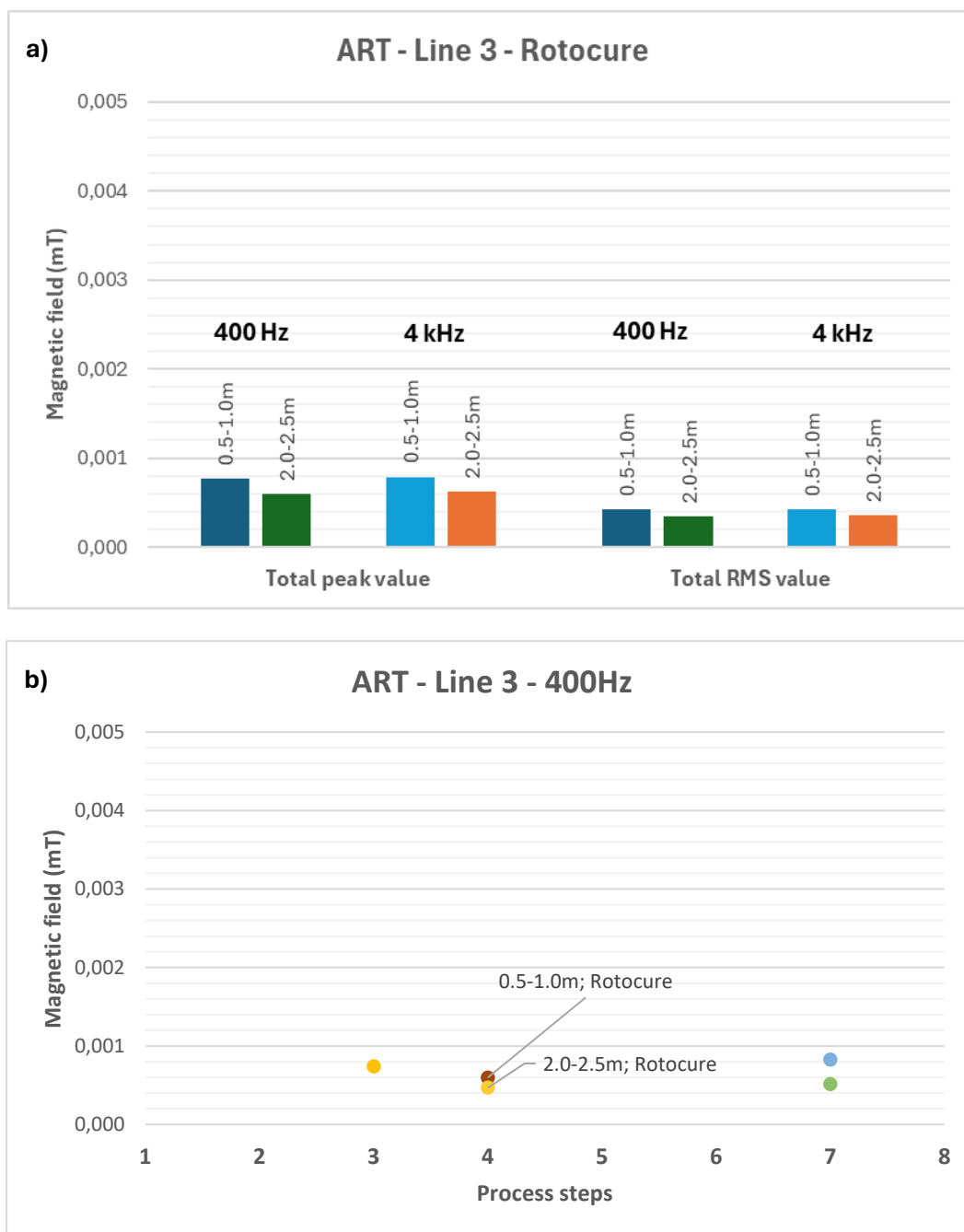


Figure 5.9. Magnetic field measurements at ARTIGO production line 3: (a) Total peak and total RMS values for the rotocure at 400 Hz and 4 kHz for several measurement distances (0.5-1.0, 2.0-2.5 m); (b) Process steps 1-8 (with identification of rotocure – step 4).

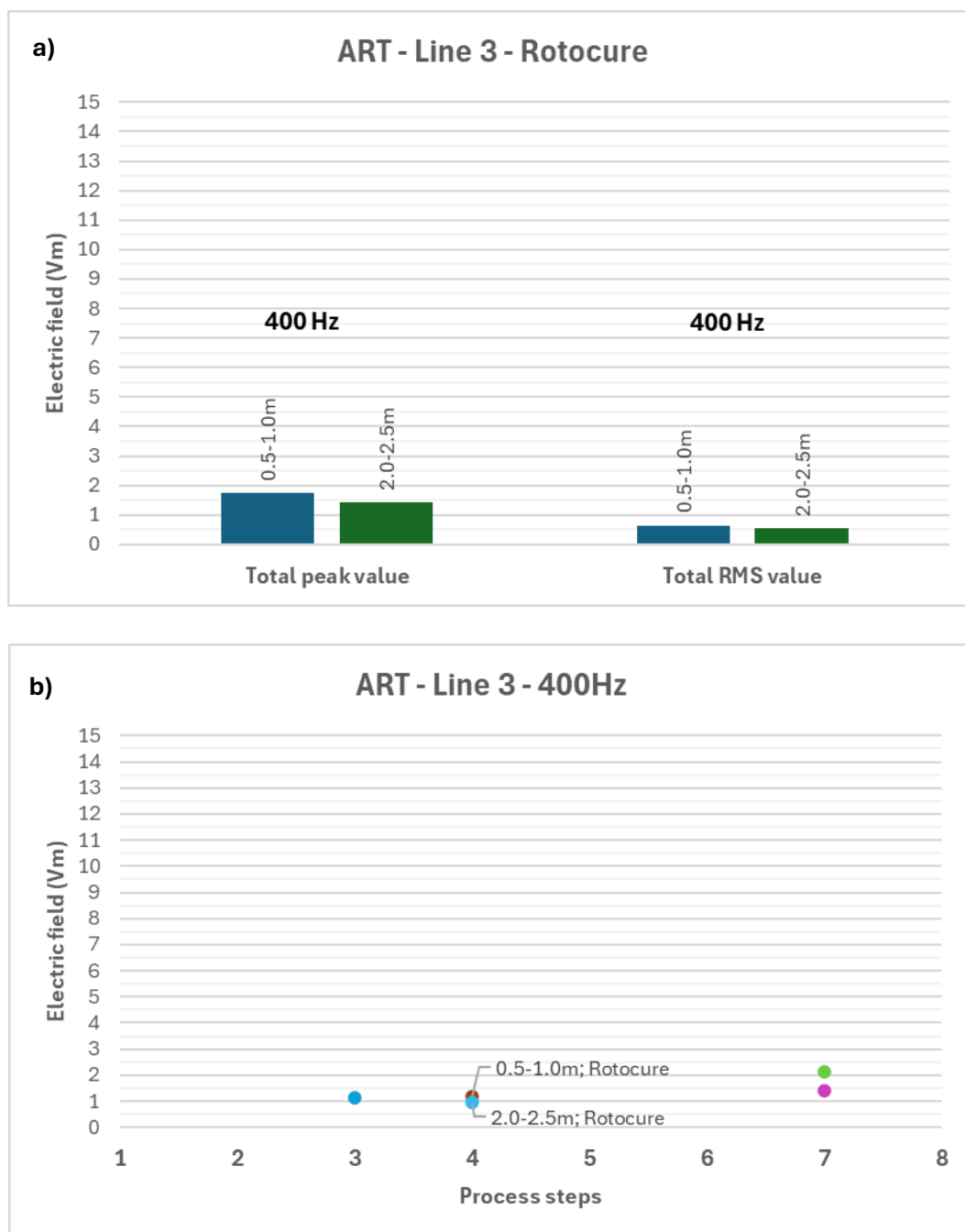


Figure 5.10. Electric field measurements at ARTIGO production line 3: (a) total peak and total RMS values for the rotocure at 400 Hz for several measurement distances (0.5-1.0, 2.0-2.5 m); (b) process steps 1-8 (with identification of rotocure– step 4).

Worker's exposure levels seem to be task-dependent, with higher values occurring during specific process steps (i.e. rotocure and pre-rotocure). The analysis consistently identifies the rotocure and the pre-rotocure as the main sources of electromagnetic fields across the ARTIGO production lines 1, 2 and 3. The reproducibility of results across different lines demonstrates the robustness and stability of the observed exposure patterns. However, all measured levels remain

well below regulatory limits, confirming safe baseline operating conditions (i.e., occupational exposure limit of 6 mT and 20 000 V/m for the magnetic and electric fields, respectively).

Although current ARTIGO operations in lines 1, 2 and 3 remain safe, the integration of new technologies should prioritise reducing operator presence in high-field areas through automation, improved layout design, and effective shielding, ensuring that distance-based exposure attenuation is maintained. Overall, the ARTIGO baseline exposure is predictable and well-controlled, supporting the safe integration of future electrification technologies.

5.2 K-FLEX EMF results

The baseline EMF assessment at the K-FLEX facilities was carried out on 12nd February 2026, under normal operating conditions. At the time of the visit, only production line 1 was active, while the adjacent line, positioned approximately 1.5–3 m away and identical in configuration, was not in operation. The facility had a workforce of roughly ten employees and an overall area of about 500 m², with the general mechanical ventilation system running continuously during the measurements. Indoor environmental conditions were stable, with a temperature of 26.2 °C and a relative humidity of 32.7 %. The layout of the eleven equipment units and corresponding process steps that constitute line 1 is schematically represented in the figure below (Figure 5.11). Line 1 is located at one end of the factory floor, and the inactivity of the neighbouring line ensured that the measurements reflected only the electromagnetic fields generated by the equipment operating in line 1. This configuration also allowed unobstructed access to each process step during the assessment.

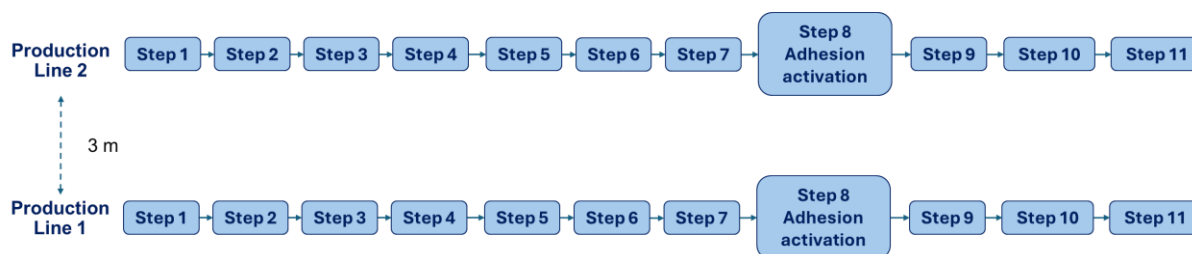


Figure 5.11. Plant of K-FLEX with the production lines 1 and 2.

Figure 5.12 shows the magnetic field levels in line 1 of K-FLEX.

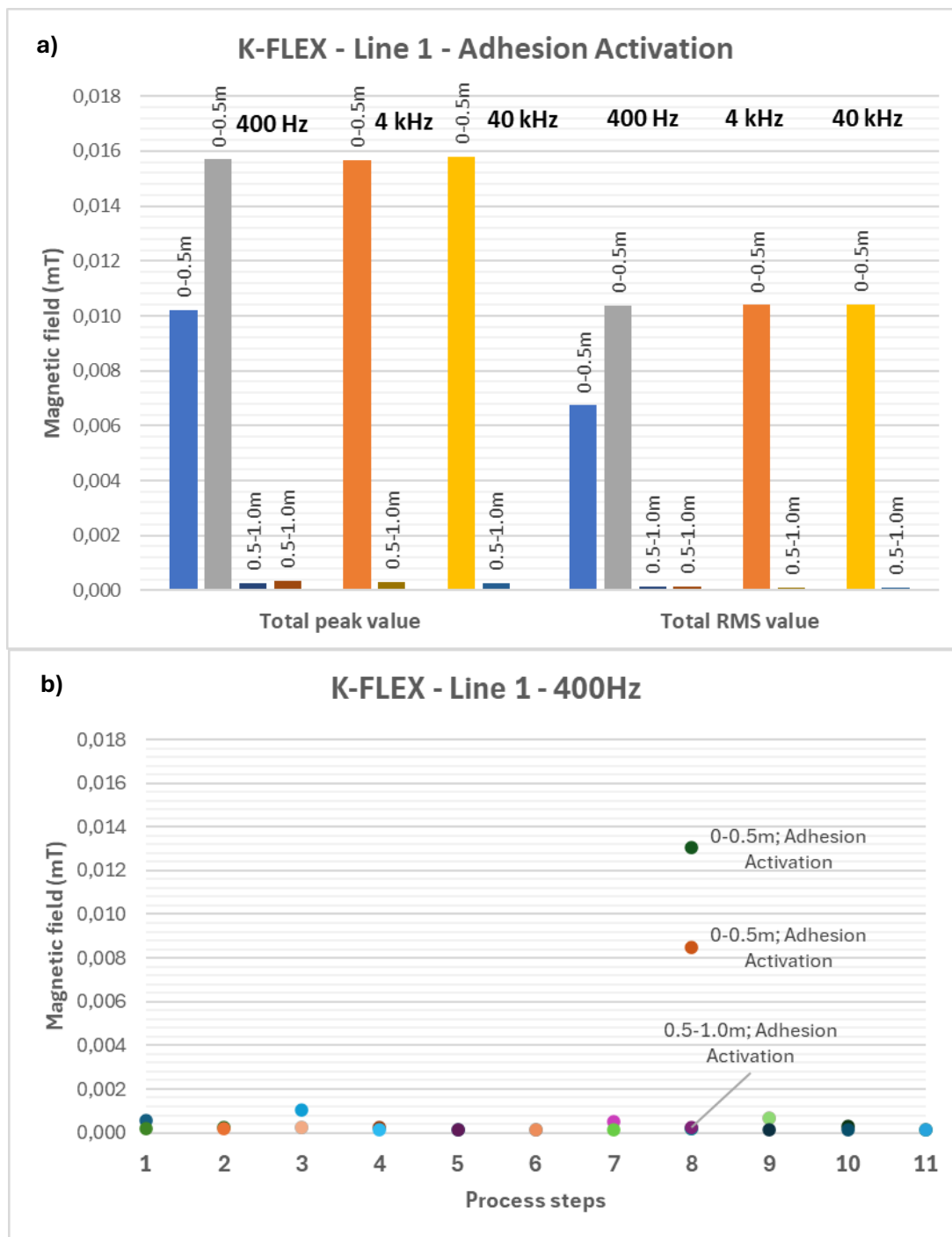


Figure 5.12. Magnetic field measurements at K-FLEX production line 1: (a) total peak and total RMS values for the Adhesion Activation Induction at 400 Hz, 4 kHz, and 40 kHz for several measurement distances (0-0.5, 0.5-1.0 m); (b) process steps 1-11 (with identification of induction adhesion activation – step 8).

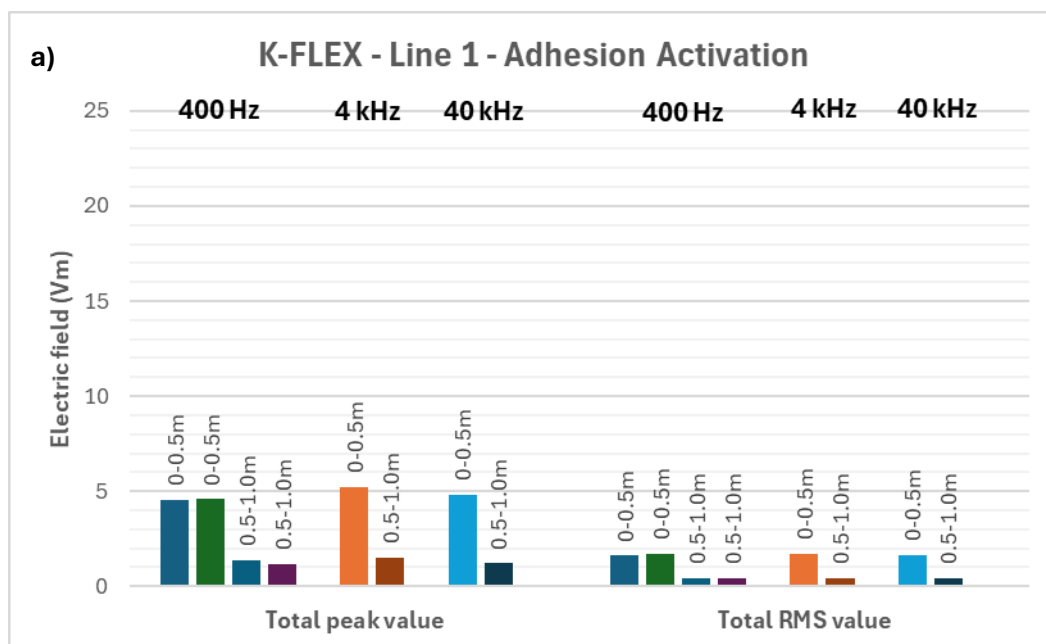
The highest magnetic field levels occur at 0–0.5 m from the induction adhesion activation system, with a sharp attenuation at 0.5–1.0 m. Peaks are concentrated at the induction adhesion-activation step (step 8), reflecting the characteristic magnetic-field output of the

induction system. No other process steps exhibit comparable values, indicating that the higher levels observed at step 8 arise from the equipment's operating behaviour rather than from measurement conditions. Although the magnetic-field levels at the induction adhesion-activation step (step 8) are higher than those observed in the remaining process steps, they remain well below the applicable exposure limits. Nonetheless, this step represents the point of highest field intensity in the line, meaning that closer operator positioning at this stage would warrant continued attention to good work practices, even under compliant exposure conditions.

Higher-frequency components (in the kHz range – 4 and 40 kHz) are also present, consistent with the switching behaviour of the induction system's power-electronics converters. However, these components remain low in magnitude and decrease rapidly with distance, indicating effective shielding and limited electromagnetic coupling.

All measured magnetic-field values remain well below the OEL of 6 mT, confirming that the current operation of the adhesion-activation system presents no significant EMF-related risks for workers.

Figure 5.13 shows the electric field levels in line 1 of K-FLEX.



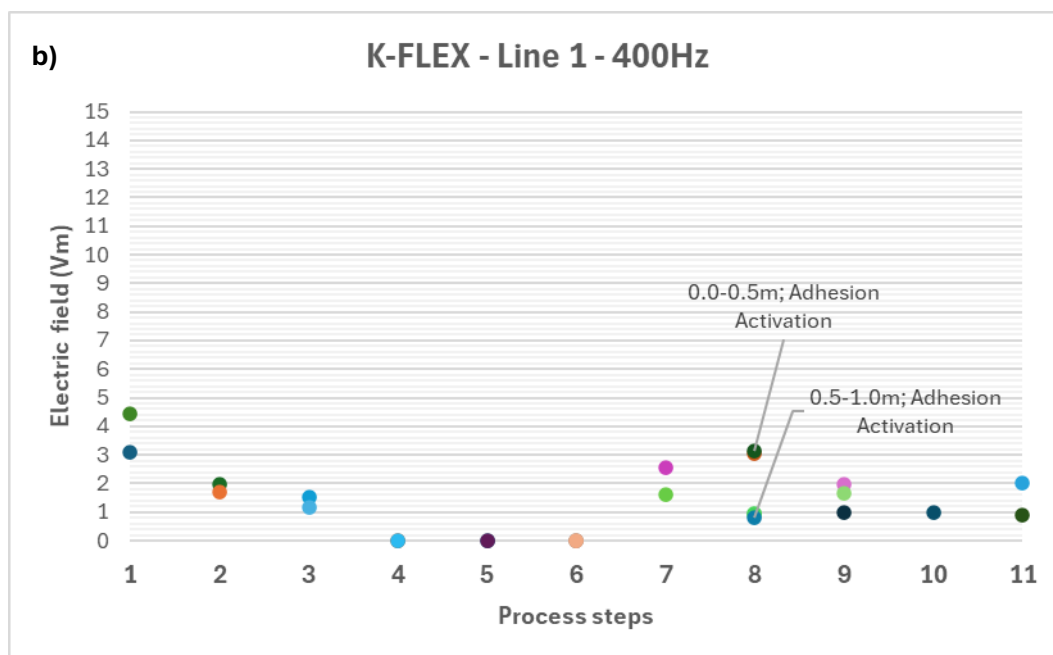


Figure 5.13. Electric field measurements at K-FLEX production line 1: (a) total peak and total RMS values for the adhesion activation induction at 400 Hz, 4 kHz, 40 kHz and 100 kHz-8 GHz for several measurement distances (0-0.5, 0.5-1.0 m); (b) process steps 1-11 (with identification of induction adhesion activation – step 8).

Electric-field values remain low across all measured frequencies, including the kHz range and up to the GHz band, and decrease consistently with distance. No significant peaks are detected, indicating that the adhesion-activation system does not generate relevant electric-field emissions beyond the expected switching behaviour of its power-electronics converters. Measured values remain far below the OEL of 20 000 V/m, confirming negligible electric-field exposure for operators.

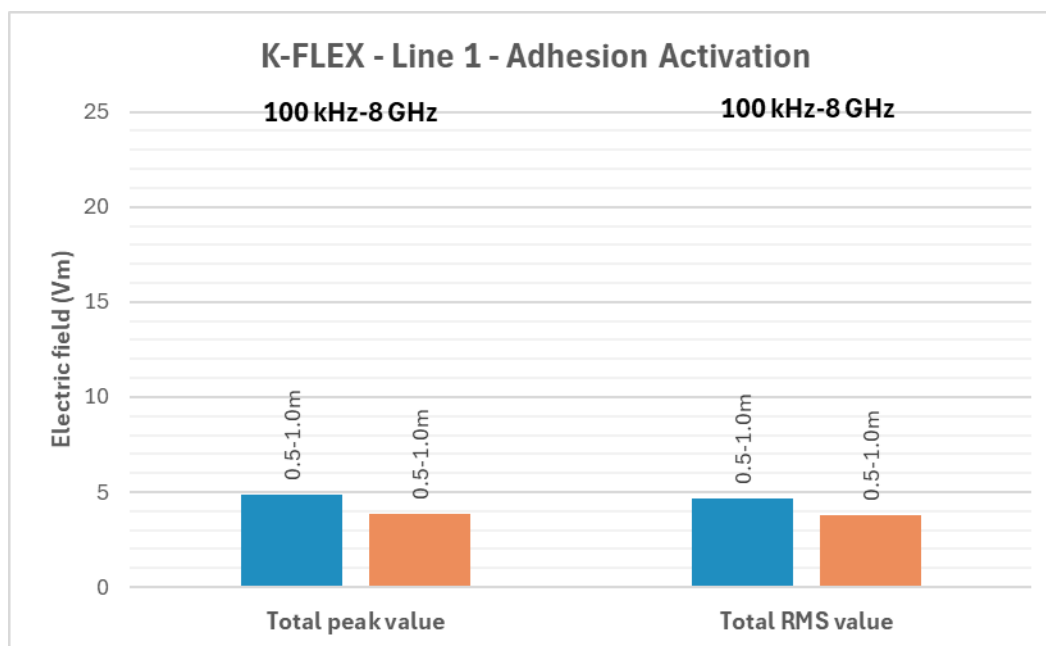


Figure 5.14. Electric-field measurements at K-FLEX production line 1, in the adhesion-activation step, obtained using a dedicated high-frequency probe (100 kHz–8 GHz).

On the other hand, measurements in the 100 kHz–8 GHz range (Figure 5.14), performed using a dedicated high-frequency probe, also show very low electric-field levels. No significant RF components were detected, indicating that the adhesion-activation system does not emit relevant high-frequency radiation beyond the expected switching behaviour of its power-electronics converters. This confirms the absence of unintended RF leakage and demonstrates effective shielding across the full frequency spectrum.

In conclusion, magnetic and electric fields in line 1 of K-FLEX are consistently well below regulatory limits, making them a non-critical factor in the overall EMF exposure profile. Exposure levels are strongly influenced by distance to the source and by specific process steps (i.e., adhesion-activation induction). Worker exposure is intermittent and closely linked to task execution, particularly during activities requiring proximity to equipment.

6 Preliminary H&S Implications of JOULIA Conceptual Designs

The assessment presented in this section provides a preliminary analysis of the H&S implications associated with the conceptual designs of the JOULIA induction and microwave heating systems. While the detailed engineering of both technologies is still under development, the conceptual designs delivered in D5.1 and D6.1 already define the fundamental operating principles, heating mechanisms, enclosure characteristics and expected EMF behaviours. These elements are essential for anticipating potential worker exposure conditions and identifying early H&S considerations that will later be refined once the final system specifications become available.

The following subsections summarise the key features of the conceptual designs and outline their relevance for H&S assessment, focusing on aspects such as heating architecture, induction and microwave coupling, shielding strategies, expected EMF emission patterns, operational interfaces and maintenance requirements. This preliminary analysis establishes the basis for defining realistic exposure scenarios and for planning the measurement strategy to be implemented once the demonstrators are installed.

6.1 Overview of JOULIA Induction System Conceptual Design (D5.1)

The conceptual design of the JOULIA induction heating system, developed under Task 5.1 and reported in Deliverable D5.1, defines the overall architecture of the induction module that will be integrated into the rotocure. The design establishes the operating principles, electromagnetic configuration, mechanical integration and thermal management strategies that underpin the future demonstrator. The level of detail achieved at this stage is sufficient to support prototype fabrication and provides the necessary basis for a preliminary assessment of H&S implications.

The system comprises induction coils, magnetic materials and a set of mechanical components that ensure structural stability, electrical insulation and controlled cooling. These include a bobbin, a plastic support base, an aluminium enclosure and forced-air ventilation. A top insulating layer provides electrical isolation while facilitating airflow. Together, these elements generate and concentrate the magnetic field, maintain mechanical integrity and ensure safe operating temperatures.

The design process began with preliminary electromagnetic simulations to explore feasible coil configurations and operating conditions. These simulations guided the definition of the coil geometry and the selection of magnetic materials, ensuring that the system operates within safe electrical, thermal and magnetic limits. A refined 3D model was subsequently developed to incorporate realistic spatial constraints, mechanical supports and enclosure requirements.

Magnetic materials were included to improve efficiency and reduce stray fields, helping to direct the magnetic flux toward the heating region. The mechanical structure was designed to secure the coils and magnetic components, maintain appropriate clearances and support active

cooling. The enclosure accommodates multiple cooling fans and includes ventilation openings to ensure adequate heat dissipation during operation.

With the full mechanical and magnetic structure defined, additional electromagnetic and thermal simulations were performed to validate the behaviour of the complete system. These analyses confirmed that magnetic flux densities remain below material saturation thresholds, that losses in the coils and magnetic components stay within acceptable limits, and that the system can maintain safe operating temperatures under representative load conditions. The airflow pattern within the enclosure supports effective heat extraction, and the design allows for additional cooling capacity if required.

A preliminary layout for the integration of the induction module into the rotocure, both for the oil-heating structure and the back-plate heating configuration, was also developed, indicating feasible power delivery and temperature uniformity. The conceptual design therefore provides a robust technical foundation for prototype construction, testing and subsequent optimisation.

From an H&S perspective, the conceptual design highlights several aspects relevant for preliminary analysis: the presence of high-frequency currents in the coils and conductors, the use of magnetic materials to concentrate flux, the role of the metallic enclosure and cooling system, the expected thermal gradients, and the physical accessibility of the module during operation and maintenance. These elements form the basis for the preliminary H&S implications discussed in the following section.

6.1.1 Preliminary H&S Implications of the Induction System

Based on the system architecture, operating principles and expected integration into the rotocure, the following hazard categories are relevant (summarized in Table 6.1):

- EMF.
- Thermal hazards.
- Electrical hazards.
- Mechanical hazards.
- Operational and maintenance hazards.

Table 6.1: Preliminary hazard identification from the JOULIA induction system conceptual design.

Hazard Category	Description
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EMF	• The system operates with high-frequency currents in the induction coils and associated conductors, which may generate localised EMF in the intermediate-frequency range. • Magnetic materials help concentrate the flux and reduce stray fields, although residual emissions may occur near openings or during maintenance. • EMF exposure during normal operation is expected to remain low due to the metallic enclosure and physical separation from operators.
Thermal	• Induction coils, magnetic components and heated surfaces may reach elevated temperatures during operation. • The enclosure and cooling system are designed to maintain safe external temperatures, but internal hot spots may occur. • Contact with hot components may pose a risk during maintenance or if access controls are bypassed.
Electrical	• The system includes power electronics and high-frequency conductors that must remain fully enclosed and insulated. • Potential risks include electric shock, arcing or exposure to energised components if enclosures are opened without proper lockout procedures.
Mechanical	• The module includes fans, ventilation openings and structural elements that require secure mounting. • Improper installation or mechanical failure could lead to vibration, component displacement or restricted airflow.
Operational and maintenance	• Accessing the interior of the enclosure may expose workers to hot surfaces, residual magnetic fields or electrical components. • Maintenance activities may require temporary removal of shielding or cooling elements, increasing exposure potential.

Three preliminary exposure scenarios can be identified, considering the conceptual design and the operational context of the rotocure. During normal operation of the rotocure, operators remain at a safe distance from the induction module, as no direct interaction with the system is required during routine production. In this scenario, the metallic enclosure, magnetic components and overall structural design act as passive shielding, significantly limiting the emission of electromagnetic fields. Thermal and electrical elements remain fully enclosed and inaccessible, ensuring that worker exposure remains minimal.

During start-up and shutdown procedures, workers may approach the system to perform visual checks or interact with control interfaces. Even in these situations, exposure levels are expected to remain low, provided that the enclosure remains closed and all safety interlocks are respected. These activities do not require direct contact with the induction module, and the system continues to operate in an isolated and protected state.

The scenario with the highest potential for exposure arises during maintenance and troubleshooting activities. Opening the enclosure may temporarily reduce the effectiveness of the shielding and expose workers to hot surfaces, residual magnetic fields or electrical components. For this reason, such interventions must follow strict lockout–tagout procedures, include adequate cooling periods and ensure controlled access to the interior of the module.

Formal maintenance protocols are essential to guarantee safe working conditions during these operations.

The conceptual design already incorporates several features that support safe operation. However, additional measures should be considered (see Table 6.2).

Table 6.2: Preliminary control measures for the JOULIA induction system.

Control category	Preliminary measures
Engineering	• Maintain a fully closed metallic enclosure with minimal openings. • Ensure adequate forced-air cooling and thermal monitoring to prevent overheating. • Integrate interlocks to prevent access to internal components while the system is energised. • Provide clear labelling of hot surfaces and electrical hazards. • Develop operating procedures for start-up, shutdown and routine checks.
Administrative	• Establish maintenance protocols including lockout–tagout, cooling time requirements and access restrictions. • Provide training on EMF awareness, thermal hazards and safe handling of induction equipment.
Exposure monitoring and verification	• Conduct EMF measurements during prototype testing and commissioning to confirm compliance with applicable exposure limits. • Verify external surface temperatures and airflow performance under representative operating conditions.

The preliminary analysis indicates that the JOULIA induction system can be operated safely when appropriate engineering and administrative controls are implemented. The enclosure, magnetic flux-guiding elements and cooling system play a central role in limiting EMF emissions and thermal risks. The next stages of prototype testing and integration engineering will provide the data required for a complete H&S assessment, including quantitative exposure measurements and validation of control measures.

6.2 Limitations of the Preliminary Analysis and Path to Final Assessment

The preliminary H&S analysis presented in this deliverable is based exclusively on the conceptual design of the induction heating system and on the information currently available within WP5 and WP6. As the engineering activities for the microwave system are still ongoing, and the subsequent technical deliverables (D5.2, D5.3, D6.1 and D6.2) have not yet been finalised,

several aspects of the assessment remain indicative and will require further refinement as the project progresses.

At this stage, the analysis does not incorporate prototype testing results, detailed performance data or measurements under operational conditions. These elements are essential to validate electromagnetic emissions, thermal behaviour, enclosure performance, and the effectiveness of the proposed control measures. Similarly, the integration engineering foreseen in Tasks 5.2 and 5.3, as well as the final system configuration to be demonstrated in WP9, will provide the necessary information to confirm exposure scenarios, maintenance requirements and operational safety procedures.

The absence of the microwave system conceptual and engineering deliverables also limits the ability to perform a complete cross-technology assessment. The final H&S evaluation must consider both heating technologies, their combined installation in the demonstrators, and any potential interactions between systems, operators and the surrounding industrial environment.

The path to the final assessment will therefore rely on:

- Prototype construction and experimental validation of the induction and microwave systems.
- Completion of the remaining design deliverables in WP5 and WP6.
- Integration engineering and installation planning.
- Exposure measurements and verification activities during commissioning and demonstration.

These upcoming stages will provide the quantitative evidence required to complete the H&S assessment, confirm compliance with applicable standards and refine the control measures proposed in this preliminary analysis.

7 Final H&S Requirements

7.1 Requirements derived from baseline EMF assessment

The combined analysis of EMF exposure levels in both demonstrators, ARTIGO and K-FLEX, confirms that occupational EMF is low, well-controlled and compliant with regulatory limits. Exposure is primarily driven by proximity to high-current equipment and specific operational tasks, rather than by continuous environmental conditions.

The current risk profile indicates that no occupational exposure limits are exceeded under any measured scenario. All measurements remain well below the established limits of 6 mT for magnetic fields and 20 000 V/m for electric fields, demonstrating full compliance with Directive 2013/35/EU [1] under baseline conditions.

These findings confirm a low-risk EMF environment in both demonstrators, providing a solid foundation for the adoption of new electrification technologies. To ensure continued safety, future systems should maintain or enhance shielding effectiveness, minimise operator proximity to EMF sources and incorporate EMF awareness, training and monitoring practices. Under these conditions, induction and microwave technologies can be safely implemented, provided that design-for-safety principles, such as enclosure, automation and distance, are consistently applied.

Based on the baseline assessment, the following requirements should guide future system design and operation:

- Maintain shielding effectiveness — ensure enclosures and cable routing minimise stray fields.
- Reduce operator proximity — prioritise automation and remote operation for high-field tasks.
- Preserve distance-based attenuation — maintain layouts that avoid unnecessary worker presence near high-current components.
- Implement EMF awareness and training — ensure operators understand proximity-driven exposure patterns.
- Integrate monitoring practices - establish periodic EMF measurements and routine verification of shielding integrity to ensure continued compliance and early detection of deviations from expected field levels.

7.2 Requirements derived from JOULIA conceptual designs

Based on the conceptual design of the JOULIA induction heating system, several preliminary requirements have been identified to ensure the safe, effective and compliant integration of the technology into the rotocure demonstrator. These requirements reflect the current level of technical maturity and will be refined as prototype testing, optimisation and integration activities progress.

The following tables consolidate these preliminary requirements into a structured format, grouping them by thematic category to support their integration into the JOULIA system design and subsequent engineering stages.

- **Technical and Integration Requirements**

Table 7.1: Technical and integration requirements.

Requirement	Description	Rationale
Mechanical stability	The induction module shall be mounted on a stable mechanical structure ensuring correct alignment of coils, magnetic components and enclosure.	Prevents misalignment, vibration and performance degradation.
Thermal management	Adequate airflow, ventilation openings and forced-air cooling must be ensured to maintain safe operating temperatures.	Avoids overheating and ensures continuous, reliable operation.
Clearance for integration	Sufficient space must be provided for installation, access to mounting points and maintenance.	Facilitates safe integration and future servicing.

- **Electrical and Control Requirements**

Table 7.2: Electrical and control requirements.

Requirement	Description	Rationale
Compatible power supply	The system shall be supplied by a power source matching the electrical specifications of the conceptual design.	Ensures stable operation and prevents electrical faults.
Enclosed electrical interfaces	All electrical interfaces must remain fully enclosed and insulated, with interlocks preventing access when energised.	Reduces risk of electric shock and unintended access.
Safe control interfaces	Start-up, shutdown and monitoring must be possible without approaching energised components.	Minimises operator exposure to electrical hazards.

- **Safety and EMF Requirements**

Table 7.3: Safety and EMF requirements.

Requirement	Description	Rationale
Magnetic-flux containment	The metallic enclosure and flux-guiding elements shall be preserved to limit stray fields.	Ensures compliance with EMF exposure limits.
Hazard labelling	Hot surfaces and electrical hazards must be clearly labelled.	Supports safe operation and hazard awareness.
Surface temperature limits	External surfaces must remain within safe temperature limits under representative conditions.	Prevents thermal contact injuries.
Support for LOTO (lockout-tagout)	The system must support lockout-tagout procedures during maintenance.	Ensures safe isolation during servicing.

- **Operational and Maintenance Requirements**

Table 7.4: Operational and maintenance requirements.

Requirement	Description	Rationale
No direct contact during operation	Routine operation shall not require physical contact with the induction module.	Reduces unnecessary exposure to heat and EMF.
Maintenance only when de-energised	Maintenance must only occur when the system is de-energised and cooled.	Prevents electrical and thermal hazards.
Restricted internal access	Access to internal components shall be limited to trained personnel.	Ensures competent handling of high-energy components.
Verification of system integrity	Maintenance procedures must include checks of enclosure integrity, cooling performance and electrical insulation.	Ensures long-term safety and performance.

7.3 Requirements to be validated/updated after final engineering

The current conceptual designs of the induction and microwave systems are not yet finalised, and several engineering elements remain under development. As a result, a number of requirements cannot be validated at this stage and will need to be updated once prototype testing, detailed engineering and demonstrator-level integration are completed.

Key aspects still require validation, including electromagnetic performance under real operating loads, thermal behaviour during continuous operation, enclosure integrity, combined operation of induction and microwave modules, and the final mechanical and electrical interfaces with the rotocure demonstrator.

These requirements depend on the outcomes of Task 5.2 (prototype testing), Task 5.3 (design optimisation), the conceptual and engineering design of the microwave system in WP6, and the integration and demonstration activities planned in WP11, as well as on the evaluation of replication potential in the selected use cases.

The table below summarises the requirements that remain conditional and will be validated, refined or completed once the final engineering designs and prototype data become available.

Table 7.5: Requirements to be completed in future stages.

Requirement	Description	Rationale
Prototype validation	Requirements will be refined following prototype testing (Task 5.2) and design optimisation (Task 5.3).	Provides quantitative data on EMF, thermal behaviour and performance.

Microwave system integration	Additional requirements will depend on the conceptual and engineering design of the microwave system (WP6).	Ensures compatibility and combined-system safety.
Demonstrator-level assessment	Final requirements will be completed after integration and demonstration activities in WP9.	Confirms real-world performance and operational safety.

These requirements will be consolidated into the final engineering package once quantitative data from prototype operation and system integration become available, ensuring that the JOULIA demonstrators meet all safety, performance and compliance criteria.

8 Conclusions

This deliverable (D4.5) builds upon the foundations established in D4.3, which analysed the operating principles of induction and microwave heating systems, identified their associated hazards and risks, and reviewed the relevant regulatory frameworks governing electromagnetic fields (EMF), electrical safety, thermal hazards and process-related risks. D4.3 demonstrated that realistic, scenario-specific assessments are essential for characterising worker exposure and for implementing effective preventive measures, and it provided the methodological and regulatory basis for the present baseline study.

Building on this foundation, D4.5 assessed EMF exposure in the real industrial environments of the JOULIA demonstrators (ARTIGO and K-FLEX), with the objective of establishing a baseline risk profile prior to the integration of the new induction and microwave heating systems. The assessment combined operator questionnaires, field observations and quantitative EMF measurements, applying a monitoring methodology aligned with technical standards. This approach ensured that the baseline reflects realistic operating conditions and captures the influence of workstation layout, task characteristics and equipment behaviour.

The baseline EMF assessment conducted in the ARTIGO and K-FLEX demonstrators confirms that electromagnetic exposure in both industrial environments is low, well-controlled and fully compliant with the exposure limits defined in Directive 2013/35/EU [1]. All measured electric- and magnetic-field values remained far below the applicable limits of 20 000 V/m and 6 mT, respectively, demonstrating that the existing processes operate within a robust safety margin and do not pose EMF-related risks to workers under normal operating conditions.

The analysis of exposure patterns shows that EMF levels are primarily influenced by proximity to high-current equipment and by specific operational tasks, rather than by general environmental conditions. This behaviour is consistent across both demonstrators and provides a reliable basis for defining future design requirements. The findings also confirm that the introduction of new electrification technologies, such as induction and microwave heating, can be safely pursued, provided that design-for-safety principles such as shielding effectiveness, distance-based attenuation and controlled operator access are consistently applied.

The requirements derived from the baseline assessment (Section 7.1) establish a clear set of conditions for maintaining safe EMF levels in future system deployments. These include maintaining enclosure integrity, minimising unnecessary operator proximity, ensuring adequate automation, and implementing structured EMF awareness and training. Together, these measures provide a stable foundation for the safe integration of advanced heating technologies in industrial environments.

In parallel, this deliverable incorporates a preliminary analysis of the Health & Safety implications of the conceptual designs for the induction and microwave systems. The resulting design-derived requirements address mechanical integration, electrical interfaces, enclosure integrity, thermal management and operational safety. These requirements reflect the current level of technical maturity and will guide the engineering activities in WP5 and WP6. However, several aspects remain dependent on future engineering stages. Prototype testing (Task 5.2),

design optimisation (Task 5.3), the conceptual and engineering design of the microwave system (WP6), and the integration and demonstration activities planned in WP11 will provide the quantitative data needed to validate EMF performance, confirm thermal behaviour, assess combined system operation and finalise the safety and operational requirements. The evaluation of replication potential in selected use cases will further refine these requirements and support broader industrial applicability.

Overall, D4.5 consolidates the baseline EMF conditions of the demonstrators, translates them into actionable safety requirements, and integrates preliminary design considerations for the JOULIA technologies. Together, these elements provide a coherent, evidence-based framework for the safe integration, validation and future deployment of induction and microwave heating systems in industrial environments, ensuring that safety, compliance and operational performance remain central throughout the development and demonstration phases of the project.

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@JouliaProjectEU



@jouliaproject.bsky.social



www.jouliaproject.eu



info@jouliaproject.eu

Partners



artigo



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