IDENTIFICATION OF PERCEIVED RELATIONSHIPS BETWEEN ENVIRONMENTAL PERFORMANCE INDICATORS IN ECODESIGN PROJECTS: THE CASE OF RAIL INFRASTRUCTURE PROJECTS

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ABSTRACT

Sharing information between stakeholders is a critical success factor for ecodesign projects. This sharing is based on indicators that can be interrelated, i.e., impacting each other.

This article focuses on the perception of environmental performance indicators' relationships during the design phase of projects. It uses a DEMATEL approach combined with a graph-database visualization linking environmental performance indicators. While the DEMATEL approach highlights the critical environmental indicators, the graph-based visualization maps the primary interrelations of these factors and defines the best scale to manage them. The novelty here lies in the complementary use of these two methods to facilitate environmental project monitoring.

This research is applied to rail infrastructure projects. The main results insist on land optimization, landscape insertion, carbon footprint, economic benefits, and biodiversity measures as critical factors when designing these projects. The graph-based visualization maps the main oriented links between indicators, allowing managers to identify the gaps between the perceived knowledge and the ground truth, facilitating their project monitoring.

Keywords: Ecodesign, Project management, Information management, Environmental performance indicators, Rail projects

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1 INTRODUCTION

Ecodesigning projects, i.e., integrating environmental performance in projects (ISO14006: 2020), is a process in which information sharing constitutes a primary success factor (Bey et al., 2013). This sharing is based on environmental performance indicators (EPIs), defined as specific information attributes issued by an emitter for a receiver regarding a particular objective (Waas et al., 2014). An example of EPI could be the rate of reused materials relative to a circular goal of reusing materials in a project. EPIs often share mutual relationships, i.e., they can directly influence each other. For example, the reuse of one material could depend on the reuse of another material. However, it is sometimes challenging for project managers to perceive these relationships and identify the most critical ones, i.e., which share multiple relationships, knowing that their perception directly impacts the project's design (Lamé et al., 2017). This is particularly true when dealing with the environmental field, where the issues and decisions can be related to many other industrial domains; and with complex projects, where many objectives are set and several stakeholders interact. This article addresses the following research question: How to select and visualize the most critical EPIs for monitoring projects' ecodesign?

The paper uses a DEMATEL approach (Gani et al., 2022; Gabus and Fontela, 1972) combined with a graph-based visualisation. This methodology allows project managers to highlight the critical indicators and understand their perceived relationships facilitating the monitoring of projects toward better integrating environmental issues. Although the DEMATEL approach has been explored and applied to various cases in the literature, the novelty here lies in its simultaneous application with a graph-oriented database. The methodology is applied to rail projects with the collaboration of the French rail infrastructure company SNCF Réseau (Mansour Salamé et al., 2021). The work aims to understand what can boost the ecodesign of these projects by identifying the most critical EPIs and mapping their perceived relationships. This would help project managers in their projects' ecodesign by mapping their perceived knowledge, comparing it to the ground truth, and reducing the gap between them.

2 LITERATURE REVIEW

2.1 EPIs' perception supporting projects' design

EPIs can be considered as knowledge vectors characterizing specific environmental attributes to describe, boost, and monitor the ecodesign of products, services, or projects. Their role is particularly highlighted in multi-stakeholder projects where stakeholders may not disclose sufficiently (Baddache and Nicolai, 2013). In this case, the lack of communication induces a lack of shared culture that can hinder decision-making (Wu, 2008).

Ecodesign's success relies on the quality of the delivered information. That is why an EPI is qualified if it satisfies a list of criteria, such as relevance regarding corporate objectives, measurability, and time sensitivity (Angelakoglou and Gaidajis, 2020). Also, EPIs, like all indicators, must be simple, i.e., easily available to their emitters and easily interpretable by their receivers (Lasswell, 1948).

However, even though each EPI satisfies all the listed criteria, decision-making can be challenging if the interrelations between EPIs' are not clearly perceived by project stakeholders. But for Gedam et al. (2021), understanding these interrelations remains challenging. This can negatively impact the project design as a gap exists between ground truth, i.e., factual relationships between environmental issues, and perceived knowledge, i.e., the understanding of these environmental issues.

As perception is an autonomous process relying on personal experience (Rock, 1985), it is essential to assess EPIs' perceived interrelations and compare them with the ground truth to facilitate projects' ecodesign.

2.2 The DEMATEL approach as a tool for characterizing perceived EPIs' links

2.2.1 General overview

The scientific literature is rich in methods that deal with environmental performance indicators' classification when ecodesigning projects (Daniel and Talaei-Khoei, 2016; Li et al., 2015). The most frequent ones are generally ANP (analytical network process), AHP (analytical hierarchy process),

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TOPSIS (Preferably technique of order by similarity with the ideal solution), and DEMATEL (decision-making testing and evaluation laboratory).
AHP and ANP are methods for classifying information from a hierarchical structure but do not allow the understanding of interrelations between distinct factors (Mangla et al., 2018). TOPSIS selects the best solution among existing ones by choosing the closest to the ideal solution (Jayant and Agarwal., 2019). However, it does not explain the different correlations between critical factors.
The DEMATEL approach, developed in 1971 by the Battelle Memorial Institute in Geneva (Gabus and Fontela, 1972), seems to fit this research purpose as it is popular for modelling relationships between multiple factors and selecting the most critical ones according to expert opinions. Indeed, Falatoonitoosi et al. (2014) argue that this approach has attracted the attention of researchers because of its effectiveness in modelling complex cause-and-effect relationships.
DEMATEL has been applied in various fields (Shen and Yao, 2017), particularly in assessing EPIs' interrelations for improving ecodesign, circular economy, and green supply chain management. For example, Zhang et al. (2021) analysed the relationships between drivers of smart waste management in China, highlighting perceived critical factors such as speed improvement and cost savings. In another context, Pinto et al. (2019) used a multicriteria model composed of the DEMATEL approach to identify the perceived relationships between green supply chain management, knowledge transfer, and innovation, concluding that knowledge transfer and innovation could be critical barriers in organizations.

2.2.2 Steps

The DEMATEL method is composed of four main steps: (Gabus and Fontela, 1972)

- Conceiving a direct relation matrix $A = (a_{ij})$, with i and j indicators, that assess the impact of row indicators on columnar indicators according to expert opinions and experience, in other terms, expert perception.
- Normalising the direct matrix as: $A_{norm} = \frac{A}{s}$ (1)

  with $s = \max\{\max(\sum_i a_{ij}), \max(\sum_j a_{ij})\}$ (2)
- Calculating the total relation matrix:

  $$T = \lim_{n \to +\infty} \sum A_{norm}^n = A_{norm} * (1 - A_{norm})^{-1} \quad (3)$$
- Expressing the vector of total influence exerted R (sum of columns of T) and the vector of total influence received C (sum of rows of T). These vectors inform on the nature of an indicator i whether it is perceived as impacting other indicators ($r_i + c_i > 0$) or impacted by others ($r_i - c_i < 0$).

The DEMATEL approach can be improved with the selection of a threshold value above which the elements of the total relation matrix T are considered significant. This threshold value can be set:

- with experts (Liang et al., 2022), but this method remains subjective and varies according to experts' profiles.
- by calculating the mean (and standard deviation) of the elements of the T matrix and considering it a threshold value (Zhang et al., 2021).
- by applying the maximum mean de-entropy algorithm (MMDE), based on the information theory. The main specificity of the MMDE algorithm is that it considers the value of each $T\_element$ rather than the holistic vision of T. More details are available with Li and Tzeng (2009) or Gani et al. (2022).

2.2.3 Visualisation

DEMATEL is most often supported by an influence diagram that classifies the indicators into four groups according to their overall impact on each other. However, when there are many indicators, it may be interesting to use other visualisation approaches from the big data environment, providing a practical and flexible framework for knowledge sharing. In particular, it seems interesting to represent the DEMATEL results in a graph database that classifies matrix elements as graph nodes and their relationships as oriented links (Raut et al., 2021). Such an approach constitutes a dynamic visualisation of the results. It also provides a more straightforward analysis as it is possible to navigate through the datasets.

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3 RESEARCH METHODOLOGY

This paper analyses the perceived relationships between 46 environmental performance indicators that can be used to support the decision-making of rail infrastructure projects' validation committees. These indicators were developed using a collaborative selection approach between the internal stakeholders of the French rail infrastructure company, SNCF Réseau, involving the participation of project managers and environmental experts. The validity of these indicators was discussed in a previous (submitted) work. The indicators are presented in the Appendix.
Since the purpose of this article is to study indicators' perceived relationships and identify the most critical ones, we base our research methodology on the DEMATEL approach, presented in section 2.2. DEMATEL is then combined with a threshold value analysis which reduces uncertainty and provides reliable findings. The results are visualized in a graph database using Neo4j software (Miller, 2013) modelling indicators' perceived relationships. The methodology is presented in Figure 1.

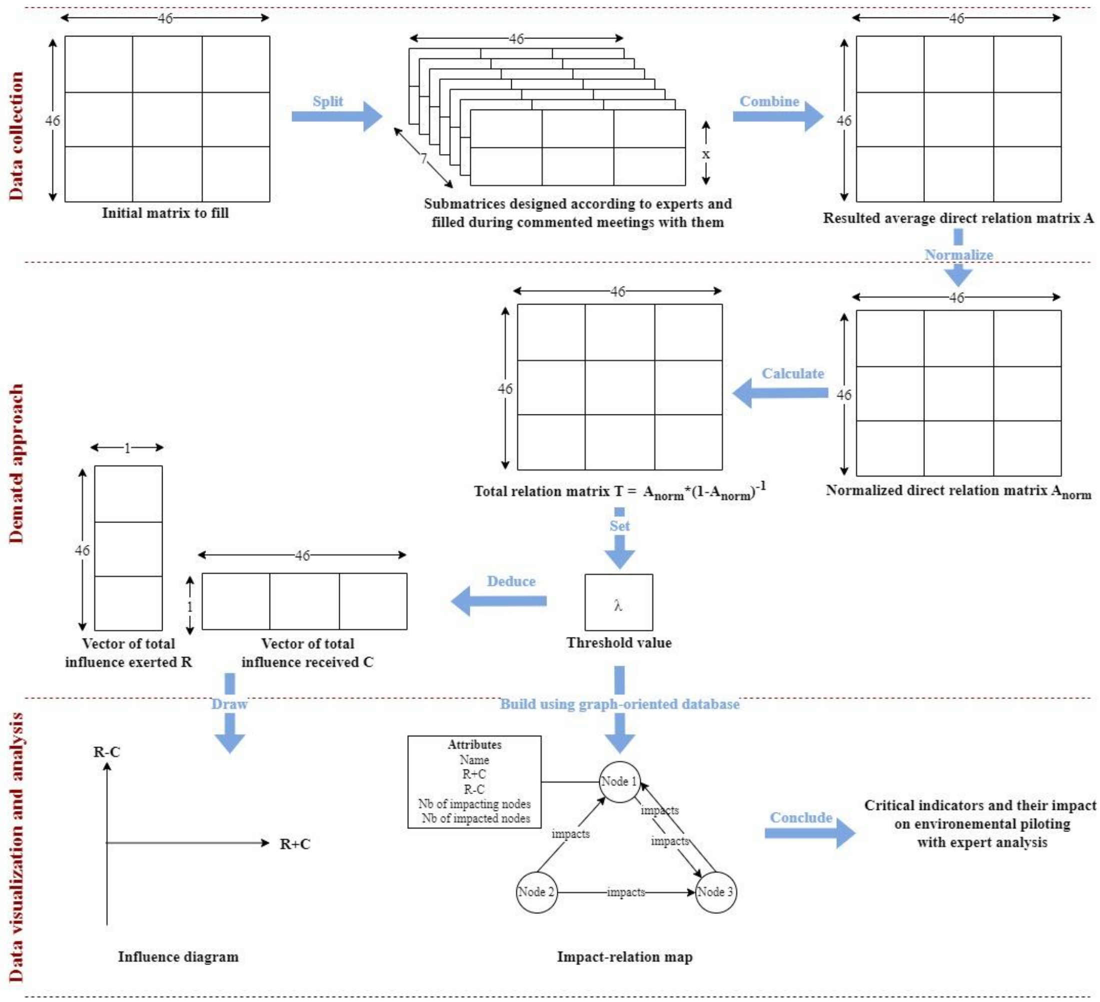

Figure 1. General methodology

The steps consist of the following:

- **Data collection:**

The 46 EPIs are grouped in a 46x46 matrix. Seven in-house environmental experts are identified, with at least one expert specialized in an environmental field such as circular economy, carbon emissions, or biodiversity. In addition, due to the difficulty of filling the whole matrix by each expert (2116 elements: time-consuming and missing knowledge on EPIs outside the expertise area), a specific matrix is designed for each expert: rows are composed of EPIs included in each expertise field (between four and nine matrix rows for each expert); columns are all 46 indicators. In other terms, each expert evaluates the EPIs he masters on all others using the scoring system of Luthra et al. (2018); 0: no impact, 1: extremely low impact, 2: low impact, 3: medium impact, 4: high impact, and

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5: extremely high impact. The expert is accompanied during a one-hour slot, letting him explicit his perception. Once all the expert answers are collected, they are grouped and averaged in the direct relation matrix A.

- **DEMATEL application:**

The guidelines for this step are those presented in section 2.3.3. A is normalized. The resulting normalized direct matrix is A_{norm}. The total relation matrix T, the vector of total influence R, and the vector of total C are calculated. These vectors are used to build the influence diagram using $R + C$ and $R - C$. The larger the R+C, the more relationships the indicator has with the other indicators. The smaller the R−C, the more indicators are influenced, and vice versa. Two threshold values representing (a) the sum of the mean and the standard deviation of the T_elements; and (b) the MMDE value are applied. The threshold value consisting of an expert choice is excluded as it is subjective.

- **Visualizing indicators and their links:**

The first results are represented in an influence diagram using Matlab software. They are then noted in a graph-database using Neo4J software. Environmental performance indicators are represented in nodes. These nodes share direct quantified relations issued from the total matrix T. The resulting graph facilitates the analysis of the prominent interrelations between nodes and enhances the piloting of environmental performance in rail infrastructure projects.

4 RESULTS

4.1 Calculation and representation of influence diagrams

The direct relation matrix A, shown in Figure 2, is obtained from the in-house experts' answers following the guidelines of section 3.2. This matrix maps the impacts of the row indicators on the column indicators. When the same indicator is found in both rows and columns, the impact is null.

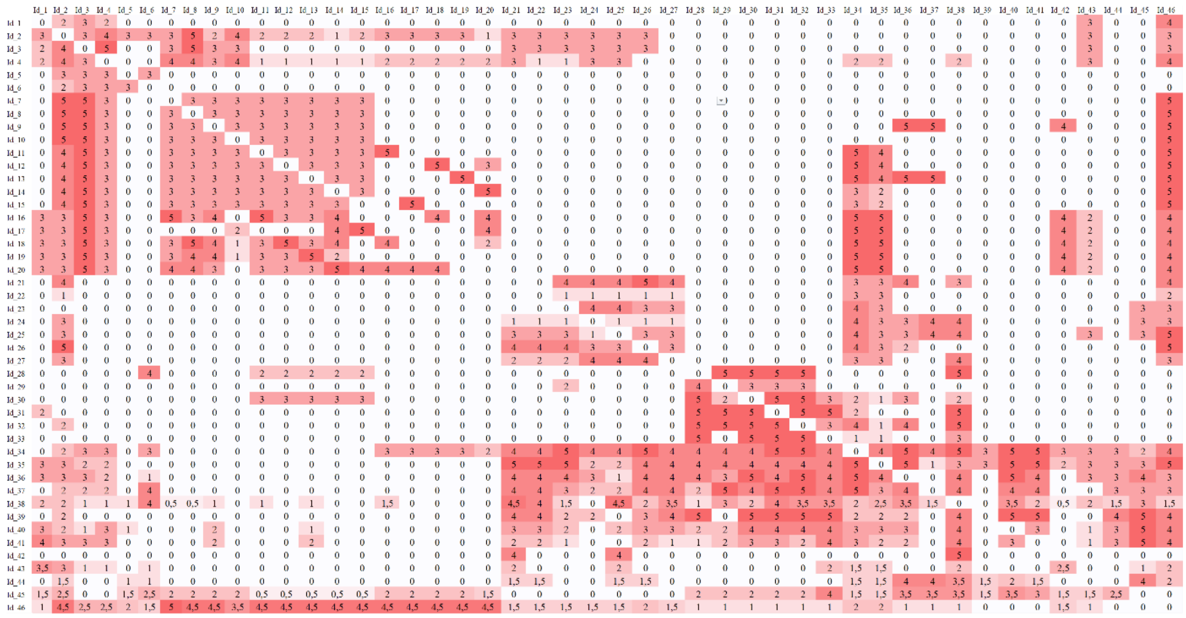

Figure 2. Direct relation matrix A

The matrixes A_{norm} and T are then calculated. We consider then two threshold values using (a) the sum of the mean with the standard deviation; and (b) the MMDE value.

- **The sum of the mean and the standard deviation of T_elements (Threshold value a)**:

The obtained influence diagram is represented in Figure 3. Four quadrants are identified (Luthra et al., 2018):

1. Voluntariness' quadrant contains EPIs that have a few perceived interrelations with others, and that can be considered as causes rather than consequences.

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2. Independencies' quadrant represents EPIs that do not have several perceived interrelations with other indicators but are consequences of other EPIs.
3. Driving Pressures' quadrant is composed of EPIs that strongly induce others.
4. Core Problems' quadrant contains intercorrelated factors induced by other EPIs.

Figure 3. Influence diagram with (Threshold value a)

The most prominent perceived EPIs are related to land use (surface, optimization and artificialization of soils), the economic balance related to environmental performance, carbon footprint, and landscape insertion. EPIs related to land use are in the driving pressure quadrant, i.e., they are perceived as the indicators with the highest impact on others in project design. This can be linked, for example, with the interview with a circular economy expert arguing that the collection of old rails (for reuse) highly depends on the planning and optimization of land use in the project design.

Carbon footprint, economic balance, and landscape insertion are perceived as core problems, i.e., they are perceived as most impacted by all other EPIs. It is interesting to link this result with the work of Zhang et al. (2021), who obtained that profit maximisation is the central core problem of promoting sustainability in green supply chain operations for waste management.

Other EPIs are mapped in the voluntariness quadrant. They consist of EPIs that could impact others, such as the number of watercourses that may impact biodiversity issues and induce compensation measurements.

The independencies' quadrant contains EPIs that are mostly perceived as clusters having a limited impact on other domains. This concerns, for example, noise reduction measurements or other regulatory issues that have a limited impact on other domains.

It is noted that, although the corporate strategy considers circular economy as a driver for projects' ecodesign, circular EPIs here are still in the voluntariness or independencies' quadrant. This probably means that circular economy is still perceived as a personal initiative rather than a standardized target.

- **The MMDE value (Threshold value b)**:

The obtained influence diagram is represented in Figure 4. This case is interesting as it is restricted to the most consistent indicators. Only seven EPIs remain: land use (surface) and its optimization, economic balance, carbon footprint, biodiversity reduction and compensation measures, and landscape insertion.

It is noted that land use (surface and optimization) remains, as in the previous case, perceived as the most critical EPI that impacts all others.

Economic balance becomes the main core problem of projects' ecodesign. The rest of EPIs are listed in the independencies' quadrant.

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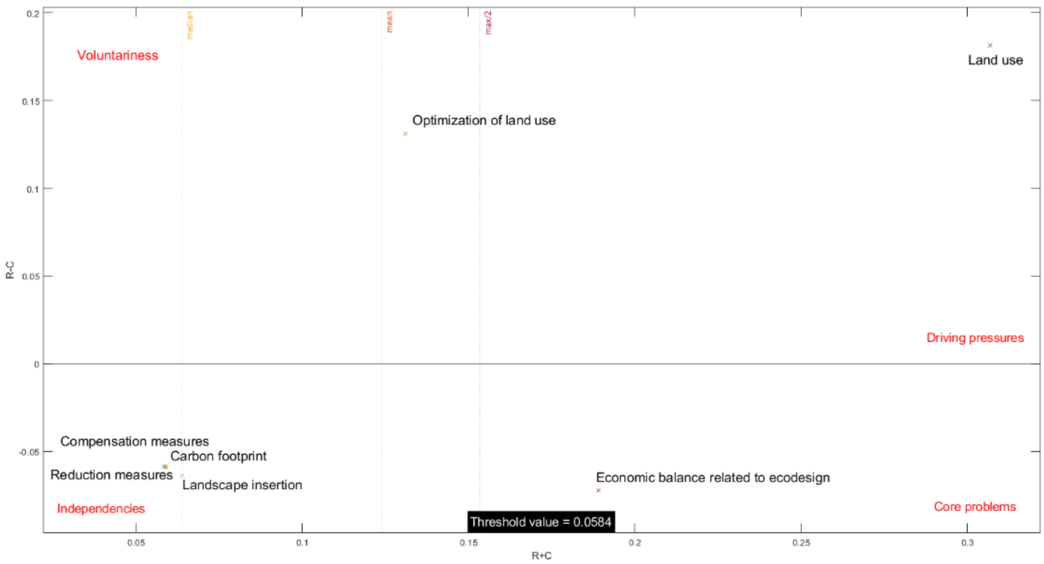

Figure 4. Influence diagram with (Threshold value b)

4.2 Visualisation of perceived EPIs' relationships

The influence diagram clusters EPIs according to the degree of their interaction with each other. However, this diagram representation does not directly map the perceived relations hips between EPIs. That is why a graph-database is used following the presented methodology in section 3.2. EPIs are filled in Neo4J software as distinct nodes of a single graph. These nodes are linked according to $T\_elements$, considering (Threshold value a) as it is less restrictive than (Threshold value b). Indeed, each non-zero $T\_element$ forms a link oriented from the row indicator to the column indicator. The weight of each relationship depends on the value of the corresponding $T\_element$. However, such a value remains incomprehensible to project stakeholders. That is why normalization has been applied: the relationships have been weighted as their sum at the entry of each node is equal to 100. In other words, the values are expressed according to their impact on EPIs. For example, if the company needs to study the relationships related to biodiversity avoidance measures, it can use the representation of Figure 5. In the present case, this means that land use, soil artificialisation, and watercourses are the main EPIs impacting avoidance measures. These measures are also perceived to be impacted by reduction and compensation ones. However, this is not true on the ground: avoidance measures are the first step for limiting biodiversity impact; they cannot be impacted by reduction and compensation measures. Here, a gap is noted between perceived knowledge and ground truth. Other examples can be found. Yet, the results need to be confronted with expert opinions to validate them.

Figure 5. Perceived relationships with biodiversity avoidance measures

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5 DISCUSSION AND CONCLUSION

5.1 Focus on the results

The DEMATEL approach mapped the expert's perceived knowledge regarding EPIs and their relationships. On one side, the results highlighted that EPIs concerning land use are the primary driver of rail projects' design. They are perceived as the main indicators that impact all others. This is also verified with the restrictive MMDE threshold value. On the other side, economic profits (economic balance), carbon footprint, and landscape insertion are the most affected EPIs by environmental decisions. It is interesting to draw a parallel between carbon footprint and economic benefits. These two indicators are similar as they represent the legitimacy of ecodesigning projects but for different stakeholders. Carbon footprint is mainly addressed to society, public investors, and other internal stakeholders. Economic profitability is more related to corporate managers, who are generally more worried about the rentability of decisions. Indeed, the lack of understanding economic benefits is always cited as the principal barrier to circular adoption in businesses and industries (Mangla et al., 2018). That is why, linking all EPIs with these two core problems can be a booster for ecodesigning projects, as this link adds legitimacy concerning all stakeholders. In this context, as circular economy is still perceived as an independent process, linking it to carbon footprint and profitability can be an opportunity to integrate it into the project design process. Finally, regulatory issues such as water, noise, and embankments are perceived as independent from other EPIs. They are perceived as being grouped in specific areas belonging to processes independent of each other. This perception may or may not be true; it is a matter of comparing it with the ground truth.

5.2 Focus on the global methodology: contributions, limitations, and perspectives

This paper used the DEMATEL approach combined with a graph-based visualisation method. While DEMATEL constitutes an approach for identifying indicators' interrelations, the graph-based visualisation transforms each indicator into a node and connects it to the other nodes. From an industrial point of view, this approach can lead to the transformation of corporate information systems, because indicators are no longer a static description but a dynamic representation facilitating project monitoring. From a scientific point of view, the method leverages features that could be used by DEMATEL to implement interconnected databases.

However, it is important to notice that the results, here, are issued by experts that perceive indicators' relationships at a specific time based on their experience at that moment. The results might not necessarily be concordant with the ground reality. For example, it was proven in the company that the reuse of rail is more impactful in reducing carbon footprint than other factors. Though, this is not translated when drawing the relationships of the graph database. This point opens a discussion with experts to validate whether this perception is related to them or to the paper's methodology. In this case, there is a gap in perceiving the relationships between EPIs. This can be due to a lack of communication between stakeholders (need to disclose), or a mischaracterization of environmental impacts (need to learn). The results thus describe how the EPIs' relationships are perceived by experts who play an important role in project ecodesign. But more than these results are needed to inform how the relationships should be perceived to facilitate the ecodesign. There are thus two major improvements to conduct. First, the perception of EPIs should be assessed directly with project managers in order to measure the difference of perception between experts and managers. Indeed, the final decision is issued by project managers, who are the main validators of their project design. Second, the ground reality should be scientifically characterized and represented with quantitative-oriented links in the graph database. This leads to comparing the grounded relationships with the perceived ones. A lack of knowledge can be highlighted if a "ground" link is not perceived. Relevant solutions should thus be proposed to boost projects' ecodesign.

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APPENDIX

Environmental performance indicators developed in the company

Environmental theme	Indicator [unit]	ID
Carbon emissions	Use of low carbon materials [volume]	Id_1
	Carbon footprint [gCO2/km*passenger]	Id_2
	(Carbon) Sensitive analysis for ecodesigned solutions [yes/no]	Id_3
	Consideration of the sensitive analysis [yes/no]	Id_4
Energy	Energy reduction [kWh]	Id_5
	Integration of renewable energy [kWh]	Id_6
Circular economy	Reuse of rails [%]	Id_7
	Reuse of sleepers [%]	Id_8
	Reuse of ballast [%]	Id_9
	Reuse of cables [%]	Id_10
	Rate of collected old rails [%]	Id_11
	Rate of collected old sleepers [%]	Id_12
	Rate of collected ballast [%]	Id_13
	Rate of collected old cables [%]	Id_14
	Rate of collected small components [%]	Id_15
	Rate of recycled rails [%]	Id_16
	Rate of recycled sleepers [%]	Id_17
	Rate of recycled ballast [%]	Id_18
	Rate of recycled cables [%]	Id_19
	Rate of recycled small components [%]	Id_20
Excavation	Spoil related to the project [volume]	Id_21
	Spoil produces by construction sites [volume]	Id_22
	Recycling rate of spoil [%]	Id_23
	Reused cuttings in non-technical backfill [volume]	Id_24
	Reused cuttings in technical backfill [volume]	Id_25
	Estimated spoil evacuation [volume]	Id_26
	Estimated excavation-embankment balance [%]	Id_27
Biodiversity	Impacted protected species [number]	Id_28
	Invasive species [number]	Id_29
	Avoidance measures [yes/no]	Id_30
	Reduction measures [yes/no]	Id_31
	Compensation measures [yes/no]	Id_32
	Impacts on ecological corridors [yes/no]	Id_33
Land use	Land use [surface]	Id_34
	Optimization of land use [text]	Id_35
	Artificialisation of soils [surface]	Id_36
	Desartificialisation of abandoned soils [surface]	Id_37
	Landscape insertion [text]	Id_38
Water	Impacted watercourses [number]	Id_39
	Rainwater harvesting [text]	Id_40
	Rainwater treatment [text]	Id_41
Noise	Noise sensitivity [yes/no]	Id_42
	Ecodesigned solutions for reducing noise [yes/no]	Id_43
Climate resilience	Identification of climate risks [yes/no]	Id_44
	Integration of solutions to climate risks [yes/no]	Id_45
Economy	Economic balance related to ecodesign [€]	Id_46

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