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Environmental, social and governance (ESG) assessment with a two-phase goal-programming-based optimization model: a comparative study of Envipark and Kalundborg eco-industrial parks

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Introduction: Eco-industrial parks (EIPs) are key infrastructures in the transition toward circular and low-carbon production systems, yet their Environmental, Social and Governance (ESG) performance is still commonly assessed through static metrics that offer limited support for improvement strategies.

Methods: This study proposes a two-phase decision-support framework: a passive goal-programming assessment that measures gaps to regulatory targets and best practices, and an active phase that identifies cost-effective portfolios of improvement measures under budgetary and technical constraints. The framework is applied to two European EIPs, Envipark (Italy) and Kalundborg (Denmark).

Results: In the passive phase, Envipark shows criticalities mainly in the environmental dimension, while Kalundborg achieves higher performance levels, with residual weaknesses in social indicators related to welfare and community engagement. The active phase confirms distinct strategic trajectories: Envipark tends toward incremental and demonstrative measures, whereas Kalundborg prioritises transformative, large-scale initiatives.

Discussion: The framework provides a transparent tool for policymakers and EIP managers to align investment decisions with ESG and decarbonization goals. Overall, it advances methodological practice by operationalizing goal programming for dual passive/active ESG assessment, offering a replicable framework for EIPs, and bridging the gap between assessment and decision-making in sustainability governance.

KEYWORDS

eco-industrial park, ESG, goal-programming model, sustainable development, urban developing strategy

1 Introduction

In recent years, European industrial policies have progressively redefined their objectives, placing the integration of economic competitiveness, environmental sustainability and social responsibility at the centre. This orientation has translated into strategic instruments such as the European Green Deal and the Fit for 55 package, which set ambitious targets for reducing emissions and converting production systems (European Commission, 2019). In Italy, this approach has been further strengthened by the introduction of the principle of sustainable development into the Constitution, which establishes the State's duty to protect the environment and biodiversity also in the interests of future generations (Parlamento Italiano, 2022). In this context, industrial areas are increasingly called upon to demonstrate their performance not only in economic terms, but also through environmental, social and governance (ESG) criteria.

Eco-Industrial Parks (EIPs) represent one of the most relevant territorial tools for implementing these objectives, as they apply the principles of industrial ecology and the circular economy to the scale of production districts (Genc and Kurt, 2024). Their origins can be traced back to the first spontaneous practices of industrial symbiosis that developed in Kalundborg starting in 1972, subsequently formalized within the theoretical framework of industrial ecology introduced by Frosch and Gallopoulos (1989). During the 1990s, experimental programs promoted by the U.S. Department of Energy and pilot initiatives such as Burnside Industrial Park in Canada marked the transition from theory to practice (Chertow, 2000), while in 1995 the Kalundborg case was recognized as the first internationally operational EIP (Gibbs and Deutz, 2007). In parallel, organizations such as UNIDO and the World Bank have supported the dissemination of EIPs globally through guidelines and technical tools (Lowe, 1997), with a particular expansion in East Asia thanks to national policies oriented towards industrial symbiosis and cleaner production (Ehrenfeld and Gertler, 1997). A turning point is the publication of the Framework for Eco-Industrial Parks in 2017, which defined shared criteria for the qualification of EIPs (UNIDO et al., 2017; Zhu et al., 2007). Today, EIPs are recognized as strategic infrastructures for the ecological transition, decarbonization, and resilience of industrial systems promoting industrial symbiosis, infrastructure sharing, and cooperation between businesses and local communities (Chertow, 2007; Conticelli and Tondelli, 2014; Tessitore et al., 2015).

Alongside this conceptual and operational development, regulatory and financial pressure has grown for ESG criteria to be integrated into decision-making processes and the management of production areas, also in response to European directives such as the Corporate Sustainability Reporting Directive and international standards such as the United Nations Principles for Responsible Investment. Empirical studies also show that ESG portfolios tend to be more resilient in times of turbulence in European markets, including Italian ones, highlighting that sustainability does not only represent a regulatory constraint, but can constitute a factor of competitiveness (Iannone et al., 2025).

Despite these developments, ESG evaluation continues to present significant methodological criticalities. Available rating systems are often heterogeneous, qualitative, and poorly comparable, with convergence levels among major providers estimated at around 60%, compared to almost complete convergence in credit ratings (Berg et al., 2022; Capizzi et al., 2021; Berk and Green, 2004). These divergences arise from the adoption of different indicator sets, highly variable weighting schemes, and limited methodological transparency due to the proprietary nature of many calculation models. Added to this is the difficulty of grasping sectoral and territorial specificities: the same entity may receive conflicting assessments depending on the provider considered, for example, due to differences in the weight given to governance or environmental performance.

These criticalities are further amplified when ESG analysis is extended from individual enterprises to complex systems such as Eco-Industrial Parks. Existing ESG models, designed primarily for individual companies, struggle to represent the systemic dynamics of industrial districts, characterized by material and energy interdependencies, plurality of actors, and infrastructure constraints. Consequently, many ESG assessments operate as true "black boxes", opaque in weighing, unclear in objectives and difficult to translate into operational guidelines (Murè et al., 2024; Agosto and Tanda, 2025).

A similar fragmentation also emerges in the scientific literature on the evaluation of EIP performance. Alongside standardized indicator-based frameworks and composite sustainability indices, quantitative approaches focused on matter and energy exchanges, based on Material Flow Analysis and Life Cycle Assessment, are widespread, as are multi-criteria methods used to analyze trade-offs and intervention priorities, often including stakeholder preferences (Anelli et al., 2024). More recently, models oriented towards the design and optimization of EIPs as dynamic industrial relations networks have been developed, shifting the focus from ex post evaluation to future performance planning (Felicio and Amaral, 2013; Lütje and Wohlgenuth, 2020; Koch et al., 2022). However, such approaches are rarely integrated into a single methodological framework capable of explicitly linking ESG performance measurement with the selection of improvement strategies under realistic economic and operational constraints.

This separation between evaluation and decision support represents a significant methodological gap, particularly in complex industrial contexts such as Eco-Industrial Parks, where decision makers need tools capable not only of measuring ESG performance but also of translating identified gaps into coherent, contextualized, and financially sustainable intervention trajectories. This study fits into this framework, proposing an innovative methodological approach based on Goal Programming for the evaluation and optimization of ESG performance at the EIP scale. The integration of a passive evaluation phase, oriented towards measuring gaps with respect to regulatory and soft law targets, and an active evaluation phase, aimed at selecting improvement strategies under explicit constraints, allows us to overcome the limitations of existing ESG approaches and transform evaluation from a descriptive exercise to a tool to support sustainable industrial governance. The definition of the objectives and methodological approach of the work, presented in the following section, is based on these foundations.

2 Aim of the work

Existing studies on EIPs mostly rely on descriptive ESG benchmarks or generic multi-criteria rankings and do not offer an operational optimisation framework that (i) jointly addresses environmental, social and governance dimensions at park scale, (ii) integrates regulatory and soft-law targets with stakeholder-derived weights, and (iii) translates ESG gaps into costed portfolios of improvement strategies under explicit constraints.

The aim of this study is to define and apply a methodological approach based on Goal Programming (GP) capable of both measuring and optimizing the ESG performance of Eco-Industrial Parks (EIPs), thereby addressing the lack of integrated assessment-and-optimization frameworks identified in the literature.

The proposed framework relies on a two-phase GP structure:

- In the first phase, a passive assessment evaluates the environmental, social and governance performance of the Turin (Italy) and Kalundborg (Denmark) EIPs against targets derived from EU regulations and international best practices.
- In the second phase, an active assessment identifies feasible improvement strategies by applying an optimization model consistent with economic and operational constraints.

This two-step structure allows the GP methodology to be used both as an evaluation tool and as a mechanism for prioritizing interventions. Overall, the approach provides a comprehensive ESG evaluation while supporting the selection of coherent and cost-efficient improvement actions. In this respect, the framework contributes to sustainable industrial policy development in alignment with UN 2030 Agenda goals no. 8, 9, 11, 12 and 13 (UN, 2015).

3 Background

The ESG assessment landscape is characterized by three main families of tools with complementary purposes: reporting frameworks, proprietary ratings developed by specialized agencies, and disclosure platforms that collect self-reported data from companies. Among the reporting frameworks, the Global Reporting Initiative (GRI) is the most widely used reference at company level. Established in 1997 as a joint initiative of CERES (Coalition for Environmentally Responsible Economies) and the United Nations Environment Programme, the GRI was designed to ensure transparency and comparability in sustainability reporting, based on the principle of materiality and structured reporting sets (Universal Standards and thematic standards) (Global Reporting Initiative, 2021).

In terms of proprietary ratings, MSCI ESG Ratings and Sustainalytics ESG Risk Ratings offer summary metrics of ESG risk exposure and management using different methodologies, weights and scales: MSCI, for example, assigns companies a rating ranging from CCC (insufficient ESG risk management) to AAA (advanced management and best practice in the sector). This score is based on sector-relevant indicators, such as CO₂ emissions

intensity per unit of revenue or the share of renewable energy in total consumption. Sustainalytics, on the other hand, uses a numerical score from 0 to 100 that measures the so-called “unmanaged” ESG risk, i.e., the share of exposure to environmental, social and governance factors that could result in negative financial impacts: the lower the score, the better the risk management (MSCI Inc., 2024; Morningstar Sustainalytics, 2023).

The CDP (Climate/Water/Forests) platform functions as a disclosure and thematic scoring system, with an emphasis on climate change, water and deforestation (CDP, 2024), while Refinitiv (LSEG) aggregates and normalizes ESG indicators from public sources to construct comparable scores across a broad base of listed companies (Refinitiv LSEG Business, 2023). In summary, these tools differ in purpose and methodology but remain essentially descriptive: they report performance or compare firms, yet they do not indicate how to solve identified ESG gaps or support multi-criteria decision-making.

These approaches differ structurally in terms of the type of indicator (qualitative descriptive vs. quantitative measurable), the nature of the standard (regulatory/mandatory vs. voluntary), and the purpose of use (reporting transparency vs. comparative risk/performance assessment). Specifically, GRI favours voluntary reporting focused on materiality (Global Reporting Initiative, 2021); ratings (MSCI, Sustainalytics, Refinitiv) produce comparative assessments using proprietary methodologies (MSCI Inc., 2024; Morningstar Sustainalytics, 2023; CDP, 2024; Refinitiv LSEG Business, 2023); CDP emphasizes self-assessment and commitments in specific environmental areas (CDP, 2024). These differences—combined with the heterogeneity of sources and a frequent lack of economic and operational constraints in scoring models—fuel asymmetries and poor comparability between outputs, as evidenced by the divergence between ratings (agreement around 60%), and the resulting difficulties in using them for stringent decision-making purposes (Berg et al., 2022; Capizzi et al., 2021; Berk and Green, 2004; Murè et al., 2024; Agosto and Tanda, 2025). Furthermore, most schemes remain “company-centric” and therefore ill-suited to capturing the systemic/territorial dimension of EIPs, where interdependencies, shared infrastructure and common constraints are important. To fill these gaps, the methodological literature has made extensive use of MCDM (Multi-Criteria Decision Making) tools and multi-objective approaches. Among the most widely used MCDM methods are the Analytic Hierarchy Process (AHP) for the hierarchical definition/weighting of criteria (Saaty, 2013), TOPSIS for selecting the alternative closest to the “ideal solution” (Hwang and Yoon, 1981), as well as weighted scoring schemes and fuzzy approaches for dealing with uncertainty, vagueness and linguistic judgements (classic contributions by Bellman and Zadeh on decision-making in fuzzy environments) (Keeney and Raiffa, 1993; Bellman and Zadeh, 1970). These evaluation tools are useful for ordering or selecting alternatives in the presence of multiple criteria, but they do not always allow choices to be traced back to explicit economic/operational constraints or to simulate trade-offs between objectives in a transparent manner. As a consequence, MCDM methods remain primarily evaluative rather than prescriptive, limiting their capacity to guide actionable decisions in constrained industrial contexts.

This led to interest in GP, which originated in the pioneering work of Charnes and Cooper and developed through increasingly rich formalizations and applications (Charnes and Cooper, 1957; Ignizio, 1976). GP allows us to: (i) manage multiple objectives by translating them into deviations (positive/negative) from targets; (ii) assign weights and priorities (weighted and preemptive/lexicographic models); (iii) incorporate realistic constraints (budgets, thresholds, interdependence logic) while remaining within the range of linear programming (Charnes and Cooper, 1957). These characteristics make it particularly suitable for ESG problems, where environmental, social and governance objectives coexist with limited resources and technical/financial constraints (Ignizio, 1976; Tamiz et al., 1998; Jones and Tamiz, 2010). However, most GP applications do not fully exploit this potential to connect performance measurement and optimization, especially in complex territorial industrial ecosystems such as EIPs.

In terms of application, GP has been used in sustainable energy planning, environmental management and highly complex industrial sectors, often in conjunction with MCDM and optimization models, highlighting its ability to transform assessment into decision support with explicit scenarios and trade-offs (Pohekar and Ramachandran, 2004). This methodological tradition provides the basis for the use of GP at the EIP scale, where the unit of analysis is the territorial system (not the individual company) and where the integration between measurement and choice of interventions is essential (Diaz-Balteiro and Romero, 2008). Nevertheless, existing studies tend to apply GP either for performance evaluation or for optimization, but rarely for both simultaneously. This reinforces the need for a two-phase GP framework capable of linking passive assessment with active, cost-constrained prioritization—the main novelty of this work.

In summary, despite the progress made, there is still a lack of methodological approaches capable of systematically connecting assessment and optimization, transforming ESG reporting from a descriptive exercise into a real governance tool. In the specific field of industrial zones and EIPs, socio-ecological and nature-inspired approaches have combined social network analysis, food web metrics and optimisation models to guide the transformation of existing industrial areas and the design of new eco-industrial parks (Genc et al., 2019; Genc et al., 2020). These contributions demonstrate the potential of circular and network-based design, but they primarily address material and energy exchanges and structural properties of the industrial network, without explicitly targeting integrated ESG performance or linking performance gaps to cost-constrained investment strategies. In particular, GP applications on real EIPs, based on observed data and consistent operational constraints, are still sporadic and mainly experimental; the estimation of marginal costs of ESG improvement, which would be a crucial element in guiding intervention priorities and allocating resources efficiently, has been little explored in the literature; the management of interdependencies between environmental, social and governance indicators is often treated informally or left to ex post assessments, with the risk of underestimating trade-offs and synergies. Furthermore, the question of integrating ESG criteria with the economic, technological and social constraints that characterize industrial districts remains largely open, as does the construction of assessment schemes capable of involving multiple actors and multiple decision-making levels, reflecting the complexity inherent in EIP (Romero and Rehman, 2003).

The literature on sustainability assessment of industrial plants and Eco-Industrial Parks (EIPs) is characterized by methodological fragmentation that limits the ability of available tools to effectively support decision-making processes. ESG indicator and benchmark approaches allow performance to be measured against regulatory or soft law targets, but remain predominantly descriptive and static, providing a diagnostic framework that does not directly translate into operational guidance. Similarly, ESG composite rating models and indices allow for synthetic comparisons between systems, but suffer from limited methodological transparency and do not incorporate economic, technical, or organizational constraints, making them difficult to use for planning concrete interventions at the territorial scale.

In parallel, the literature on industrial symbiosis and the analysis of material and energy flows offers sophisticated tools for the environmental optimization of industrial systems, but tends to focus almost exclusively on the environmental dimension, neglecting the social and governance components that are central to contemporary ESG frameworks. Finally, multi-criteria approaches and optimization models applied to sustainability are widely used to analyze trade-offs between competing objectives, but are often employed either as evaluation tools or as prescriptive tools, rarely consistently integrating both functions.

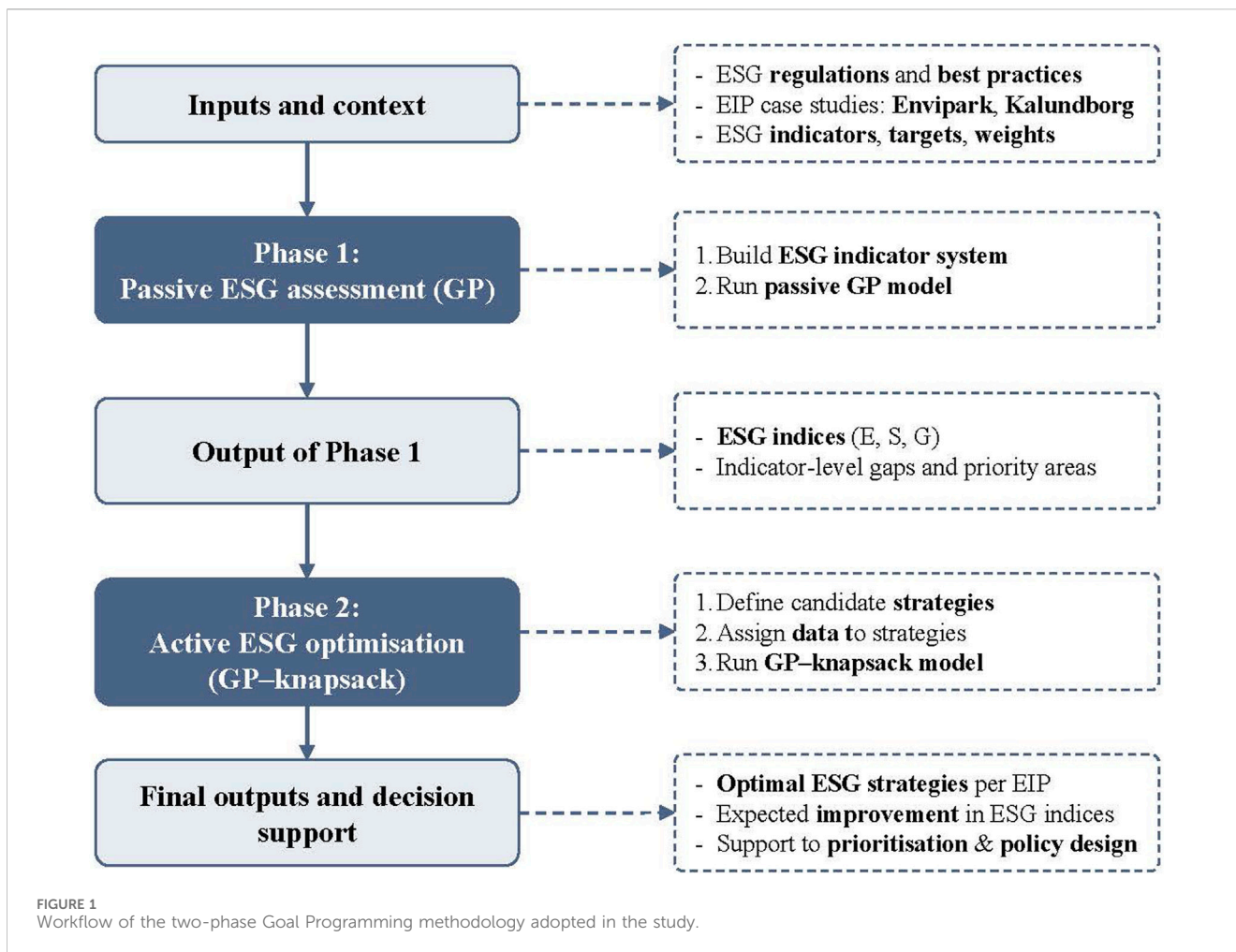
The proposed model lies at the intersection of these strands, overcoming their limitations through a two-stage structure based on Goal Programming. The passive evaluation phase allows for the transparent and systematic measurement of ESG gaps against explicit targets, maintaining the comparability and readability typical of indicator-based approaches. The active evaluation phase, on the other hand, transforms these gaps into optimal intervention portfolios, integrating budget constraints, logical dependencies between actions, and minimum performance thresholds, elements that reflect real decision-making conditions and are often absent in existing ESG models.

Compared to traditional approaches, the main advantage of the model lies in the ability to directly link ESG performance measurement to the definition of operational improvement trajectories, financially sustainable and adapted to the specific context of each EIP. In this way, ESG assessment is no longer conceived as a static compliance exercise, but as a dynamic governance support process, capable of guiding differentiated strategic decisions based on the scale, degree of maturity, and infrastructure assets of the industrial systems analyzed. This integration between assessment and decision-making represents a significant methodological advancement compared to the existing literature and expands the application potential of ESG tools in complex industrial contexts.

4 Methodology

The proposed methodology, summarised in the workflow of Figure 1, is structured into two complementary and sequential phases:

1. Passive assessment of ESG performance with respect to regulatory or best practice targets;
2. Active assessment aimed at the optimal selection of ESG improvement strategies, taking into account economic and logical constraints.



The entire approach is based on GP, suitably adapted to address the specific characteristics of the EIP context. The choice of GP is theoretically supported by its extensive use in sustainability-related optimization problems, particularly where multiple and non-homogeneous objectives must be balanced under explicit constraints (Tamiz et al., 1998; Jones and Tamiz, 2010). Previous applications in environmental planning, resource allocation, energy systems and industrial ecology demonstrate that GP is well suited for contexts—such as EIPs—in which decision-makers must simultaneously consider regulatory targets, resource limitations and interacting objectives (Pohekar and Ramachandran, 2004).

GP is a mathematical programming technique introduced by Charnes and Cooper (1957) to deal with multi-objective optimization problems in which each goal is expressed as the achievement of a predetermined target. Unlike traditional linear programming, which seeks the optimum of a single objective function, GP aims to simultaneously minimize deviations from multiple heterogeneous objectives, often measured in non-comparable units.

In its classical form, goal programming assumes that for each objective j the following goal constraint holds (Equation 1):

$$f_j(x) + d_j^- - d_j^+ = g_j \quad (1)$$

where:

- $f_j(x)$ is the value of the j th objective function, calculated over the decision variables x ;
- g_j is the desired target;
- d_j^- and d_j^+ are the negative and positive deviations from g_j , respectively (both non-negative).

The aggregated objective function of the classical GP model consists in minimizing a linear combination of these deviations, with weights w_j^- and w_j^+ reflecting the relative importance of negative and positive deviations. The model also requires non-negativity constraints and any additional technical or resource constraints characterizing the problem under analysis. This formulation aligns with ESG evaluation logic in EIPs, where performance is interpreted as deviation from normative thresholds, and where multidimensional sustainability objectives require a formal mechanism to aggregate heterogeneous indicators. In the passive assessment of ESG performance for EIP, the classical GP model was specified as follows:

1. Target (g_j): defined on the basis of European regulatory frameworks and best practices in the field of ESG performance;

2. Variables (x_j): represent the normalized performance (0–1) of indicator j ;
3. Deviations considered: only the negative deviations (d_j^-) as the purpose is to measure the gaps to be closed;
4. Constraints: budget constraints for each indicator and non-negativity constraints.

This adaptation preserves the mathematical structure of the classical GP, while orienting its application towards measuring performance with respect to regulatory targets within a multidimensional sustainability framework. The decision to structure the methodology into two phases follows established decision-analysis frameworks that distinguish between the measurement of performance and the identification of feasible improvement actions. In the context of EIPs, this separation ensures conceptual clarity and directly addresses the methodological gap identified in the literature, by linking ESG assessment with constrained optimization in a unified GP-based model.

4.1 First phase. Passive assessment

The first phase of the proposed model aims to measure the degree of alignment between the current performance of each EIP and the performance targets defined on the basis of current ESG regulations, sectoral best practices and institutional benchmarks. To this end, a classical GP model was developed, structured to quantify the negative deviation of each indicator from its reference target threshold and to aggregate the indicators' results into a synthetic performance index for each ESG dimension (environmental, social and governance).

The underlying logic assumes that each observed ESG indicator may show a more or less pronounced gap from the desired target, and that the overall intensity of these gaps represents a reliable measure of the distance of the EIP from a condition of full alignment with ESG objectives.

The model considers a set of n ESG indicators belonging to each of the three dimensions mentioned above. For each indicator j , the following variables are defined:

1. $x_j \in [0,1]$: current performance level of indicator j , normalized in relation to its target value;
2. $g_j \in [0,1]$: normalised target threshold of indicator j ;
3. $d_j^- \geq 0$: negative deviation variable, quantifying the shortfall of the indicator in relation to its target value.

This target–deviation structure is consistent with GP applications in environmental management, where performance gaps are quantified relative to regulatory or best-practice thresholds, making it particularly suitable for ESG assessment frameworks.

The objective function of the model consists of minimizing the weighted sum of the negative deviations from the regulatory targets (Equation 2):

$$\min \sum_{j=1}^n w_j \cdot d_j^- \quad (2)$$

where $w_j \in [0,1]$ represents the relative weight assigned to indicator j . These weights were determined through a

questionnaire administered directly to the Sustainability Teams of Envipark and Kalundborg, which assigned each indicator a level of importance on a 1–5 scale. The values were then normalized so that their total sum equalled 1. The use of weights makes it possible to explicitly model the subjective or strategic relevance attributed to different indicators by the stakeholders directly involved. Stakeholder-derived weights are widely used in sustainability assessment and multicriteria decision-making, as they allow the model to reflect context-specific priorities and ensure legitimacy of the evaluation process in multi-actor systems such as EIPs (Keeney and Raiffa, 1993).

The model constraints are Equation 3:

$$x_j + d_j^- \geq g_j \quad \forall j \quad (3)$$

which ensures that each performance level x_j , together with its possible negative deviation d_j^- , reaches at least the target g_j .

Other constraints impose the non-negativity of the deviation variables $d_j^-, d_j^+ \geq 0$ (2), and the normalization of the performance variables $x_j \in [0,1] \quad \forall j$ (3).

No logical interdependence constraints between indicators were introduced, since this methodological phase is intended solely to measure current performance, without simulating improvement strategies or functional dynamics. Any causal or structural relationships between indicators will be explicitly modelled in the next phase (active assessment), in which coherent and feasible intervention plans will be defined.

Consistently with established decision-analysis frameworks, no logical or economic constraints are introduced in the passive phase, which is conceived as a measurement-oriented model aimed at capturing the current state of performance. Causal and functional interdependencies are explicitly addressed only in the prescriptive phase, where decision feasibility becomes central (Keeney and Raiffa, 1993; Diaz-Balteiro and Romero, 2008).

The variables and parameters used in the model are summarized in Table 1.

4.2 Second phase. Active assessment

The second phase of the methodology is prescriptive in nature and focuses on defining an optimal set of ESG strategies to be implemented, with the aim of maximizing the overall improvement of the EIP's ESG performance while complying with realistic economic and technical constraints. The adoption of a GP–knapsack formulation follows established practices in environmental and industrial decision-making, where feasible intervention sets must be selected under resource constraints and where actions may exhibit precedence or compatibility relationships.

This phase is formulated as a GP problem with binary (0–1) variables, analogous to a knapsack problem, where each “item” represents an ESG improvement strategy and its “weight” corresponds to the cost of implementation.

To formulate the active assessment model, it was first necessary to define the set of potentially feasible interventions aimed at improving the ESG performance of the EIP. Each intervention is

TABLE 1 Summary of variables and parameters used in the GP model for the passive ESG performance assessment phase.

Symbol	Description
j	ESG indicators (with $j = 1$)
n	Total number of ESG indicators considered for each dimension
x_j	Normalized value of indicator j (current performance, [0,1])
g_j	Normalized ESG target value of indicator j ([0,1])
d_j^-	Negative deviation of indicator j from its target g_j
w_j	Normalized weight assigned to indicator j , obtained from questionnaire

characterized by an expected performance improvement (ΔESG_j), expressed in normalized terms on a [0,1] scale, which measures the gain in proximity to the target in case of implementation.

Each intervention was also associated with a total cost ($C_{j,tot}$), calculated as the sum of the maintenance cost of existing strategies and the investment cost required to close the gap with the target. The model assumes the availability of an overall budget (B) representing the maximum financial resource allocated to the implementation of improvement strategies.

For each intervention j , the decision to implement it or not is represented by a binary variable x_j , which takes the value 1 if the intervention is selected and 0 otherwise. Finally, a parameter $\beta \in [0,1]$ was introduced to define the minimum desired level of aggregated performance at the end of the implementation phase, ensuring an overall level of alignment with ESG objectives.

The objective function aims to maximize ESG performance (Equation 4):

$$\max \sum_{j=1}^m \Delta ESG_j \cdot x_j \quad (4)$$

This formulation, based exclusively on ESG increments, ensures comparability among EIPs operating in different economic and regulatory contexts.

The constraints include:

- Budget constraint (Equation 5):

$$\max \sum_{j=1}^m C_{totj} \cdot x_j \leq B \quad (5)$$

ensuring that the total cost of the selected interventions does not exceed the available budget.

The explicit inclusion of budget constraints is consistent with sustainability-oriented optimization approaches, where limited financial resources represent a structural condition rather than a secondary assumption, and are essential to ensure the operational realism of the selected intervention portfolios (Pohekar and Ramachandran, 2004; Diaz-Balteiro and Romero, 2008).

- Logical interdependence constraints (Equation 6):

$$x_i \leq x_k \quad (6)$$

if intervention i requires the completion of intervention k .

Logical interdependence constraints are widely used in multi-criteria and network-based optimization models to represent technical, functional or organizational dependencies among actions. Their inclusion is particularly relevant in Eco-Industrial Parks, where interventions are embedded in interconnected infrastructures and symbiotic relationships, and where the feasibility of certain strategies depends on the prior implementation of enabling measures (Romero and Rehman, 2003; Genc et al., 2020).

The optimal solution provides:

- The list of strategies to be implemented ($x_j = 1$);
- The overall ESG performance improvement achievable within the available budget and under the logical and performance constraints;
- The new average ESG performance level of the EIP after the implementation of the plan.

This approach makes it possible to translate the results of the passive assessment into a coherent, realistic, and replicable operational plan of ESG interventions. By integrating budget limits, logical dependencies and performance thresholds, this phase directly addresses the limitation of existing ESG tools, which typically do not support the translation of assessments into cost-effective and operational intervention plans.

5 Case studies and ESG indicators

5.1 Envipark EIP district

The Envipark EIP, located in Turin, is an innovation and technology transfer hub focused on environmental technologies and energy efficiency. The park hosts a wide range of companies, start-ups and research centres operating in the fields of renewable energy, energy efficiency, sustainable waste management and low-emission mobility. The presence of infrastructures such as integrated photovoltaic systems, a hydroelectric power plant and hydrogen production systems from waste enables the park to generate renewable energy on-site, in compliance with the requirements of the RED III Directive.

In the field of energy efficiency, Envipark has implemented radiant systems for climate control, charging stations for electric vehicles and thermal insulation measures on buildings, positioning itself as an entity potentially subject to audit and improvement obligations under the Energy Efficiency Directive. The park also hosts companies active in waste management and recovery, whose practices are consistent with the provisions of the Waste Framework Directive (2008/98/EC). Although it is not classified as an ETS plant, some of its activities are indirectly involved in climate change mitigation policies, making reference to the European Climate Law particularly relevant. The equipment and sectoral composition of Envipark therefore provide a solid basis for applying European regulatory targets in the areas of energy, waste, efficiency and emissions reduction.

5.2 Kalundborg Symbiosis

The Kalundborg Symbiosis represents the world's most renowned example of industrial symbiosis and is located in the

region of Western Zealand, Denmark (Cheshmehzangi, 2025). The territorial network includes large industrial plants such as the Asnæs Power Station (now converted to biomass), the Kalundborg Bioenergy biogas facility, the Avista Green unit for oil regeneration, wastewater treatment and reuse plants, as well as chemical, pharmaceutical and food production sites. This configuration makes the park a strategic hub for both the production and consumption of renewable and recovered energy, subject to direct and indirect obligations on energy and emission reduction as defined by the RED III Directive and the European Climate Law.

The waste treatment facilities and interconnected industrial processes fall within the principles—and, in some cases, the obligations—of the Waste Framework Directive and related legislation on the recovery of materials and by-products. Water management within the park, with an estimated annual saving of about 3 million m³, aligns with the objectives of the Water Framework Directive (2000/60/EC) and EU Regulation 2020/741 on water reuse. Several participating companies operate in sectors covered by the EU Emissions Trading System (ETS), making compliance with emission reduction thresholds and related regulations mandatory. The presence of advanced infrastructure for CO₂ capture and reuse, although not compulsory, is consistent with European strategies for climate neutrality, reinforcing the relevance of specific sectoral targets within the EIP context.

5.3 Environmental indicators and data sources

In the present model, environmental ESG performance is measured through a set of indicators consistent with the E dimension of the ESG framework, whose targets are derived from binding European regulations or, where unavailable, from recognized best practices. Although these regulations were not originally designed as ESG instruments, they provide official, objective and comparable threshold values that enable a transparent and defensible assessment of the environmental performance of the EIPs under analysis. Table 2 reports the information related to each environmental indicator for the two EIPs considered.

For the construction of the model, it was considered appropriate to distinguish between environmental indicators associated with binding regulatory targets and indicators based on non-binding best practices. Inclusion in the first category presupposes the presence, within the analysed EIP, of activities that effectively fall within the scope of European regulations. In the absence of such operational correspondence, the indicators were classified as “strategic voluntary indicators”, serving as guidance tools for ESG performance improvement.

Based on the analysis of activities carried out in Envipark (Turin) and Kalundborg (Denmark), a detailed verification of the applicability of the main EU directives and regulations was conducted. The indicators were therefore classified into two groups:

- Mandatory indicators, referring to quantitative targets established by European regulations (e.g., RED III, Energy

Efficiency Directive, Waste Framework Directive, European Climate Law, Water Framework Directive, and EU Regulation 2020/741);

- Strategic voluntary indicators, relevant to overall performance but not subject to binding performance thresholds (e.g., presence of sustainable facilities, green mobility initiatives, hydrogen production).

In parallel, the European regulatory framework on sustainability and ESG reporting includes instruments of different nature. Some set binding and measurable targets (such as the directives mentioned above), while others provide criteria or standards without defining quantitative thresholds, such as the EU Taxonomy Regulation (2020/852), the Corporate Sustainability Reporting Directive (CSRD 2022/2464), and the GRI Standards. The latter were mainly considered as a policy and reporting coherence framework, rather than as direct sources for defining numerical targets in the model.

In summary, the distinction between mandatory and voluntary indicators made it possible to separate the regulatory aspects from those aimed at strategic ESG improvement. Tables 3 and 4 report the two categories as applied to the Turin and Kalundborg case studies.

In Figure 2, the weights assigned to each indicator—derived from the questionnaire administered to the sustainability team members of the two EIPs—are shown.

5.4 Social indicators and data sources

The social dimension of the ESG assessment was developed through a common set of indicators relevant to both EIP (Envipark and Kalundborg). The selection was based on their recurrence in major international frameworks, data availability, and their ability to represent key aspects of the relationship between the industrial park, the workforce, and the surrounding territory.

The indicators were divided into two groups:

- Mandatory indicators, defined by binding regulations (hard law) or by widely recognized international standards (soft law);
- Strategic voluntary indicators, oriented toward the voluntary improvement of ESG performance.

The notion of “obligatoriness” adopted in this model encompasses both legally binding references and non-binding but consolidated instruments such as the UNIDO Framework for EIP (2021), the GRI Standards (2023), the ISO Guidelines (ISO, 2018) and the UN Sustainable Development Goals (2015). In this sense, indicators defined as mandatory do not necessarily derive from national legislation but are prescribed by internationally recognized standards, representing a minimum condition of ESG compliance.

Tables 5 and 6 present the classification of the indicators for each EIP, together with their respective targets and references.

Tables 7 and 8 report the normalized values of the mandatory and strategic voluntary social indicators, respectively, for Envipark and Kalundborg.

Figure 3 illustrates the weights assigned to each social indicator, as derived from the questionnaire administered to the sustainability teams of Envipark and Kalundborg.

TABLE 2 Environmental indicators used for the assessment of the E dimension in the two Eco-Industrial Parks (Envipark, Italy, and Kalundborg, Denmark).

n	Indicator	EIP	
		Envipark (Italy)	Kalundborg (Denmark)
1	Use of energy produced by renewable sources	About 55% of total energy comes from the on-site photovoltaic systems and the hydroelectric power plant	100% of shared steam is produced from sustainable biomass (Asnæs power station)
2	Territorial extension	30,000 m ²	5,000,000 m ²
3	Actions aimed at improving energy efficiency	€100,000 invested in 2023	Recovery of residual heat through heat pumps and decarbonization of district heating networks
4	Presence of renewable energy plants	Presence of photovoltaic systems and a hydroelectric power plant	Presence of biogas and biomass upcycling plants
5	Environmental certifications	ISO 14001	ISO 14001 (environmental management), ISO 9001 (quality), ISO 50001 (energy), ISO 22000 (food safety), and ISO 45001 (health and safety at work)
6	Active sustainable facilities	Radiant heating systems, EV charging stations, beehive	Asnæs biomass power plant, Kalundborg bioenergy biogas facility, Avista green (oil regeneration), wastewater treatment plant with heat pumps, COMET and Meliora bio (biomass upcycling), unibio (proteins from biogas)
7	Hydrogen production systems from waste	Not present	Present
8	Initiatives for green mobility and thermal insulation	Present	Present
9	Industrial waste recovery in a circular economy framework	Circular economy and sustainable biomass projects in place	100% of waste from companies becomes input for other processes
10	CO ₂ reduction	Approximately 65% reduction for 2023–2024 compared to the 2019 baseline	48% reduction in CO ₂ emissions since 2019 (80% overall reduction since 2015)
11	Indirect emissions	Scope 3 represents the main source of indirect emissions (about 80% of total estimated emissions)	In 2023, with around 444 vessel movements, estimated emissions were approximately 2,964 tCO ₂ /year
12	Active water-saving systems	Deficit in savings due to higher consumption in some laboratories and wear of a hydroelectric component	Active water reuse management (700,000 m ³ /year from Statoil → Asnæs)
13	CO ₂ capture and reuse projects	Not present	Present

5.5 Governance indicators and data sources

Tables 9 and 10 present the classification of the indicators for each EIP, together with their respective targets and references.

Tables 11 and 12 report the normalized values of the mandatory and strategic voluntary social indicators, respectively, for Envipark and Kalundborg.

Figure 4 illustrates the weights assigned to each social indicator, as derived from the questionnaire administered to the sustainability teams of Envipark and Kalundborg.

6 Results

6.1 Passive assessment results

6.1.1 Environmental

The passive assessment of the environmental performance of the two EIP was conducted using a classical GP model with normalized weights and a minimizing objective function. The aim of the model was to reduce, for each case study, the weighted sum of the negative deviations (d_j^-) between the normalized observed value of each environmental indicator (x_j) and the corresponding reference target

($g_j = 1$). The weights (w_j) were transparently derived from the importance ratings (on a 1–5 scale) expressed by the Envipark management team through a questionnaire, and subsequently normalized so that their total equalled one. The resulting environmental ESG index therefore reflects a combination of internal relevance and objective consistency with regulatory gaps. The application of the model produced, for each EIP, an overall value of the objective function.

Envipark shows significant gaps in the following indicators:

- Energy efficiency: despite investments in audits and interventions, objective data on the total potential achieved are lacking; therefore, a prudential value of $x = 0.50$ was assigned. This penalises its score compared to Kalundborg, which actively uses heat pumps and energy recovery systems.
- Indirect emissions (mobility): Envipark depends heavily on commuting-related mobility, estimated to account for around 80% of its total GHG emissions. In the absence of specific quantitative data, an intermediate value of $x = 0.20$ was used, highlighting a significant gap.
- Water savings: while Kalundborg actively manages the reuse of approximately 700,000 m³/year of recycled water, Envipark shows a considerable deficit, with $x = 0$.

TABLE 3 Mandatory environmental indicators, targets, observed values, and normalised scores for Envipark and Kalundborg, with corresponding EU regulatory sources.

n	Indicator	Target g_j	Value x_j		Normalized value (x_j)	
			Envipark	Kalundborg	Envipark	Kalundborg
1	Use of energy produced by renewable sources	Renewable share of 42.5% by 2030	About 55% from on-site photovoltaic systems and the hydroelectric power plant	100% of shared steam produced from sustainable biomass (Asnæs power station)	0.55	1
		Regulatory source				
		RED III – EU/2023/2413				
3	Actions aimed at improving energy efficiency	100% of efficiency potential	€100,000 invested in 2023	Recovery of residual heat through heat pumps and decarbonization of district heating networks	0.5 (conservative assessment)	1
		Regulatory source				
		Energy efficiency directive – EU 2023/1791				
4	Presence of renewable energy plants	Presence = 1	Photovoltaic systems and a hydroelectric power plant present	Presence of biogas and biomass upcycling plants	1	1
		Regulatory source				
		RED III – EU/2023/2413				
9	Industrial waste recovery in a circular economy framework	65% recycling rate by 2035	Circular economy and sustainable biomass projects in place	100% of companies' waste becomes input for other processes	0.8	1
		Regulatory source				
		Direttiva 2008/98/CE				
10	CO ₂ reduction	–55% by 2030	–65% reduction (2023–2024 vs. 2019 baseline)	–48% reduction since 2019 (80% overall reduction since 2015)	1	1
		Regulatory source				
		European climate law – EU 2021/1119				
12	Active water-saving systems	Optimal sectoral target	Deficit in savings due to higher consumption in some laboratories and wear of a hydroelectric component	Active water reuse management (700,000 m ³ /year from Statoil → Asnæs)	0.5	1
		Regulatory source				
		Directive – 2000/60/EC + EU Regulation 2020/741				

6.1.2 Social

The passive assessment of the social component made it possible to compare the performances of Envipark (Italy) and Kalundborg (Denmark) based on a common set of nine indicators, divided into mandatory ones (soft law and supranational directives) and strategic voluntary ones (consistent with UNIDO guidelines and international EIP practices).

Envipark achieved a social ESG index of 0.900, exceeding the targets in almost all areas, including the voluntary ones. Particularly positive results were recorded in hosted events, training and inclusion activities, community relations, and onboarding programmes. The only gap concerns the number of direct employees (300 compared to a target of 1,000).

Kalundborg achieved an index of 0.783. Strengths emerged in the number of direct employees (over 7,000), collaboration with the education sector, technical training programmes, and average employee tenure (13 years compared to a target of 10). Weaknesses were observed in corporate welfare services (limited to insurance and bonus schemes, with no additional support structures) and in the number of hosted events.

6.1.3 Governance

The analysis of the governance dimension returned overall high values for both case studies (index 0.980 for Envipark and 0.958 for Kalundborg), although a disaggregated examination highlights significant differences in the governance models adopted.

Envipark is characterised by a formalised governance structure, consistent with European directives and leading voluntary standards. Among the instruments adopted are an internal Sustainability Board, a risk management system inspired by Legislative Decree 231/2001, whistleblowing procedures compliant with EU Directive 2019/1937, and the publication of a Sustainability Report aligned with GRI standards, providing a clear definition of decision-making roles.

Kalundborg, while also showing strong performance, adopts a more relational and distributed model, lacking formal bodies such as a Sustainability Board. Coordination is ensured through thematic committees and continuous cooperation among companies and local stakeholders. However, the absence of structured whistleblowing mechanisms, a standardised sustainability report, and formalised risk management procedures represents a limitation with respect to emerging European benchmarks.

TABLE 4 Strategic voluntary environmental indicators, targets, observed values, and normalized scores for Envipark and Kalundborg, based on international best practices and voluntary frameworks.

n	Indicator	Target g_j	Value x_j		Normalized value (x_j)	
			Envipark	Kalundborg	Envipark	Kalundborg
2	Territorial extension	UNIDO EIP framework	30,000 m ²	5,000,000 m ²	0.006	1.00
5	Environmental certifications	Presence = 1	ISO 14001	ISO 14001 (environmental management), ISO 9001 (quality), ISO 50001 (energy), ISO 22000 (food safety), and ISO 45001 (health and safety at work)	1.00	1.00
		Best practice source				
		ISO 14001				
6	Active sustainable facilities	Presence = 1	Radiant systems, EV charging stations, beehive	Asnæs biomass power plant, Kalundborg bioenergy biogas plant, Avista green (oil regeneration), wastewater treatment plant with heat pumps, COMET and Meliora bio (biomass upcycling), unibio (proteins from biogas)	1.00	0
		Best practice source				
		EIP best practice				
7	Hydrogen production systems from waste	Presence = 1	From waste	Not present	1.00	0
		Best practice source				
		EU hydrogen strategy (COM/2020/301)				
8	Initiatives for green mobility and thermal insulation	Presence = 1	Present	Present	1.00	1.00
		Best practice source				
		EU mobility package				
11	Indirect emissions	Absence = 0 movements	Scope 3 represents the main source of indirect emissions (about 80% of the total estimated)	In 2023, with around 444 vessel movements, estimated emissions were about 2,964 tCO ₂ /year	0.2	0
		Best practice source				
		EU green deal/Voluntary scope 3				
13	CO ₂ capture and reuse projects	Presence = 1	Not present	Present	0	1.00
		Best practice source				
		EU CCUS strategy				

6.2 Active assessment results

Following the results obtained from the passive evaluation phase of the two EIPs, the active evaluation phase of the proposed methodological approach was conducted to identify the strategies that each park can implement to reduce the main gaps detected in the ESG dimensions. Accordingly, the active evaluation was carried out for the environmental component of both EIPs and for the social component of Kalundborg. In fact, Envipark's social dimension already showed strong robustness and adequacy, as also observed in the governance dimension of both parks.

6.2.1 Environmental

The analysis of passive ESG environmental performance highlights a clear differentiation between the two EIP, both in terms of mandatory and strategic voluntary indicators, with significant implications for identifying improvement priorities.

In the case of Envipark (Turin), the overall level of compliance with environmental targets is high; however, two major gaps remain:

- Active water-saving systems—the normalized value $x_j = 0.5$ reveals a structural issue related to both equipment wear and increased water consumption in certain laboratories. Although the relative weight of this indicator (0.055) mitigates its aggregate impact on the index, the strategic relevance of water efficiency in the context of resource circularity suggests it should be treated as a priority area for intervention.
- Territorial extension—among the voluntary indicators, this dimension records a particularly penalizing value ($x_j = 0.006$), well below the benchmark proposed by UNIDO (UNIDO et al., 2017). Although it has a low weight (0.073), improving this indicator could enable scale synergies and enhance the park's attractiveness to new productive investments.

Additionally, Envipark shows a partial gap for indirect emissions (Scope 3), with $x_j = 0.2$, currently representing the park's main source of emissions. Although this indicator is not mandatory, its

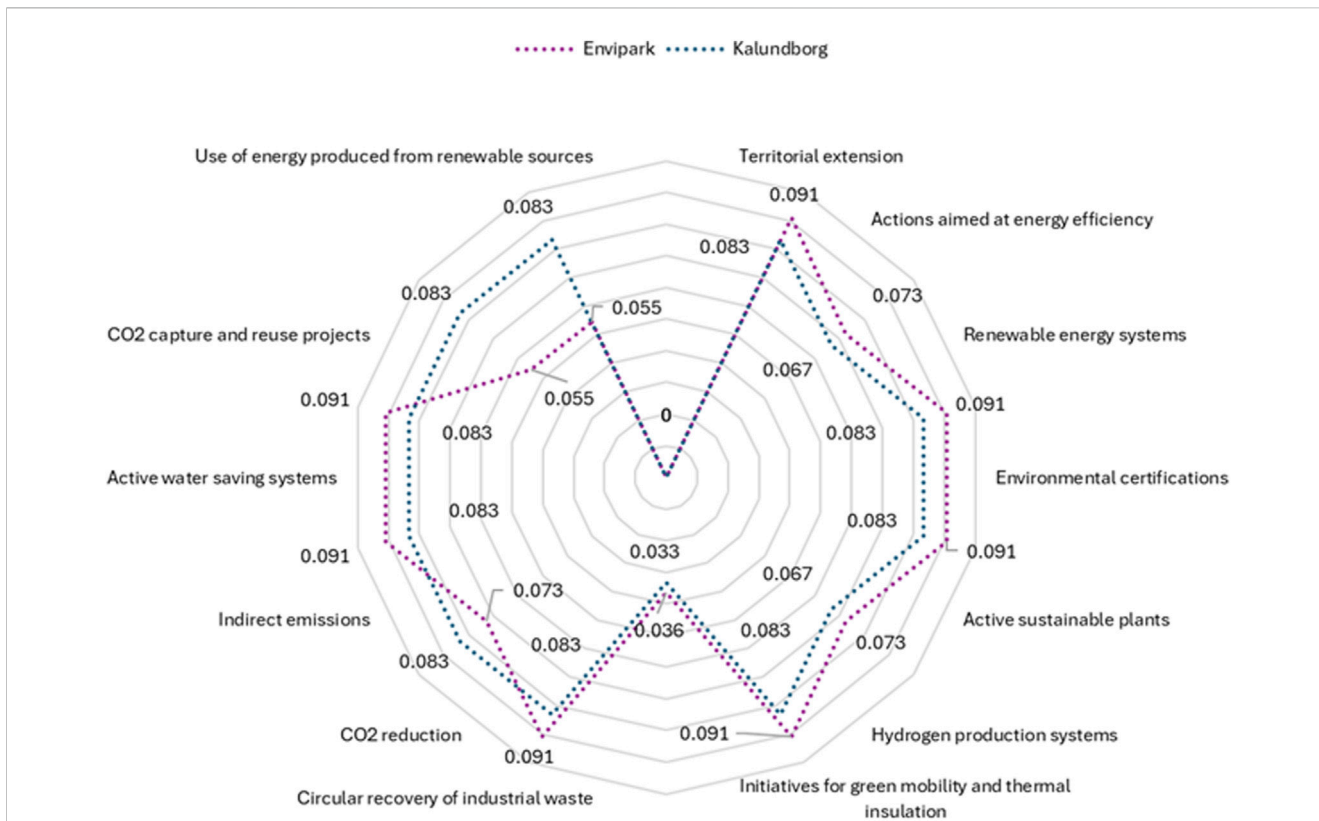


FIGURE 2 Weights assigned to each environmental indicator, derived from the questionnaire submitted to the sustainability teams of Envipark and Kalundborg.

TABLE 5 Mandatory social indicators, targets, observed values, and references for Envipark and Kalundborg.

n	Indicator	Value x_j		Target	References
		Envipark	Kalundborg		
3	Active corporate welfare services	13 services	Health insurance and company bonuses	3	Mandatory according to UNIDO framework
4	Hosted events	10 per year	2 international events per year	4	UNIDO/GIZ benchmark
5	Training, equality and inclusion programmes	Active (SDG 4, 5, 8, 10)	Active (symbiosis training program and the development of the Kalundborg Campus, in collaboration with industrial and educational partners, promote education and innovation)	Present and active	Required for compliance with international social policies (SDG 4,5,10; GRI 404/405)
6	Collaboration with schools and universities	Over 50 students and researchers are involved in tests and experiments	Student visits/internship opportunities	2	Benchmark from international EIP guidelines
7	Average tenure of employees	12 years	13 years	10	UNIDO – proxy indicator of employment stability
8	Community relations	Guided visits for schools or public bodies on request; public initiatives such as <i>Fabbriche Aperte Piemonte and Le Settimane della Scienza</i>	Support for Helix Lab and the HTX scholarship (3,000 DKK)	Present and active	Mandatory in EIP models according to GRI 413 and SDG 11
9	Onboarding and career development programmes	Present	Present	Present	Included in ISO 30414 requirements for human capital management

TABLE 6 Strategic voluntary social indicators, targets, observed values, and benchmarks for Envipark and Kalundborg.

n	Indicator	Value x_j		Target	Benchmark
		Envipark	Kalundborg		
1	Companies within the park	70	17	50	Average observed among European and OECD EIPs with similar structures (denves, beringer, Kitakyushu)
2	Direct employees	300	7,000	1,000	Minimum number of workers in consolidated EIP structures (denves)

TABLE 7 Normalized values of mandatory social indicators for Envipark and Kalundborg.

n	Indicator	Value x_j		Normalized value (x_j)	
		Envipark	Kalundborg	Envipark	Kalundborg
3	Active corporate welfare services	13 services	Health insurance and company bonuses	1	0.66
4	Hosted events	10 per year	2 international events per year	1	0.5
5	Training, equality and inclusion programmes	Active (SDG 4, 5, 8, 10)	Active (symbiosis training program and the development of the Kalundborg Campus, in collaboration with industrial and educational partners, promote education and innovation)	1	1
6	Collaboration with schools and universities	Over 50 students and researchers are involved in tests and experiments	Student visits/internship opportunities	1	0.5
7	Average tenure of employees	12 years	13 years	1	1
8	Community relations	Guided visits for schools or public bodies on request; public initiatives such as <i>Fabbriche Aperte Piemonte</i> and <i>Le Settimane della Scienza</i>	Support for Helix Lab and the HTX scholarship (3,000 DKK)	1	1
9	Onboarding and career development programmes	Present	Present	1	1

TABLE 8 Normalized values of strategic voluntary social indicators for Envipark and Kalundborg.

n	Indicator	Value x_j		Normalized value (x_j)	
		Envipark	Kalundborg	Envipark	Kalundborg
1	Companies within the park	70	17	1	0.34
2	Direct employees	300	7.000	0.33	1

weight (0.091) and its alignment with the latest European Green Deal directives make it a critical aspect to be monitored.

For Kalundborg, the Danish EIP achieves very high environmental performance across almost all mandatory indicators ($x_j = 1$), except for hydrogen production and active sustainable facilities, for which no significant evidence was found. The first, although voluntary and low-weight (0.033), is strategically relevant in a transition perspective. The second represents a true strategic gap ($x_j = 0$) in a key area (weight 0.083), where Envipark shows a more developed infrastructure.

A further critical issue for Kalundborg is represented by the “indirect emissions” indicator ($x_j = 0$), which—although voluntary—has a relatively high weight (0.083) and falls within the broader European framework of growing attention to low-

emission supply chains and logistics. Conversely, the CO₂ capture and reuse project ($x_j = 1$ in Kalundborg and $x_j = 0$ in Envipark) stands out as a distinctive strength of the Danish park and a potential development area for Envipark.

Overall, the results indicate that:

- Envipark demonstrates strong regulatory compliance, but faces infrastructural gaps in key areas (water, Scope 3, scale).
- Kalundborg shows technological leadership (waste recovery, industrial symbiosis, direct decarbonization), but with specific thematic gaps in sustainable mobility, green infrastructure, and indirect emission monitoring.

These findings will guide the subsequent active evaluation phase, aimed at optimizing ESG improvement strategies by taking into

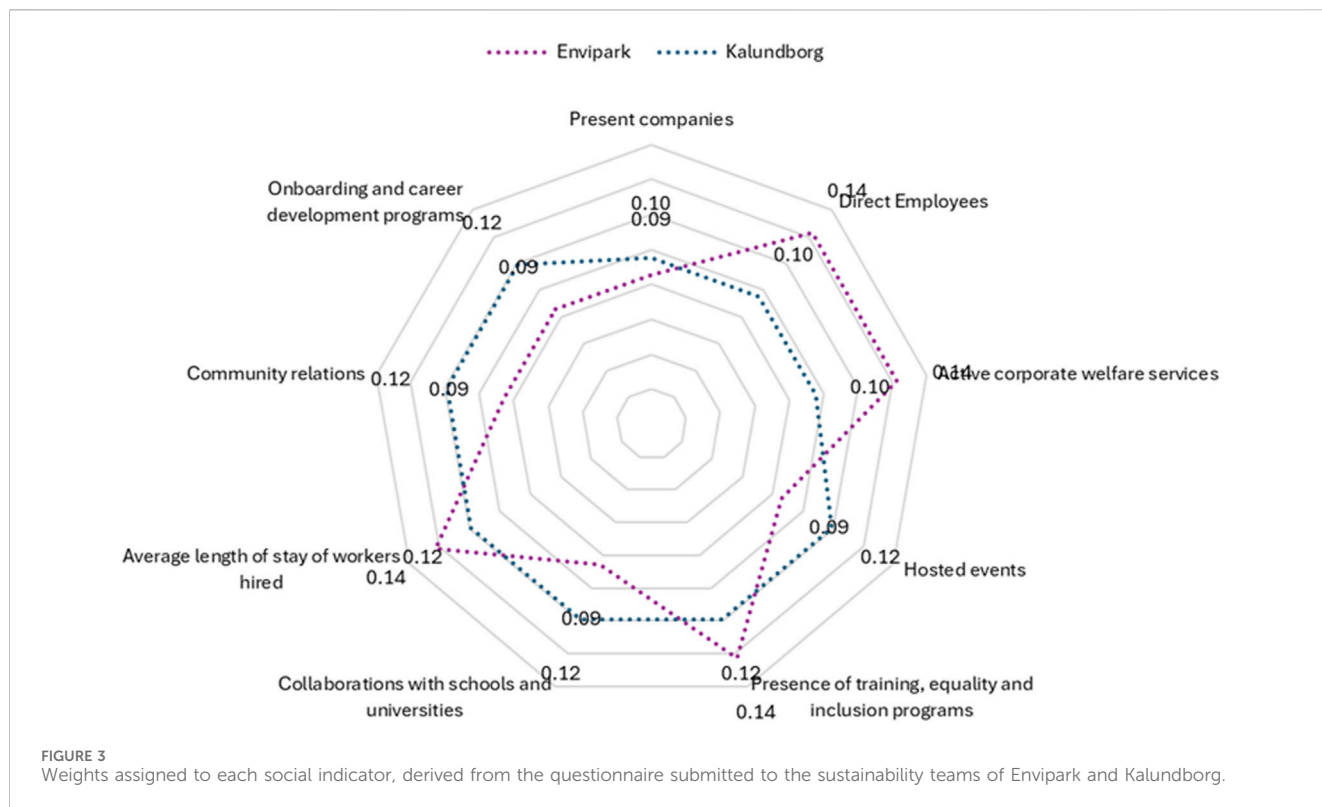


TABLE 9 Mandatory governance indicators for Envipark and Kalundborg, with corresponding targets and reference standards.

n	Indicator	Value x_j		Target	References
		Envipark	Kalundborg		
2	Formal risk management structure	Yes – based on model 231, comparable to enterprise risk management (ERM) in structure and objectives	Non-formalised system with quarterly meetings on ethical and corruption risks	Present	Recommended by GRI 102-15, ISO 31000, OECD guidelines
3	Anti-corruption training sessions	Scheduled	Scheduled	At least one session	Required by ISO 37001 and GRI 205; established anti-corruption practice
7	Code of conduct	Present	Present and extended to suppliers and audits	Formally adopted and published code	Minimum standard required by GRI, ISO 37001, OECD, UNGC
8	Whistleblowing programme	Yes, through the “WhistleblowingPA” platform – compliant with Italian regulation	Kalundborg adopts a standard whistleblowing channel, at least at the company level	Present and active	Mandatory for organizations with >50 employees in the EU (directive 2019/1937)

account weights, estimated costs, and logical interdependencies among the proposed interventions.

6.2.1.1 Envipark

For each environmental aspect, the actions required to close the identified gaps were defined, estimating both gross and net costs, and assessing the possibility of adopting European or national grants and funding schemes to reduce gross implementation costs. The total budget considered amounts to €750,000. The total cost of each improvement action was considered equal to the net implementation cost in cases where an environmental gap was identified, or to the maintenance cost of existing and active strategies in cases where no gap was detected. The estimation of

the costs associated with Envipark’s environmental improvement strategies was conducted through a triangulation approach, combining institutional sources, market data, and technical documentation available at national and European levels.

The improvement strategies considered for Envipark include several actions, such as:

- Expansion of photovoltaic capacity and purchase of green energy to increase the share of renewable energy production;
- New waste recovery contracts to enhance circular reuse and resource efficiency;
- Installation of a water recycling and phytoremediation system to activate water-saving mechanisms;

TABLE 10 Strategic voluntary governance indicators for Envipark and Kalundborg, including descriptive values and reference frameworks.

n	Indicator	Value x_j		Target	References
		Envipark	Kalundborg		
1	Existence of a sustainability board	Active since 2022	Advisory boards tematici (energy, water, materials, etc.)	Present	Not required but recommended by ISO 37000 and UNIDO
4	Transparent governance system	Board of directors + board of Auditors	General Assembly, a board of directors, a Secretariat, an innovation board, and an Advisory board. Formally established in 2012	Present	Recommended by GRI 102-18, OECD, ISO 37000
5	Voluntary publication of a sustainability report	Envipark voluntarily publishes the “OLTRE” sustainability report, structured according to the ODCEC Turin method and aligned with GRI standards	Kalundborg, through Kalundborg Refinery, publishes an annual sustainability report documenting environmental, social, and safety performance	Annual report published	Not mandatory for EIPs but consistent with GRI and the forthcoming CSRD
6	Awards and recognitions	Premio Impresa Ambiente (2024), Industria Felix high Honour for financial reporting (2023)	The governance model has been cited as a best practice by UNEP, OECD, the Ellen MacArthur foundation, and the European Commission	At least one recognition received	Expression of external reputation

TABLE 11 Normalized values of mandatory governance indicators for Envipark and Kalundborg.

n	Indicator	Value x_j		Normalized value (x_j)	
		Envipark	Envipark	Envipark	References
2	Formal risk management structure	Yes – based on model 231, comparable to enterprise risk management (ERM) in structure and objectives	Non-formalized system with quarterly meetings on ethical and corruption risks	1	0.5
3	Anti-corruption training sessions	Scheduled	Scheduled	1	1
7	Code of conduct	Present	Present and extended to suppliers and audits	0.8	1
8	Whistleblowing programme	Yes, through the “WhistleblowingPA” platform – compliant with Italian regulation	Kalundborg adopts a standard whistleblowing channel, at least at the company level	1	0.8

TABLE 12 Normalized values of strategic voluntary governance indicators for Envipark and Kalundborg.

n	Indicator	Value x_j		Normalized value (x_j)	
		Envipark	Kalundborg	Envipark	Kalundborg
1	Existence of a sustainability board	Active since 2022	Advisory boards tematici (energy, water, materials, etc.)	1	0.8
4	Transparent governance system	Board of directors + board of Auditors	General Assembly, a board of directors, a Secretariat, an innovation board, and an Advisory board. Formally established in 2012	1	1
5	Voluntary publication of a sustainability report	Envipark voluntarily publishes the “OLTRE” sustainability report, structured according to the ODCEC Turin method and aligned with GRI standards	Kalundborg, through Kalundborg Refinery, publishes an annual sustainability report documenting environmental, social, and safety performance	1	1
6	Awards and recognitions	Premio Impresa Ambiente (2024), Industria Felix high Honour for financial reporting (2023)	The governance model has been cited as a best practice by UNEP, OECD, the Ellen MacArthur foundation, and the European Commission	1	1

- Deployment of micro-Carbon Capture and Storage (CCS) systems and carbon credit compensation schemes to reduce, capture, and reuse CO₂ more efficiently;

- Upgrading of HVAC (heating, ventilation, and air conditioning) systems, LED lighting, and Building Management Systems (BMS).

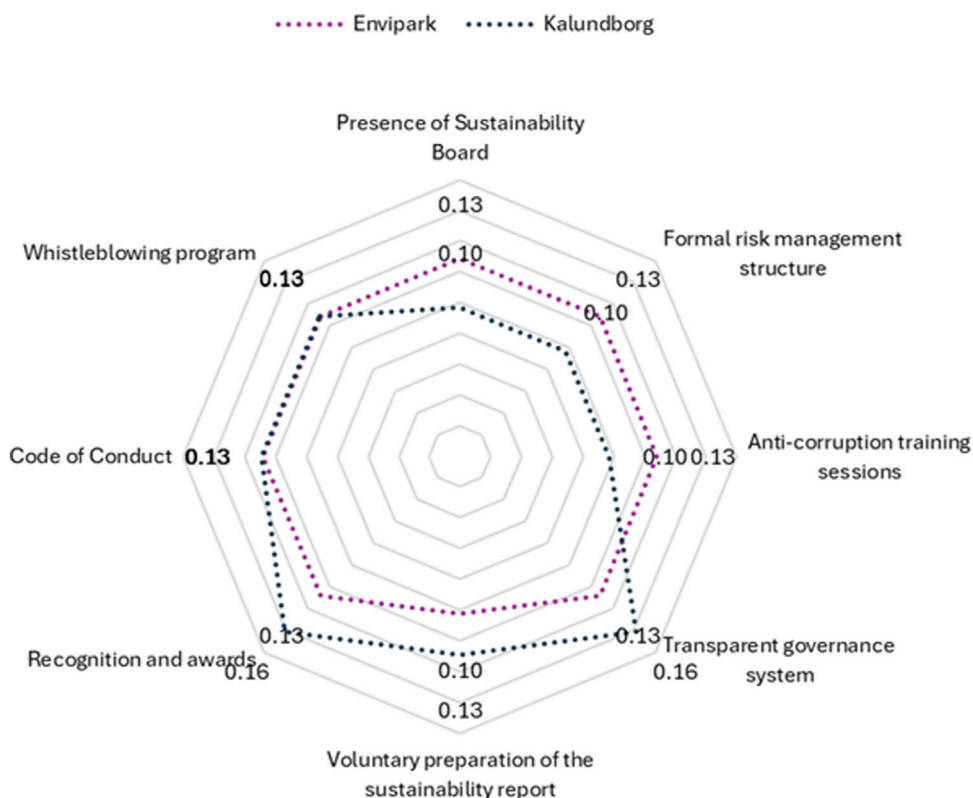


FIGURE 4 Weights assigned to each governance indicator, derived from the questionnaire submitted to the sustainability teams of Envipark and Kalundborg.

Table A in the Appendix reports the sources used for cost estimation and the subsidy schemes considered for Envipark.

These primarily concern the need to reinforce the existing photovoltaic capacity, which is essential to maintain current environmental certifications, support sustainable mobility, and improve building insulation. This intervention also contributes to reducing CO₂ emissions generated by the EIP, with the possibility of compensation through carbon credits. Additional constraints include, on the one hand, the obligation to adopt a sustainable mobility plan in order to preserve the EIP’s environmental certification level, and on the other, the need to increase hydrogen production, which is functionally linked to optimizing circular waste recovery processes.

6.2.1.2 Results for Envipark

The results obtained from the application of the GP–knapsack model suggest that the optimization of Envipark’s environmental gaps can be achieved through the combined activation of the following strategies:

- Enhancement of photovoltaic capacity and purchase of green energy (S1);
- Upgrading of HVAC, LED, and BMS systems (S3);
- Maintenance of environmental certifications (S5);
- Expansion of hydrogen production capacity (S7);
- Activation of new circular waste recovery contracts (S9);

- Improvement of CO₂ reduction efficiency with carbon credit compensation (S10);
- Development of a sustainable mobility plan (S11);
- Implementation of a process water recycling and phytoremediation plant (S12);
- Creation of a micro–Carbon Capture and Storage (CCS) system (S13).

With an effective cost of €355,000, a weighted overall improvement of 0.4 would be achieved, meaning that Envipark’s environmental performance index would increase from 0.61 to 1.00. The selection of these strategies reflects consistency with the park’s existing infrastructure while directly addressing the gaps identified in the passive evaluation phase. Table 13 presents the selected and excluded strategies, the covered gaps, and the corresponding net costs.

The decision to enhance photovoltaic capacity and purchase green energy (S1) aligns with Envipark’s role as a technology hub focused on renewable energy. The EIP already operates photovoltaic systems and a hydroelectric plant, yet the passive evaluation revealed room for improvement with respect to the renewable energy target. This intervention not only helps consolidate existing environmental certifications (ISO 14001, ISO 50001, etc.), but also ensures compliance with the RED III Directive and enables access to national and European incentive mechanisms. In parallel, the selection of energy efficiency interventions on HVAC, LED, and BMS systems (S3) builds on initiatives already undertaken by

TABLE 13 Environmental improvement strategies for Envipark selected and excluded by the GP–knapsack optimization model, showing the associated performance increments (Δx_j), net implementation costs, and binary decision variables.

Strategy	Δx_j	Net cost	Binary variable
S1	0.45	60,000.00 €	1
S3	0.5	25,000.00 €	1
S4	0	5,000.00 €	0
S5	0	5,000.00 €	1
S6	0	10,000.00 €	0
S7	0.1	40,000.00 €	1
S8	0	5,000.00 €	0
S9	0.3	20,000.00 €	1
S10	0.35	40,000.00 €	1
S11	0.4	40,000.00 €	1
S12	1	45,000.00 €	1
S13	1	80,000.00 €	1

Envipark in the field of energy optimization. The presence of radiant systems and electric vehicle charging infrastructure already demonstrates a consolidated commitment to consumption reduction. The model confirms the need to strengthen these measures to close the remaining gap ($x_j = 0.5$), in line with the European Energy Efficiency Directive. The maintenance of environmental certifications (S5), although not generating a direct performance increase ($\Delta x_j = 0$), is confirmed as a necessary strategy. This aspect is particularly relevant for an EIP such as Envipark, which bases part of its attractiveness on the possession of integrated environmental certifications (e.g., ISO 14001), ensuring accountability and credibility toward stakeholders and institutional partners. The expansion of hydrogen production capacity (S7) is consistent with the park's positioning as a centre of innovation. Envipark already hosts pilot systems for hydrogen production from waste, and strengthening this area responds to the need to align with EU hydrogen strategies (COM/2020/301) while enhancing internal industrial symbiosis potential. The activation of new waste recovery contracts (S9) and the use of carbon credit compensation schemes (S10) represent complementary strategies: the former aimed at reinforcing circularity (already partially present through sustainable biomass projects), and the latter at consolidating the reduction of residual emissions. These actions respond to the requirements of the Waste Framework Directive and the European Climate Law, strengthening the pathway toward climate neutrality. The model also selected the development of a sustainable mobility plan (S11), consistent with Envipark's existing e-mobility infrastructure and with the need to close the gap on indirect (Scope 3) emissions, currently the park's main source of GHG emissions. Particularly significant is the activation of a water recycling and phytoremediation plant (S12), which directly addresses the identified deficit in water management and enhances the park's infrastructural resilience, in line with the Water Framework Directive (2000/60/EC). Finally, the creation

of a micro–Carbon Capture and Storage (CCS) system (S13) represents an innovative strategy that helps close one of the main gaps with Kalundborg, which already operates advanced CO₂ capture and reuse facilities. The introduction of this technology, supported by Horizon Europe funding, contributes to aligning Envipark with the EU's 2050 climate neutrality targets.

6.2.1.3 Kalundborg

For the Danish EIP, the active evaluation phase was carried out under a different budget constraint from that of Envipark, amounting to €860,000. The calculation of the total cost of improvement strategies followed the same methodological logic. The estimation of costs associated with Kalundborg Symbiosis' environmental improvement strategies was based on institutional sources, technical reports, and market benchmarks relevant to the Danish and broader European context. The gross values represent market estimates for plants, technologies, and services related to the ecological transition, while the net values take into account the presence of specific economic support mechanisms available in Denmark and through the European Union. The strategies identified to enhance the environmental performance of Kalundborg primarily include: (i) a Power-to-X hydrogen plant producing green hydrogen via water electrolysis powered by renewable electricity (solar or wind); (ii) integration of green maritime fuels, port electrification, and port logistics optimization, aiming for full decarbonisation by combining the use of alternative fuels such as green hydrogen or biofuels with the electrification of docks to drastically reduce emissions and noise pollution from ships at berth; (iii) upgrading of bioenergy systems and carbon credit compensation mechanisms. Table B in the Appendix reports the sources used for cost estimation and the funding or subsidy programmes considered for Kalundborg.

The logical interdependence constraints applied in the active evaluation model concern the following aspects:

- The joint presence of renewable energy systems and Power-to-X hydrogen production facilities is essential to reduce pollution generated by indirect emissions from maritime transport;
- The maintenance of existing renewable energy and energy efficiency systems is indispensable for enabling the operation of a green hydrogen production plant.

6.2.1.4 Results for Kalundborg

The GP–knapsack model selected the following strategies to optimize the environmental performance of the Danish EIP:

- Maintenance of active renewable energy systems (S1);
- Installation of a Power-to-X plant for green hydrogen production (S7);
- Adoption of green maritime fuels and port electrification (S8);
- Upgrading of bioenergy systems with carbon credit compensation (S10);
- Optimisation of port logistics (S11).

With an effective cost of €520,000, the model estimates a weighted overall improvement of 0.2, which would raise Kalundborg's environmental performance index from 0.8 to 1.0. The selected strategies reflect coherence with the park's existing

TABLE 14 Environmental improvement strategies for Kalundborg selected and excluded by the GP–knapsack optimization model, showing the associated performance increments (Δx_j), net implementation costs, and binary decision variables.

Strategy	Δx_j	Net cost	Binary variables
S1	0	80,000.00 €	1
S3	0	50,000.00 €	0
S4	0	25,000.00 €	0
S5	0	10,000.00 €	0
S6	0	80,000.00 €	0
S7	1	120,000.00 €	1
S8	0.5	150,000.00 €	1
S9	0	40,000.00 €	0
S10	0.07	50,000.00 €	1
S11	0.5	120,000.00 €	1
S12	0	35,000.00 €	0
S13	0	100,000.00 €	0

infrastructure while simultaneously addressing the key gaps identified during the passive evaluation phase. **Table 14** reports the strategies selected and excluded by the model, along with the corresponding performance gains (Δx_j), net costs, and binary decision variables.

The application of the GP–knapsack model to the case of Kalundborg selected a set of strategies consistent with the structural characteristics and ongoing development trajectories of Europe's most advanced EIP. The total cost of the optimal interventions amounts to €520,000.

The maintenance of existing renewable energy systems (S1), although not resulting in a direct performance increase ($\Delta x_j = 0$), represents a fundamental condition for safeguarding the environmental standards already achieved. Kalundborg benefits from a diversified mix of renewable sources (wind, biomass, and high-efficiency cogeneration) powering its industrial symbiosis network. The model highlights that maintenance and upgrading of these infrastructures are essential to ensure the continuity of environmental certifications and compliance with national decarbonisation commitments. The installation of a Power-to-X plant for green hydrogen production (S7) emerges as the most impactful strategy ($\Delta x_j = 1$). Kalundborg is already engaged in Danish hydrogen initiatives and hosts pilot projects funded under the Horizon Europe programme. The inclusion of this option in the optimal set confirms the park's role as a living laboratory for the energy transition, capable of integrating new value chains (green hydrogen and synthetic derivatives) with existing energy and material flows. This choice is fully aligned with the European Commission's Hydrogen Strategy and Denmark's national goal of becoming a net hydrogen exporter by 2030. Equally relevant is the adoption of green maritime fuels and port electrification (S8), contributing $\Delta x_j = 0.5$. The port of Kalundborg is a central component of the local production system, hosting energy and manufacturing import–export flows. The electrification of docks (cold ironing) and the use of e-fuels are

crucial measures to reduce emissions associated with maritime transport and to comply with both the EU FuelEU Maritime Regulation and the International Maritime Organization (IMO) guidelines. The bioenergy upgrade with carbon credit compensation (S10), although addressing a limited gap ($\Delta x_j = 0.07$), aligns with Kalundborg's incremental approach to residual emission management. The park already operates advanced bioenergy and CO₂ capture plants, but the integration of market-based mechanisms such as carbon credits allows remaining gaps to be closed, reinforcing the trajectory toward climate neutrality by 2050. Finally, the optimization of port logistics (S11), with a contribution of $\Delta x_j = 0.5$, underscores the importance of organizational and managerial solutions alongside technological ones. The port logistics system of Kalundborg—linked to both freight transport and energy distribution—represents one of the main sources of indirect environmental impact. Measures aimed at improving flow efficiency and digitalizing the supply chain help reduce consumption and emissions, while enhancing the overall resilience of the system.

6.2.1.5 Comparative results between Envipark and Kalundborg (environmental dimension)

The application of the GP–knapsack model highlights two distinct trajectories of environmental improvement, reflecting not only the intrinsic nature of the two EIP but also their different cost structures and the impact profiles of the selected strategies.

For Envipark, the model identified a set of interventions with a total cost of approximately €355,000, distributed relatively evenly between low-cost strategies (e.g., certification maintenance, S5, €5,000) and larger-scale investments (e.g., micro-CCS, S13, €80,000; phytoremediation system, S12, €45,000). The greatest impact derives from innovative and structural strategies—phytoremediation ($\Delta x_j = 1$) and micro-CCS ($\Delta x_j = 1$)—which together address two of the park's most critical environmental gaps. Meanwhile, the expansion of photovoltaic capacity (S1, $\Delta x_j = 0.45$) and energy efficiency improvements (S3, $\Delta x_j = 0.5$) consolidate the ongoing emission reduction trajectory.

Overall, Envipark's spending profile is characterized by a combination of low-cost incremental actions (e.g., S5, S9, S10) and high-impact demonstrative solutions (S12, S13), consistent with the park's smaller scale and its role as a technological laboratory.

For Kalundborg, by contrast, the selected investment package is significantly more expensive (€520,000 in total) and comprises transformative, large-scale strategies. The main investment concerns the Power-to-X hydrogen plant (S7, €120,000), which is the most impactful action ($\Delta x_j = 1$), followed by port electrification and green maritime fuels (S8, 150,000 €, $\Delta x_j = 0.5$) and maritime logistics optimization (S11, 120,000 €, $\Delta x_j = 0.5$). Together, these three strategies absorb over 70% of the total budget, reflecting Kalundborg's emphasis on decarbonizing transport and energy flows, both structural sectors of its industrial system. Consolidation actions, such as maintaining renewable energy systems (S1, 80,000 €, $\Delta x_j = 0$) and upgrading bioenergy with carbon credit compensation (S10, 50,000 €, $\Delta x_j = 0.07$), complement this framework, ensuring the continuity of already achieved performance levels.

6.2.2 Social component (Kalundborg)

The second phase of the evaluation process was applied exclusively to the social component and limited to the case of Kalundborg Symbiosis. This methodological choice is based on two main considerations. First, the synthetic ESG social performance index calculated for Kalundborg (0.78) is significantly lower than that of Envipark (0.90), indicating greater potential for improvement in the former. Second, for Envipark, no gaps were identified with respect to the targets for any mandatory indicators, making the activation of additional improvement strategies unnecessary within the present framework.

For Kalundborg, the active analysis focused exclusively on mandatory social indicators, as these represent minimum requirements of accountability and compliance, derived from international soft-law standards (UNIDO, GRI, SDG, ISO). The voluntary strategic indicators (n. 1 and n. 2, referring to the total number of enterprises and direct employees) were excluded from the analysis because they are not directly actionable in the short term by the EIP management and no clear, measurable improvement strategies could be defined in terms of costs and incremental impacts. For each mandatory indicator showing a positive gap from its target, it was possible to:

- identify one or more intervention strategies consistent with the park's operational context;
- estimate gross and net implementation costs, considering potential European and national funding mechanisms;
- construct a matrix of alternatives, associating each strategy with the expected improvement in performance (Δx_i), the net cost, and any logical interdependencies among interventions.

The objective of the model was to maximize the synthetic social performance index through the optimal selection of strategies to be implemented, subject to a budget constraint of €450,000, applying a binary knapsack-type algorithm.

For the social component, and specifically for Kalundborg, potential subsidies were considered for strategies such as: experimental corporate welfare services; events in collaboration with NGOs and local schools; the creation of a social incubator for youth and students. Among the most relevant European programmes are:

- ESF+ (European Social Fund Plus), supporting initiatives for labour inclusion and gender equality;
- EaSI (Employment and Social Innovation), funding social enterprise and incubator projects;
- Erasmus+ – Key Action 2 and Alliances for Innovation, promoting cooperation between educational institutions, companies, and local actors;
- Creative Europe and Interreg, supporting cultural and territorial engagement initiatives.

The co-financing rates for these programmes typically range from 50% to 90%, depending on the type of applicant, partnership composition, and project scale.

In the GP model used for the active evaluation, these subsidies were explicitly integrated by distinguishing between gross costs (full strategy cost) and net costs (after applying estimated co-financing).

This ensures a more realistic representation of the financial impact of each strategy and facilitates the identification of an optimal, sustainable mix of interventions, both environmentally and economically. The number of companies and employees was excluded from the active evaluation, as these variables are closely tied to the territorial extension of the Symbiosis Park and cannot be directly increased by management actions. The budget considered was €450,000.

The improvement strategies selected for Kalundborg aim to: introduce experimental corporate welfare services; organize at least two annual events in collaboration with NGOs and local schools; continue the Symbiosis Training Program and partnerships with Campus Kalundborg; create a social incubator for cooperatives or inclusive start-ups; ensure retention and employee wellbeing strategies; continue funding scholarships for the Helix Lab; maintain active platforms for onboarding and career development programmes.

The logical interdependence constraints adopted were as follows: (i) the creation of a social incubator for cooperatives or inclusive start-ups requires that the Symbiosis Training Program and Campus Kalundborg collaborations remain active; (ii) maintaining a high average employee tenure depends on the presence of corporate welfare services; (iii) efficient onboarding and career development programmes require retention and wellbeing strategies.

6.2.2.1 Results for Kalundborg (social component)

The GP-knapsack model identified the following strategies to optimize the social performance of the Kalundborg Symbiosis:

- Activation of experimental corporate welfare services (S3);
- Organization of at least two annual events in collaboration with NGOs and local schools (S4);
- Continuation of the Symbiosis Training Program and partnerships with Campus Kalundborg (S5);
- Creation of a social incubator for cooperatives or inclusive start-ups (S6);
- Funding scholarships for the Helix Lab (S8).

The effective cost of the optimal strategy mix is €228,000, yielding an estimated weighted overall improvement of 0.1, which raises the social performance index of Kalundborg from 0.78 to 0.88. In this case, the model does not reach the maximum value of 1, as strategies related to increasing the number of companies and direct employees were excluded. For the first indicator (number of companies), the gap identified during the passive phase was 0.66, which would have had a significant influence if the corresponding strategies had been included. [Table 15](#) reports the selected and excluded strategies, along with the covered gaps, net costs, and binary decision variables from the model.

The application of the GP-knapsack model to the social component of Kalundborg selected a set of five strategies consistent with the district's profile—characterized by a long-standing tradition of collaboration with the education system and high employment stability—while also highlighting the need to address specific gaps identified in the passive assessment, particularly in corporate welfare and community engagement activities.

TABLE 15 Social improvement strategies for Kalundborg selected and excluded by the GP–knapsack optimization model, showing the associated performance increments (Δx_j), net implementation costs, and binary decision variables.

Strategy	Δx_j	Net cost	Binary variables
S3	0.34	20,000.00 €	1
S4	0.5	6,000.00 €	1
S5	0	70,000.00 €	1
S6	0.5	130,000.00 €	1
S7	0	157,500.00 €	0
S8	0	2,000.00 €	1
S9	0	28,000.00 €	0

The selection of S3 ($\Delta x_j = 0.34$; 20.000 €) directly responds to the lack of structured welfare services, which are currently limited to conventional benefits. The introduction of innovative measures, such as on-site childcare or flexible working schemes, represents a cost-effective and strategic intervention to attract and retain skilled workers in a highly specialized industrial context. S4 ($\Delta x_j = 0.50$; 6.000 €) emerges as the most efficient strategy in terms of the impact-to-cost ratio. Organizing events in collaboration with NGOs and local schools strengthens the community dimension of the EIP, addressing a clear gap in the “events hosted” indicator. When coordinated with the continuation of Helix Lab scholarships (S8), these initiatives translate territorial engagement into concrete learning opportunities, enhancing both social capital and the park’s reputation. The continuation of the Symbiosis Training Program and partnerships with Campus Kalundborg (S5), although not directly improving performance ($\Delta x_j = 0$; 70.000 €), has been included as a maintenance measure for a key strategic asset. This training programme is a cornerstone of the park’s identity and a logical prerequisite for the creation of a social incubator (S6). Without continuity in these educational initiatives, there would be a high risk of performance regression. The creation of a social incubator for cooperatives and inclusive start-ups (S6, $\Delta x_j = 0.50$; 130.000 €) represents the most transformative intervention. It institutionalizes a pathway from training to inclusive entrepreneurship, consolidating existing educational collaborations and translating them into projects with tangible social and economic impact. Despite its higher cost, this measure generates significant positive externalities in terms of social inclusion, youth employment, and territorial cohesion, fully aligned with Sustainable Development Goals 4, 8, 10, and 11. Finally, S8 ($\Delta x_j = 0$; 2.000 €) was selected as a low-cost, high-reputation maintenance measure. The Helix Lab scholarships reinforce the relationship between businesses, research, and the local community, ensuring the continuity of a highly skilled human capital base. Conversely, strategies such as employee retention (S7) and onboarding/career development programmes (S9) were not selected, as their respective indicators were already in line with the targets identified during the passive phase—average employee tenure in Kalundborg exceeds European benchmarks, and onboarding processes are fully operational. Their exclusion reflects the efficiency logic of the model, which avoids allocating resources to areas with no remaining improvement potential.

7 Discussion

This section discusses the results described in the previous sections. While Section 5 presented the ESG indices and the optimal strategy portfolios in a descriptive way, the focus here is on interpreting the observed patterns, highlighting cross-case differences and similarities, and reflecting on the methodological implications and limitations of the proposed framework.

7.1 Passive assessment: interpretation of ESG indices

The passive assessment phase yielded distinct ESG profiles for Envipark and the Kalundborg Symbiosis across the environmental, social and governance dimensions. In this subsection, the indices and gaps reported in Section 6.1 are interpreted, with attention to the underlying structural drivers and their consistency with previous studies on EIPs and industrial symbiosis.

7.1.1 Environmental

The difference in the environmental ESG index between Envipark and Kalundborg mainly reflects structural divergences between the two Eco-Industrial Parks, more than just a different degree of regulatory compliance. Envipark’s lower score can be traced back to localized critical issues—particularly related to territorial scale, water conservation, energy efficiency and indirect emissions—while Kalundborg shows a systemic environmental performance, supported by an infrastructure endowment and consolidated industrial symbiosis networks.

Empirical evidence on the Kalundborg case documents significant reductions in CO₂ emissions and significant resource savings, indicating how symbiotic exchanges and shared utilities produce cumulative long-term environmental benefits. The observed gap can therefore be interpreted as the effect of differences in terms of scale, maturity of symbiotic relationships and infrastructure investments, in line with what is highlighted by the literature on mature EIPs compared to more localized and incremental configurations (Jacobsen, 2006; Florencio de Souza et al., 2020; UNIDO et al., 2017).

7.1.2 Social

The comparison between the two case studies highlights differentiated approaches to social sustainability in Eco-Industrial Parks. Envipark, while operating on a smaller scale, displays a more integrated and widespread social ESG strategy, while Kalundborg, while representing a mature model of industrial symbiosis, presents welfare and human capital development tools that are less structured than emerging European standards. This result confirms that the environmental and infrastructural maturity of an EIP does not automatically translate into equivalent social performance, as already observed in the literature on sustainable industrial systems.

In detail, two complementary social models emerge. Envipark values territorial proximity and relationships with the local innovation ecosystem to invest in training, inclusion, and community engagement, exceeding many social targets despite its small size. Kalundborg, by contrast, is founded on a broad and stable employment base and strong links with the education system, but

shows room for improvement in corporate welfare and community engagement policies. This configuration is consistent with the debate on just transition and decent work in industrial contexts, which emphasizes how social strategies require dedicated interventions and do not automatically derive from environmental or technological excellence (ILO, 2015; UNIDO et al., 2017).

7.1.3 Governance

Passive evaluation of the governance dimension highlights two distinct approaches that are consistent with the context of the respective Eco-Industrial Parks. Envipark adopts a predominantly regulatory compliance-oriented model, based on formal governance structures, procedures, and reporting tools, while Kalundborg is based on a community-based model, characterized by relationships of trust, territorial proximity, and informal cooperation between actors. Both approaches are effective in terms of ESG performance, suggesting that different governance models can sustain comparable outcomes if adequately aligned with the target institutional and organizational context.

This duality reflects the distinction, widely discussed in the literature, between compliance-based governance models and lattice or relational models in the contexts of Eco-Industrial Park and regional innovation systems. Envipark represents an example of formalized and regulatory governance, while Kalundborg embodies a structure based on dense inter-organizational networks and place-based collaboration mechanisms. The high scores obtained by both parks indicate that different combinations of formal and informal tools can support effective ESG governance; at the same time, they suggest that more relational models could, over time, benefit from the selective integration of reporting and compliance tools to respond to increasingly stringent regulatory requirements without compromising their flexibility (Schaltegger and Burritt, 2018).

7.2 Active assessment: interpretation of optimization strategies

The active assessment phase translated the ESG gaps identified in the passive evaluation into cost-constrained portfolios of improvement strategies. In this subsection, the optimal sets of actions obtained for Envipark and Kalundborg are interpreted in terms of their strategic meaning, coherence with the existing infrastructures and governance arrangements, and implications for the transition trajectories of the two EIPs.

7.2.1 Environmental - Envipark

The results of the active environmental assessment for Envipark show how the Goal Programming model promotes a transition path consistent with the structural characteristics of a small-scale, high-intensity, innovative Eco-Industrial Park. Rather than maximizing individual indicators, the selected optimal portfolio reflects a balanced strategy, oriented towards reducing the main environmental gaps that emerged in the passive phase without forcing solutions incompatible with the economic and organizational constraints of the context.

From an interpretative perspective, the combination of low-cost incremental measures (such as maintaining certifications and new

waste recovery contracts) and a limited number of high-visibility technological interventions (such as micro-CCS and phytoremediation) suggests that small-scale EIPs can maximize environmental effectiveness through hybrid strategies, rather than through large-scale infrastructure investments. This approach is consistent with the literature on innovation-oriented Eco-Industrial Parks, which highlights the role of demonstration and modular interventions in fostering progressive and replicable improvement trajectories (Yu et al., 2014).

In the case of Envipark, the selected portfolio strengthens the park's function as a technology laboratory and testbed for emerging environmental solutions, demonstrating how multi-objective optimization can support gradual but potentially transformative transition paths. In line with studies highlighting the importance of aligning environmental ambition, financial capacity, and local financing opportunities, the findings indicate that environmentally effective strategies do not necessarily require massive interventions, but a targeted selection of actions consistent with the EIP profile and the relevant institutional context (Morano et al., 2021).

7.2.2 Environmental - Kalundborg

The results of the active phase for the Kalundborg environmental component outline a path for improvement strongly oriented towards strengthening and evolving already established infrastructure, integrating high-impact border interventions at the territorial scale. Unlike what was observed for Envipark, the selected portfolio prioritizes strategies related to logistics decarbonization, port infrastructure electrification, and the adoption of Power-to-X technologies, reflecting Kalundborg's nature as an open system, deeply interconnected with national and international energy and transport networks.

From an interpretative point of view, these results indicate that in large, infrastructure-intensive Eco-Industrial Parks the most relevant ESG improvements do not mainly arise from the optimization of internal processes, but rather from interventions located at the interface between the park and larger territorial systems. The centrality attributed to green marine fuels, port electrification, and renewable hydrogen highlights the need to align local industrial symbiosis networks with decarbonization strategies in the energy and transportation sectors, as widely discussed in the literature on sustainable industrial and logistics transitions (Geels, 2002; Acciaro and Wilmsmeier, 2015).

In this sense, the optimized path for Kalundborg confirms that environmental performance in mature industrial symbiosis parks increasingly depends on the ability to coordinate investment, governance, and technological innovation across multiple scales and across a variety of actors. The application of the GP-knapsack model thus shows how multi-objective optimization tools can support complex strategic decisions, strengthening existing development trajectories and filling residual gaps through coherent, operationally achievable, and systemically integrated interventions.

7.2.3 Social - Kalundborg

The results of the active evaluation for the Kalundborg social component outline a targeted improvement path, consistent with the profile of a mature Eco-Industrial Park, where the priority is not

to bridge large structural gaps, but to strengthen specific areas of weakness while consolidating existing social assets. The selected optimal portfolio combines incremental, low-cost measures with maintenance actions and high-impact transformative intervention, confirming the ability of the GP-knapsack model to identify solutions that are not only economically efficient, but also sensitive to the park's context and evolutionary identity.

From an interpretive perspective, the findings highlight how, in large industrial parks with high employment stability, relatively limited but highly visible interventions in corporate welfare and community engagement can generate significant social benefits. The introduction of experimental welfare services, collaborative initiatives with schools, NGOs, and local stakeholders, as well as the creation of spaces dedicated to social innovation, serves as a strategic complement to established training and employment policies. This approach is consistent with literature highlighting the role of welfare and community engagement investments in strengthening industrial district social license to operate and improving its attractiveness for skilled workers and young graduates (Crisuolo et al., 2022; Gunningham et al., 2004).

7.3 Comparative discussion: scale, infrastructure and governance

Overall, the results of the two evaluation phases show how Eco-Industrial Parks respond to ESG frameworks in a highly context-dependent manner, highlighting limitations of purely descriptive and target-based approaches. Passive evaluation allows gaps to be systematically identified against regulatory and soft law standards, while active evaluation transforms these gaps into coherent, financially sustainable intervention portfolios tailored to the structural specificities of each EIP. In this sense, the proposed model fills a recurring gap in the ESG literature by integrating performance measurement and strategic decision support. The approach demonstrates that ESG compliance is not a static objective, but a dynamic process that requires tools capable of translating assessment into credible operational trajectories, differentiated by scale, maturity, and governance arrangements. The differentiation of improvement trajectories between Envipark and Kalundborg is consistent with classical evidence from the industrial symbiosis literature, which highlights symbiosis profiles and configurations that are strongly dependent on the production and infrastructure context (Chertow, 2000). The presence of differentiated optimal portfolios across parks is interpreted as a function of prerequisite relationships and cost constraints, consistent with studies using integrated modeling approaches to support sustainability decisions on complex systems (Demartini et al., 2022).

From a comparative perspective, a clear divergence emerges:

- Envipark focuses its spending on targeted, technologically innovative, and locally scalable actions, capable of maximizing environmental performance improvement within a more limited budget. The relative importance of each intervention is evenly distributed, with a balanced cost-impact relationship.
- Kalundborg, on the other hand, requires larger investments to act on high-emission-intensity sectors such as maritime transport and energy production. Here, the model reveals a more concentrated cost-benefit profile, where a few strategies (S7, S8, S11) absorb most of the resources and generate the major share of environmental improvement.

This comparison confirms that the GP-knapsack approach does not yield a single optimal solution, but rather produces differentiated, context-sensitive pathways. Envipark prioritises low-cost, demonstrative, and scalable interventions, while Kalundborg directs its spending toward large-scale infrastructural transformations—essential to maintain its European leadership in industrial symbiosis and to align with the targets of the Green Transition.

When these environmental trajectories are read together with the social and governance results, a more articulated picture emerges. Envipark combines a relatively modest environmental index with strong social and governance performance, supported by formalised structures, intensive engagement with local stakeholders and a broad portfolio of inclusion and training initiatives. Kalundborg, by contrast, achieves very high environmental scores, but shows residual gaps in corporate welfare and community engagement and relies more heavily on relational, network-based governance mechanisms.

7.4 Methodological implications and robustness

The comparison highlights how ESG scoreboards interact differently with EIPs depending on scale, infrastructure intensity, and governance maturity. Smaller, innovation-oriented parks tend to benefit from incremental and modular strategies, while large-scale symbiosis systems require capital-intensive and system-wide interventions. This confirms that ESG assessment in EIPs cannot be based on uniform benchmarks but must be integrated into context-sensitive decision-making frameworks, as conducted in this study. Moreover, the differences in scores and priorities identified reflect not only the specificities of the cases but also the methodological variability observed in the literature on sustainability and complex industrial systems assessment approaches (Demartini et al., 2022; Vahidzadeh et al., 2025).

In some cases, normalized values were assigned based on qualitative judgments due to limited data availability. While this introduces a degree of uncertainty, the assumptions were made explicit and consistently applied across cases. The resulting scores should therefore be interpreted as indicative rather than absolute, and their primary function remains comparative and decision-support oriented, rather than predictive. However, in the absence of fully comparable data, the inclusion of normalized qualitative judgments is advocated as a methodologically acceptable practice in MCDA contexts, where qualitative and quantitative information is integrated (D'Adamo et al., 2025; Lindfors, 2021; Morano et al., 2025).

Future work should explicitly address these issues by conducting systematic sensitivity and robustness analyses. Possible extensions include testing alternative normalization rules and weighting

schemes, exploring interval-valued or stochastic Goal Programming formulations, and using Monte Carlo simulations to assess how uncertainties in qualitative scores and weights propagate to ESG indices and optimal strategy portfolios. Such analyses would make it possible to identify the most influential indicators, prioritize data collection efforts, and provide decision-makers with ranges or confidence intervals instead of single-point estimates.

8 Conclusion

Eco-Industrial Parks (EIPs) are increasingly called upon to demonstrate measurable ESG performance comparable to the scale of territorial industrial systems. However, as widely recognized in the literature, many sustainability assessments applied to EIPs remain predominantly descriptive and provide limited support for decision-making processes and operational prioritization. In this context, the present study demonstrates that the integration between a gap-to-target ESG assessment and a cost-constrained optimization phase allows to transform ESG performance analysis into an operational decision support tool at the industrial park scale, bridging a recurring gap between assessment and sustainability governance (Gibson, 2006).

The results highlight how ESG profiles and optimal improvement paths are strongly context-dependent. In line with the literature on EIPs and industrial symbiosis, which highlights the heterogeneous and systemic nature of such configurations (Chertow, 2000; Boons et al., 2011), Envipark and Kalundborg show different transition trajectories: in the first case, predominantly incremental and demonstration strategies emerge, while in the second, large-scale infrastructure and decarbonization measures are prioritized. This confirms that there are no universally optimal ESG solutions for EIPs, but rather intervention portfolios consistent with the structural, technological, and institutional specificities of each context.

From a scientific perspective, the work contributes to the ESG assessment literature by proposing a replicable two-stage framework based on Goal Programming, which consistently integrates (i) ESG measurement against regulatory and soft law targets and (ii) the selection of intervention strategies under economic constraints. The main methodological contribution lies in operationalizing an explicit link between ESG assessment and decision-making processes, filling a recurring gap between performance analysis and sustainability governance in complex industrial contexts (Jones and Tamiz, 2010).

Operationally, the framework offers EIP managers and public decision makers a concrete tool to: (i) identify the most critical ESG gaps at the size and individual indicator levels; (ii) explore realistic intervention portfolios in the presence of budget constraints and prerequisite relationships between measures; and (iii) distinguish between incremental and transformative transition paths as a function of the EIP archetype considered (e.g., small-scale innovation-oriented parks versus infrastructure-intensive industrial symbiosis systems). This supports investment prioritization, the design of targeted financing schemes, and more transparent ESG governance at the park scale.

The study has some limitations that need to be explicitly recognized. First, the availability of ESG indicator data is heterogeneous across

dimensions and case studies; in some cases, performance levels have been normalized based on transparent qualitative assumptions, which may influence composite scores. Second, the model structure assumes linear relationships in both the aggregation of deviations and performance gains, only partially capturing systemic interdependencies and feedbacks between ESG dimensions and strategies. These critical issues are widely discussed in the literature on multicriteria methods applied to sustainability and represent a still open methodological challenge (Cinelli et al., 2014). Third, the indicator weighting scheme, while based on stakeholder input, introduces an element of subjectivity that can impact the hierarchization of priorities. Furthermore, cost estimates—including net ones after the co-financing assumption—are scenario-based and do not systematically incorporate indirect benefits, spillover effects, or learning dynamics over time. Finally, the generalizability of the framework is currently supported by only two European case studies, necessitating further applications to derive more robust benchmarks.

Future developments will be focused on improving the following issues of this research: (i) integrating non-linear conditions in the model and managing scarcity of data; (ii) extending the framework to multi-stakeholder scenarios, accounting for conflicts and synergies; (iii) including indirect impacts and positive externalities through multi-criteria analysis and extended cost-benefit approaches; (iv) testing the model on a broader set of EIPs and other industrial or territorial systems; (v) systematically embedding sensitivity and robustness analyses to explore the effects of alternative normalisation rules and weighting schemes; and (vi) adapting the approach to sectoral or national-scale sustainability assessments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and the institutional requirements.

Author contributions

DA: Validation, Conceptualization, Project administration, Data curation, Supervision, Methodology, Writing – review and editing, Writing – original draft, Investigation, Resources, Visualization, Funding acquisition, Formal Analysis, Software. PM: Validation, Project administration, Formal Analysis, Writing – review and editing, Conceptualization, Writing – original draft, Supervision, Resources. FF: Data curation, Writing – original draft, Visualization, Investigation,

Validation, Writing – review and editing. ES: Validation, Writing – review and editing, Data curation, Investigation, Writing – original draft, Visualization.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Acciaro, M., and Wilmsmeier, G. (2015). Energy efficiency in maritime logistics chains. *Res. Transportation Business Manage.* 17, 1–7. doi:10.1016/j.rtbm.2015.11.002
- Agosto, A., and Tanda, A. (2025). Divergence and aggregation of ESG ratings: a survey. *Open Res. Eur.* 5 (28), 28. doi:10.12688/openreseurope.19238.2
- Anelli, D., Morano, P., Tajani, F., and Sabatelli, E. (2024). “Impacts of urban decay on the residential property market: an application to the city of Rome (Italy),” in *International Conference on Computational Science and Its Applications*, (Cham: Springer Nature Switzerland), 36–48. doi:10.1007/978-3-031-65318-6_3
- Bellman, R. E., and Zadeh, L. A. (1970). Decision-making in a fuzzy environment. *Manag. Sci.* 17 (4), B-141. doi:10.1287/mnsc.17.4.B141
- Berg, F., Kölbl, J. F., and Rigobon, R. (2022). Aggregate confusion: the divergence of ESG ratings. *Rev. Finance* 26 (6), 1315–1344. doi:10.1093/rof/rfac033
- Berk, J. B., and Green, R. C. (2004). Mutual fund flows and performance in rational markets. *J. Political Econ.* 112 (6), 1269–1295. doi:10.1086/424739
- Boons, F., Spekkink, W., and Mouzaktis, Y. (2011). The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. *J. Cleaner Production* 19 (9–10), 905–911. doi:10.1016/j.jclepro.2011.01.003
- Capizzi, V., Gioia, E., Giudici, G., and Tenca, F. (2021). The divergence of ESG ratings: an analysis of Italian listed companies. *J. Financial Manag. Mark. Institutions* 9 (02), 2150006. doi:10.1142/s2282717x21500067
- CDP (2024). *Scoring methodology (climate change/water security/forests)*. London: CDP.
- Charnes, A., and Cooper, W. W. (1957). Management models and industrial applications of linear programming. *Manag. Sci.* 4 (1), 38–91. doi:10.1287/mnsc.4.1.38
- Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energy Environ.* 25 (1), 313–337. doi:10.1146/annurev.energy.25.1.313
- Chertow, M. R. (2007). “Uncovering” industrial symbiosis. *J. Industrial Ecol.* 11 (1), 11–30. doi:10.1162/jiec.2007.1110
- Cheshmehzangi, A. (2025). “Loops of value: the kalundborg industrial symbiosis and the architecture of circular exchange in Denmark,” in *Resourceful urbanism: designing regenerative cities through adaptive reuse and circular innovation* (Singapore: Springer Nature Singapore), 77–90.
- Cinelli, M., Coles, S. R., and Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecol. Indicators* 46, 138–148. doi:10.1016/j.ecolind.2014.06.011
- Conticelli, E., and Tondelli, S. (2014). Eco-industrial parks and sustainable spatial planning: a possible contradiction? *Adm. Sci.* 4 (3), 331–349. doi:10.3390/admsci4030331

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- Crisuolo, C., Gonne, N., Kitazawa, K., and Lalanne, G. (2022). An industrial policy framework for OECD countries: old debates, new perspectives.

- Demartini, M., Tonelli, F., and Govindan, K. (2022). An investigation into modelling approaches for industrial symbiosis: a literature review and research agenda. *Clean. Logist. Supply Chain* 3, 100020. doi:10.1016/j.clscn.2021.100020

- Diaz-Balteiro, L., and Romero, C. (2008). Making forestry decisions with multiple criteria: a review and an assessment. *For. Ecol. Manag.* 255 (8–9), 3222–3241. doi:10.1016/j.foreco.2008.01.038

- D’Adamo, I., Di Leo, S., Gastaldi, M., and Paris, A. (2025). Evaluating sustainability in Europe with composite indicators. *Discov. Sustain.* 6 (1), 1251. doi:10.1007/s43621-025-02129-1

- Ehrenfeld, J., and Gertler, N. (1997). Industrial ecology in practice: the evolution of interdependence at Kalundborg. *J. Industrial Ecol.* 1 (1), 67–79. doi:10.1162/jiec.1997.1.1.67

- European Commission (2019). *The European green deal*. Brussels: European Commission.

- Felicio, M., and Amaral, D. C. (2013). Environmental indicators applied to reality of Eco-Industrial Park (EIP). doi:10.14279/depositonce-3753

- Florencio de Souza, F., Bigarelli Ferreira, M., Valéria Saraceni, A., Mendes Betim, L., Lucas Pereira, T., Petter, R. R. H., et al. (2020). Temporal comparative analysis of industrial symbiosis in a business network: opportunities of circular economy. *Sustainability* 12 (5), 1832. doi:10.3390/su12051832

- Frosch, R. A., and Gallopoulos, N. E. (1989). Strategies for manufacturing. *Sci. Am.* 261 (3), 144–153. doi:10.1038/scientificamerican0989-144

- Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res. Policy* 31 (8–9), 1257–1274. doi:10.1016/s0048-7333(02)00062-8

- Genc, O., and Kurt, A. (2024). Mimicking nature to design eco-industrial parks: exploring the influence of connectance on industrial network optimization. *J. Clean. Prod.* 475, 143704. doi:10.1016/j.jclepro.2024.143704

- Genc, O., van Capelleveen, G., Erdis, E., Yildiz, O., and Yazan, D. M. (2019). A socio-ecological approach to improve industrial zones towards eco-industrial parks. *J. Environ. Manage.* 250, 109507. doi:10.1016/j.jenvman.2019.109507

- Genc, O., Kurt, A., Yazan, D. M., and Erdis, E. (2020). Circular eco-industrial park design inspired by nature: an integrated non-linear optimization, location, and food web analysis. *J. Environmental Management* 270, 110866. doi:10.1016/j.jenvman.2020.110866

- Gibbs, D., and Deutz, P. (2007). Reflections on implementing industrial ecology through eco-industrial park development. *J. Clean. Prod.* 15 (17), 1683–1695. doi:10.1016/j.jclepro.2007.02.003

- Gibson, R. B. (2006). Sustainability assessment: basic components of a practical approach. *Impact Assessment Project Appraisal* 24 (3), 170–182. doi:10.3152/147154606781765147
- Global Reporting Initiative (2021). *GRI universal standards 2021: GRI 1 – foundation; GRI 2 – general disclosures; GRI 3 – material topics*. Amsterdam: Global Reporting Initiative.
- Gunningham, N., Kagan, R. A., and Thornton, D. (2004). Social license and environmental protection: why businesses go beyond compliance. *Law Social Inquiry* 29 (2), 307–341. doi:10.1111/j.1747-4469.2004.tb00338.x
- Hwang, C. L., and Yoon, K. (1981). “Methods for multiple attribute decision making,” in *Multiple attribute decision making: methods and applications – a state-of-the-art survey* (Berlin, Heidelberg: Springer Berlin Heidelberg), 58–191.
- Iannone, B., Dutillo, P., and Gattone, S. A. (2025). Evaluating the resilience of ESG investments in European markets during turmoil periods. *Corp. Soc. Responsib. Environ. Manag.* doi:10.1002/csr.3225
- Ignizio, J. P. (1976). *Goal programming and extensions*. Lexington, MA: Lexington Books.
- ILO. (2015). Guidelines for a just transition towards environmentally sustainable economies and societies for all.
- Jacobsen, N. B. (2006). Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. *J. Industrial Ecology* 10 (1–2), 239–255. doi:10.1162/108819806775545411
- Jones, D., and Tamiz, M. (2010). *Practical goal programming*. New York: Springer, 141.
- Keeney, R. L., and Raiffa, H. (1993). *Decisions with multiple objectives: preferences and value trade-offs*. Cambridge: Cambridge University Press.
- Koch, C., Tomasin, L., Lolli, F., Butturi, M., and Sellitto, M. (2022). Performance assessment of an Eco-Industrial Park: a strategic tool to help recovering energy and industrial waste. *Chem. Eng. Trans.* 91, 481–486. doi:10.3303/CET2291081
- Lindfors, A. (2021). Assessing sustainability with multi-criteria methods: a methodologically focused literature review. *Environ. Sustain. Indic.* 12, 100149. doi:10.1016/j.indic.2021.100149
- Lowe, E. A. (1997). Creating by-product resource exchanges: strategies for eco-industrial parks. *J. Clean. Prod.* 5 (1–2), 57–65. doi:10.1016/s0959-6526(97)00017-6
- Lütje, A., and Wohlgemuth, V. (2020). Tracking sustainability targets with quantitative indicator systems for performance measurement of industrial symbiosis in industrial parks. *Adm. Sciences* 10 (1), 3. doi:10.3390/admsci10010003
- Morano, P., Tajani, F., Guarnaccia, C., and Anelli, D. (2021). An optimization decision support model for sustainable urban regeneration investments. *WSEAS Trans. Environ. Dev.* 17, 1245–1251. doi:10.37394/232015.2021.17.114
- Morano, P., Anelli, D., Fariello, F., Locurcio, M., and Di Liddo, F. (2025). “Urban green spaces and housing prices: the impact of metric choice on econometric models,” in *International Conference on Computational Science and Its Applications*, (Cham: Springer Nature Switzerland), 320–331. doi:10.1007/978-3-031-97603-2_20
- Morningstar Sustainalytics (2023). *ESG risk ratings methodology*. Amsterdam: Morningstar Sustainalytics.
- MSCI Inc (2024). *MSCI ESG ratings methodology*. New York: MSCI.
- Murè, P., Giorgio, S., Antonelli, V., and Crisafulli, A. (2024). “ESG score” vs. “ESG rating”: a conceptual model for the sustainability assessment and self-assessment of European SMEs. *Front. Environ. Econ.* 3, 1452416. doi:10.3389/frevc.2024.1452416
- Parlamento Italiano (2022). *Legge costituzionale 11 febbraio 2022, n. 1. Modifiche agli articoli 9 e 41 della Costituzione*. Gazzetta Ufficiale della Repubblica Italiana. Rome, Italy: Istituto Poligrafico e Zecca dello Stato S.p.A.
- Pohekar, S. D., and Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planning—a review. *Renew. Sustain. Energy Rev.* 8 (4), 365–381. doi:10.1016/j.rser.2003.12.007
- Refinitiv, an LSEG Business (2023). *ESG scores methodology*. London: LSEG/Refinitiv.
- Romero, C., and Rehman, T. (2003). *Multiple criteria analysis for agricultural decisions*. Amsterdam: Elsevier, 11.
- Saaty, T. L. (2013). “Analytic hierarchy process,” in *Encyclopedia of operations research and management science* (Boston, MA: Springer), 52–64.
- Schaltegger, S., and Burritt, R. (2018). Business cases and corporate engagement with sustainability: differentiating ethical motivations. *J. Business Ethics* 147 (2), 241–259. doi:10.1007/s10551-015-2938-0
- Tamiz, M., Jones, D., and Romero, C. (1998). Goal programming for decision making: an overview of the current state-of-the-art. *Eur. J. Operational Res.* 111 (3), 569–581. doi:10.1016/s0377-2217(97)00317-2
- Tessitore, S., Daddi, T., and Iraldo, F. (2015). Eco-industrial parks development and integrated management challenges: findings from Italy. *Sustainability* 7 (8), 10036–10051. doi:10.3390/su70810036
- UN (2015). *Transforming our world: the 2030 agenda for sustainable development*. New York: United Nations.
- UNIDO, World Bank Group, and GIZ (2017). *An international framework for eco-industrial parks*. Vienna: United Nations Industrial Development Organization.
- Vahidzadeh, R., Domini, M., and Bertanza, G. (2025). Life cycle assessment of industrial symbiosis for circular solid waste management: a literature review. *Clean. Technol.* 7 (4), 100. doi:10.3390/cleantechnol7040100
- Yu, C., Davis, C., and Dijkema, G. P. (2014). Understanding the evolution of industrial symbiosis research: a bibliometric and network analysis (1997–2012). *J. Industrial Ecol.* 18 (2), 280–293. doi:10.1111/jiec.12073
- Zhu, Q., Lowe, E. A., Wei, Y. A., and Barnes, D. (2007). Industrial symbiosis in China: a case study of the Guitang group. *J. Industrial Ecol.* 11 (1), 31–42. doi:10.1162/jiec.2007.929