AI 5.0 Platform for circular economy optimization in the ESIA process

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Introduction

Herambiente Spa is a leading company in waste treatment and is the first Italian operator in the environmental sector. For years, it has ensured the sustainable management of all types of waste for companies and local communities, as well as, carrying out remediation activities for contaminated areas and sites. The company manages 97 plants and treats approximately 7 million tons of waste annually, including over 5 million tons of special waste and more than 1.5 million industrial waste.

Such a large network of facilities requires continuous monitoring and control, focusing on management, process, and analytical parameters across various environmental matrices: air, water, soil, waste, noise. These activities generate millions of data points each year. For instance, waste-to-energy plants alone produce over 200,000 data annually related to emissions.

Currently, the primary purpose of this extensive monitoring is to ensure that all operations comply fully with sector regulations. Looking forward, the goal is to enhance the value of this vast amount of information to optimize processes with a focus on sustainability and support ecological transition.

To achieve this, Herambiente has joined a project to develop an artificial intelligence-based platform. This platform will process environmental and contextual data (e.g. weather, air and water quality, and traffic), to assess the sustainability of the plants in relation to their surroundings. Additionally, it will provide recommendations for reducing environmental impacts and risks through prevention, mitigation, compensation, and monitoring measures.

Project Objective

The project is part of the IAIA25 *Impact Assessment in the Age of Artificial Intelligence* initiative. Its goal is to enhance and scale the existent regional institutional screening system (DGR n. 5223/21) by integrating it into a comprehensive Environmental Impact Assessment (EIA) methodology that leverages Artificial Intelligence applications. This aims to define effective and adaptive corrective actions within a 5.0 framework. The Permitting Platform 5.0 framework involves the participation of institutional evaluators, evaluated companies, consultants, solution providers (suppliers), and technical/technological enablers.

The objective of the project is the shared definition of an economic incentive system capable of supporting the managerial and structural decisions of companies, based on the level of materiality and effectiveness of those decisions in relation to the actual needs of the local territorial context.

The system is structured into the following components:

1. **Data acquisition** related to the devices/industrial processes and their network of market/supply chain relationships and interconnections;

2. **Impact measurement and assessment**, both in diagnostic terms (causes) and correlational terms (effects);
3. **Recommendation of actions** for:
   (a) improving the site-specific knowledge framework of individual production sites (measurements);
   (b) mitigating impacts/risks for each specific impact component (operations, indicators);
   (c) compensating environmental, economic, and social impacts, including through the creation of tools with financial value.

The specific objective of the project is to implement a tool that enhances the vast environmental data set available, thereby supporting Herambiente in adopting more sustainable practices. The Q-Cumber ESIA (Environmental and Social Impact Assessment) Platform was selected for this purpose. This platform is powered by AI-driven dynamic computational GIS impact processor (DCGIS® system).

Materials and methods

The Platform

The Platform aims to objectively measure and evaluate both the direct and indirect, specific and cumulative environmental impacts of an industrial activity. It does this by developing indicators that ensure complete comparability and transparency in impact assessments. Using an evidence - based model, the Platform formulates operational recommendations, which include information integration, mitigation strategies, and measures for impact compensation Additionally, it enables the management of an adaptive monitoring system of the related to the assessment of these impacts. Specifically, the Platform allows for the evaluation of:

1. the effectiveness of the recommendations in reducing impacts and risks (operation tuning);
2. the consistency of these recommendations with sustainability objectives, going beyond mere regulatory compliance (DSS tuning).

The Platform also supports the enhancement of positive environmental performances across the supply chain by quantifying large-area impacts and the identifying and quantifying impact credits on a site-specific scale.

An important feature of the Platform is the promotion of structured stakeholder participation, during both the planning and implementation phases of projects. This is achieved through specific mechanisms that ensure well-defined sharing and information transparency among companies, institutions and citizens.

The implementation methodology integrates industry standards with artificial intelligence tools. Once fully operational, this approach allows for predictive assessments and adaptive monitoring, providing detailed information in real-time. As a pioneering initiative, it actively involves institutions, communities and businesses, significantly contributing to the mitigation of environmental impact and the improvement of ESIA performance. This is accomplished through effective use of AI in a participatory governance model and includes an automatic performance control system compliant with the EU AI Act.

The methodology: evaluation of the environmental and social sustainability of the plant

By using the Platform, which collects territorial context data and processes it alongside plant data, we can achieve two key outcomes: a measure of the plant's actual sustainability within its operating territory and site-specific operational recommendations for improving its environmental impacts. This process utilizes a methodology based on systems engineering applied to territorial systems, whit the following steps:

Phase A1 – Methodological sharing of the Permitting 5.0 model. This phase involves proactively engaging institutional stakeholders, including Ministry of the Environment, Regions, Provinces, Municipalities, ARPA, and ASL, to foster the construction of the multi-stakeholder network.

Herambiente Multi-stakeholder network

Phase A2 – DCGIS® methodology for Impact Assessment evaluation;

1. Definition of the reference spatial domain (**R**).
2. Definition of the reference time domain (**T**).
3. Identification of the **elements** of the system (**pressure** and **vulnerability elements**: $\boldsymbol{E} = \boldsymbol{E_\sigma}, \boldsymbol{E_\varepsilon}$).
    a. Characterization of the **project/plant** (**σ_1**): conceptual model through the georeferenced characterization of the main operations carried out (OP_j , e.g. water discharge points, atmospheric emissions, etc.).
    b. Characterization of the reference **territorial-environmental context: elements of environmental vulnerability** (**ε_0 -** biodiversity, human communities, landscape, soil, water, air...) and **territorial stressors** (**σ_0** – infrastructures, industrial plants, quarries, landfills, farms...) present in the surrounding territory within a radius of at least 1500 m.
4. Identification of element $\boldsymbol{e = u_j, v_k}$**attributes (pressure and vulnerability attributes,**).
   To define the attributes, predictive/statistical data, nominal data (authorisation maximums) and real data (deriving from monitoring carried out/management data) can be used.

5. Definition of the **Relationships** between elements/attributes (**E x E, uj x uj , E xu**):

   a. Measurement and evaluation of **specific direct impacts** on environmental resources (ER)

   $$I(\sigma_1) = Z_{\sigma_1}^{ER} = Z_{m_1}^{ER}$$

   b. Measurement and evaluation of **cumulative direct impacts** on environmental resources (ER)

   $$I(\sigma_0) = Z_{\sigma_0}^{ER} = Z_{\overline{m_1}}^{ER}$$

   The calculation of impacts (typically annual) is based on standard emission factors and benchmarks (e.g. EEA). For cumulative impacts, the platform compares the plant's emission load with that of other environmental stressors present within 1500 m.

   c. Measurement and evaluation of **specific indirect impacts**;

   $$I(\sigma_1) = Z_{\sigma_1}^{HC,ES} = Z_{m_1}^{EC,ES}$$

   d. Measuring and evaluating **cumulative indirect impacts**.

   $$\boldsymbol{I(\sigma_0) = Z_{\sigma_0}^{HC,ES} = Z_{\overline{m_1}}^{HC,ES}}$$

   To assess indirect impacts on human communities (HC) and ecosystems (ES), the platform uses fallout models based on management and context data, allowing the calculation of emissions on sensitive receptors and the generation of analytical reports.

6. Construction of the analytical database containing the **detected states (a_i)**, starting from which it is possible to carry out:
   a. Analysis of the trend of the collected data (univariate analysis, bivariate analysis, multivariate analysis);
   b. Evaluation against attention thresholds/benchmarks;
   c. Diagnostics (Machine Learning).
7. Identifying any issues encountered in the domain of the selected relationships.
8. The identification and evaluation of the impact components of optimized Improvement Actions (A), given any identified/predicted environmental/social problem

   $$A = q - [\sigma_1(\varepsilon_0 + \varepsilon_1)\ |\beta|\ \sigma_0(\varepsilon_0 + \varepsilon_1)]$$

   β = *Machine Learning predictors*

Phase A3 – Planning of strategic/operational improvement objectives and related key actions through specific Impact Performance Improvement Plans, broken down into objectives and key results/indicators (OKR Plans) which include impact measurement/mitigation/compensation actions, defined in a measurable and site-specific manner, which can be monitored over time in an adaptive manner.

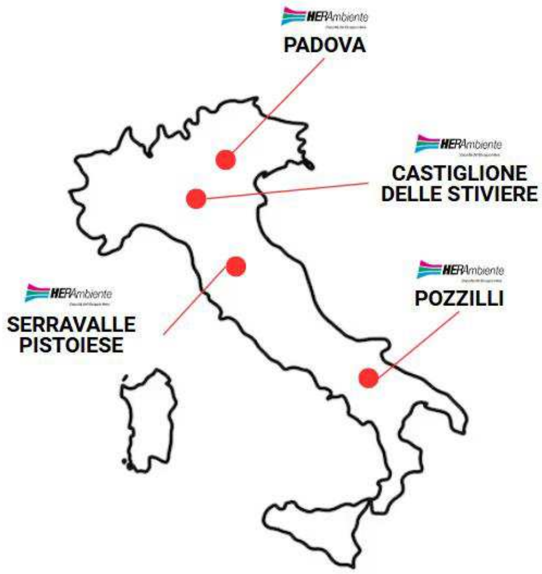
Phase A4 – Execution of the actions foreseen by the OKR Plan

Phase A5 - Operational management of the dynamic measurement and preventive/predictive monitoring system (ML-BCA)

9. Monitoring the impact of actions, assessing the impact of actions and identifying corrective actions based on machine learning and predictive control calibrated with counterfactual outcomes (ML – BCA – Machine Learning Based Corrective Actions).

Plant sites being studied

To provide consistency to the project, the Platform has been established at four plant sites selected for their diverse treatment processes, location, and public and social significance:



1. a non-hazardous waste co-incineration plant in the municipality of Pozzilli (IS)
2. a non-hazardous waste incinerator in Padua;
3. a selection and recovery plant for urban waste from separate collection, along whit non-hazardous special waste, located in the municipality of Castiglione delle Stiviere (MN);
4. a landfill for non-hazardous waste in the municipality of Serravalle Pistoiese (PT).

The waste-to-energy plant in Pozzilli (Molise) was selected as a case study to demonstrate the voluntary implementation of the AI Platform aimed at objectively assessing the environmental impact of the plant. This initiative seeks to verify its sustainability and identify potential improvement actions, including prevention, mitigation, compensation, and monitoring.

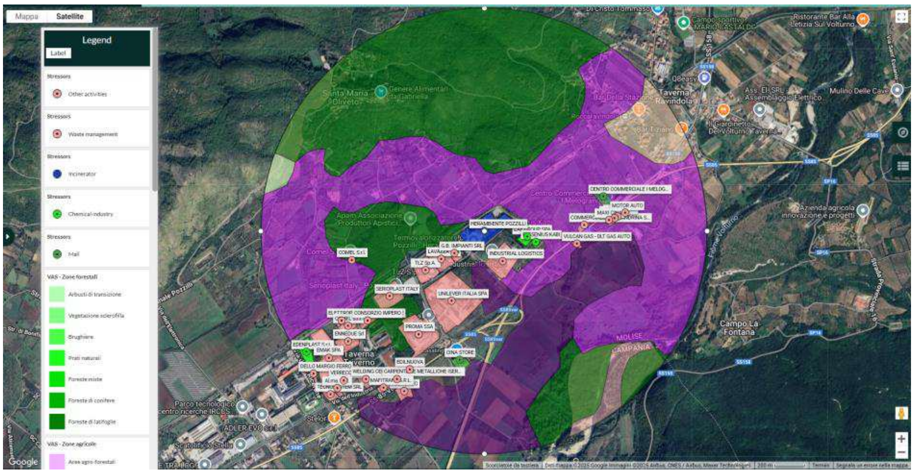
Results and Discussion

The non-hazardous waste co-incineration plant is situated in the industrial area of Pozzilli, which is part of the Isernia-Venafro industrial nucleus in the province of Isernia. It is authorized to co-incinerate non-hazardous waste (CSS, CDR, and some other special waste) with a capacity of 93,500 tons per year designated for energy recovery. The facility consists of a treatment line with a nominal thermal capacity of approximately 50 MWt and a nominal electrical power output of 11.5 MWe. The thermal energy produced by the furnace is used to generate electrical energy for the plant's self-consumption, with an excess energy sold to the national grid. On average, the plant sells approximately 85,000 MWh of electricity per year to the grid.

The **operational domain of analysis** (**R**) for the case study is defined by a circular area centred on the centre of gravity of the Pozzilli waste-to-energy plant, which is located in the Piana del Venafro. This plain is a typical intramontane basin situated in the southwestern sector of the province of Isernia, characterized by complex orographic and climatic condition.

The **time domain of analysis** (**T**) pertains to the period from 2016 to 2023 whit a focus on evaluating company performance specifically in the year 2023.

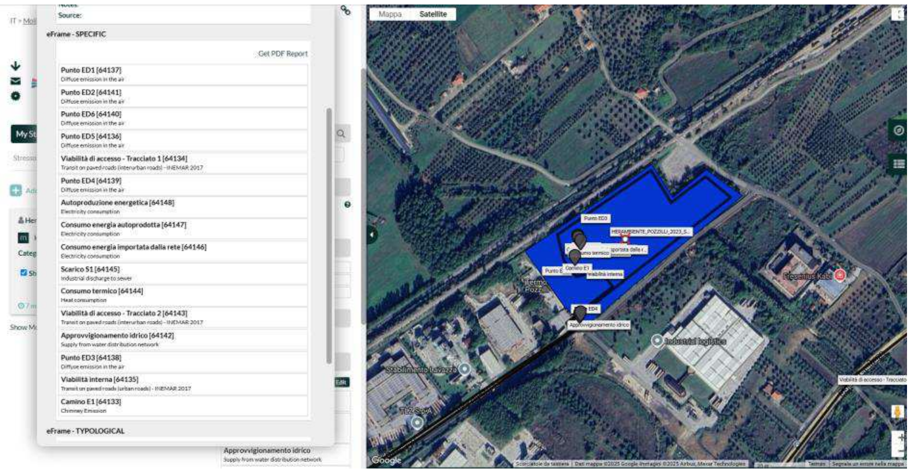
From the identification of the **system elements present in the context** (**E**), a total of 34 pressure elements ($\boldsymbol{\sigma_0}$) have been identified. Regarding vulnerability elements ($\boldsymbol{\varepsilon_0}$), the analysis reveals the presence of forest areas (33% of the operational domain), agricultural areas (48%), Sites of Community Interest (5%) and areas with high population density (2%).



Identification of the pressure elements ($\boldsymbol{\sigma_0}$) and vulnerability elements ($\boldsymbol{\varepsilon_0}$) in the reference context

In the conceptual model of the company under study ($\boldsymbol{\sigma_1}$), **16 operations** have been identified that may impact environmental resources. This include:

- elements reported in the Environmental Impact Assessment AIA, such as chimney emissions E1, exhaust emissions S1, and consumption of water, heat, and energy),
- elements that are monitored annually, including diffuse emissions related to the waste storage area, light ash discharge, and slag loading
- contributions from induced traffic associated with the delivery end removal of waste and raw materials, which accounted for 4304 vehicles in 2023, based on data provided by the plant).



Conceptual model of the Pozzilli waste-to-energy plant

For the identification of the **attributes**, the following factors were considered: predictive/statistical data for the reference context, and nominal data (authorization maximums) and real data (deriving from the monitoring conducted from 2016 to 2023, representing approximately 15,000 data point per year) for the waste-to-energy plant.

The analysis of the **relationships** between elements and attributes was conducted by measuring and evaluating both **specific and cumulative direct and indirect impacts.**

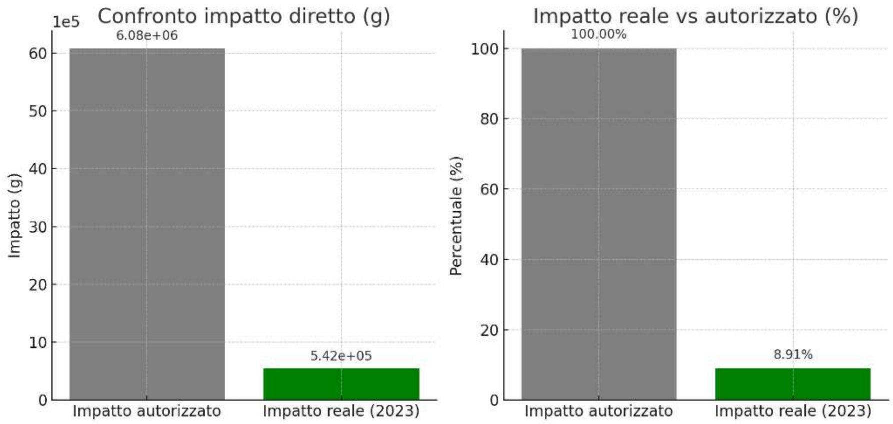
Recent studies by the relevant authorities have assessed air quality in the Piana, revealing critical issues related to winter weather conditions that hinder pollutant dispersion. These studies identified biomass combustion as the primary source of pollution. Given the specific characteristics of the area, PM_{10} was selected for the analyses presented here. This choice was made as a precautionary measure, equating PM_{10} to Total Suspended Dust (TSP), a parameter that is continuously monitored by the SME. The selection of PM_{10} it was based on its status as a legally regulated parameter, allowing for direct comparison with current legal limits.

Number of PM10 impacts of the reference context = n. 104

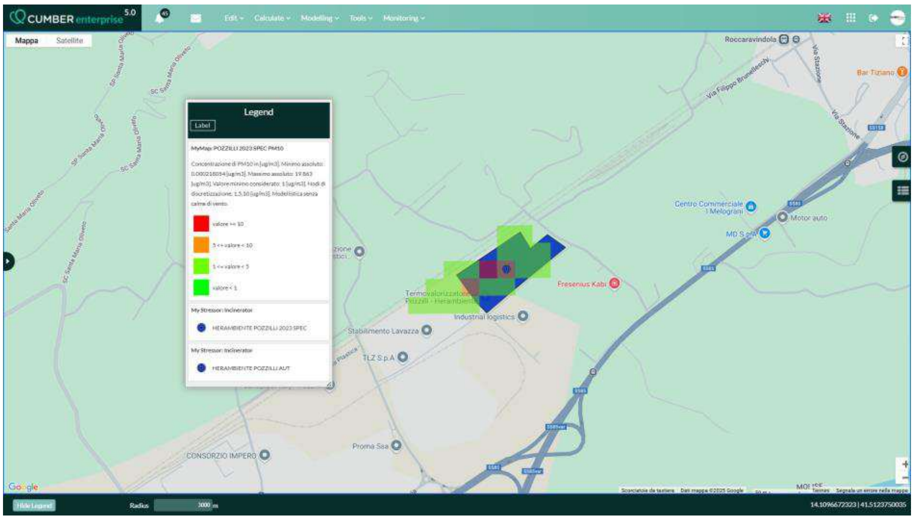
In 2023, we conducted an analysis of the environmental performance of the waste-to-energy plant. This analysis compared actual emission data with the limits established by the AIA to assess the plant’s efficiency in terms of regulatory compliance and its impacts on the environmental.

The findings revealed that the direct PM10 emissions from the plant, which encompass all its operational processes, account for only about 8.91% of the potential impact that could arise if the plant were to operate at the authorized emission limits. Additionally, a modeling analysis of specific indirect impacts indicated potential consequences within the surrounding area primarily associated with the plant's operations.

	Indicator	Environmental Resource	Flux direction	Stressor category	Stressor	Direct impact[*] Sum: 6.63e+6 g
1	PM10	Air	toER	Incinerator	HERAMBIENTE POZZILLI AUT	6.08e+06 g
2	PM10	Air	toER	Incinerator	HERAMBIENTE POZZILLI 2023 SPEC	5.42e+05 g



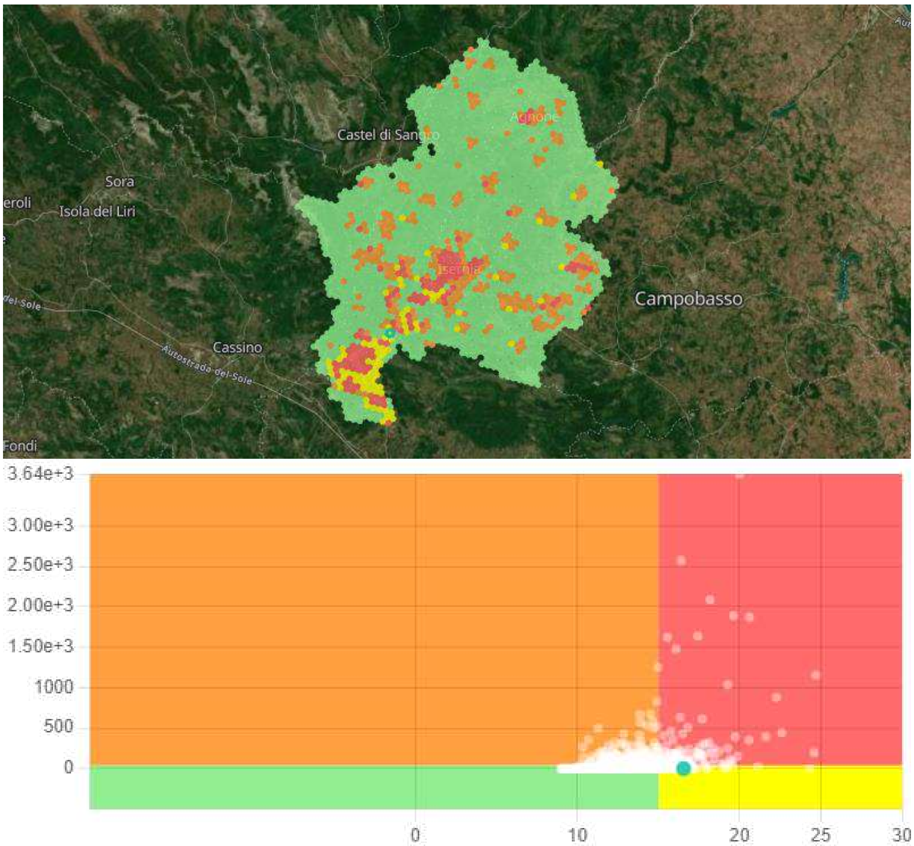
Direct impacts specific to the waste-to-energy plant – Analysis of the positive impact performance (2023)



Specific indirect impacts of the waste-to-energy plant (2023)

This result indicates a highly positive environmental performance, showcasing the plant's efficient management and technological process.

The assess the materiality of the impacts within the reference context, we conducted a bivariate analysis as outlined in the methodology.



Level of materiality of the impacts of the reference context

<table>
<tr><th colspan="2">Vulnerabilità del contesto (Popolazione)</th><th colspan="2">Pressione del contesto (PM10)</th><th colspan="2">Pressione del termovalorizzatore (PM10)</th></tr>
<tr><td colspan="2">ε0</td><td colspan="2">σ0</td><td colspan="2">σ1</td></tr>
<tr><td>X</td><td></td><td></td><td>X</td><td>X</td><td></td></tr>
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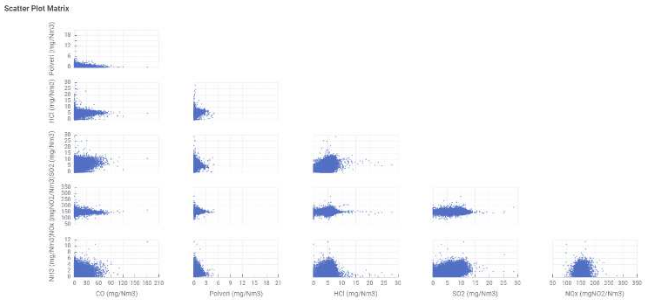
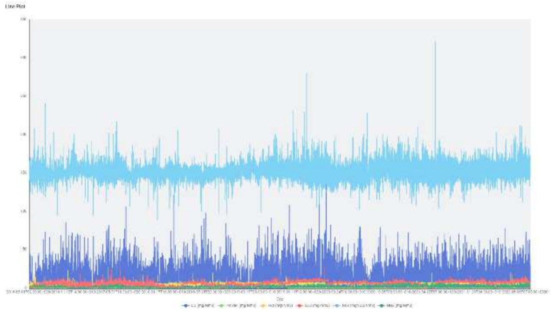
Materiality rating score representation diagram

Building on this, we conducted the first multi-variate correlation analyses of the data from the SME. This step is essential before configuring the AI module dedicated to diagnostic and predictive analyses. The AI module will also incorporate additional management data from the company, such as the consumption of reagents, energy, water and incoming waste, along with contextual data from the ARPA Molise environmental monitoring network.





Conclusions: Lesson learnt

The platform serves as a standardized methodological tool for identifying, implementing, and managing measures to improve environmental and social impacts. The methodology has shown that it is possible to create an innovative decision-support system, which utilizes both industry standards and extensive databases developed through machine learning algorithms. This system is capable of measuring and continuously improving performances relating to impacts. Initial applications conducted on the case study have revealed that:

1. data holds tremendous potential for verifying compliance with specific regulations and assessing environmental and social sustainability;
2. The overall territorial context - geographical, residential and productive - is an integral and substantial part in the evaluation of the actual impacts and, consequently, of the environmental and social sustainability of the company;
3. Sharing available data sets among companies, regulatory agencies, and local authorities enables more accurate, objective, and transparent assessments;
4. Models-based approaches will increasingly play a crucial role in the objective determination of issue, which will help guide actions at all levels effectively;
5. Clearly representing the results of these complex assessments makes it easier for Local Communities and relevant Authorities to understand;
6. the transparency and usability of information foster a climate of trust and constructive collaboration among various stakeholders, leading to positive social outcomes.

The initial results achieved have established a foundation for the collaborative implementation of a general model (Framework 5.0) designed to utilize AI in supporting *permitting activities.* This framework serves two main purpose*:*

1. identifying the *driver* indicators that have the greatest impact on improving outcomes, which will help define effective actions and solutions, and
2. to facilitate adaptive monitoring of the performance of the implemented solutions (such as mitigations, compensations, and monitoring) based on of the environmental and social evidence gathered.

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