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Performance Assessment of an Eco-Industrial Park: a Strategic Tool to Help Recovering Energy and Industrial Waste

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The purpose of this study is to propose and test a tree-like structure for assessing the operational performance of an eco-industrial park composed of a managerial, focal company, and five manufacturing companies that exchange, generate, or reuse energy, waste, and by-products from different sources. The top term is the EIP operational overall performance, supported by indicators retrieved from the literature and organized in four constructs: (i) internal relationships; (ii) external relations; (iii) energy recovery; and (iv) materials recovery. The first construct encompasses relationships between companies, leadership, mutual trust and technological exchange, communication, and integrated information systems. The second encompasses relations with government, stakeholder communication, compliance, and social responsibility. The third encompasses the reuse of biomass, refuse-derived fuels, heat, fluids (water, gases, steam), and the energy efficiency of facilities. The last encompasses reuse of waste, reuse of byproducts, efficiency in the logistical process, and efficiency in the manufacturing process. The structure embraces the three main pillars of sustainability, since the first and second constructs include social issues, whereas the third and fourth include economic and environmental ones. The research method is qualitative modeling. Managers employed a Likert scale of agreement [0 = strongly disagree ... 1 = strongly agree] to evaluate the importance and performance of indicators. The importance depends on the influence on the construct and the influence that the construct exerts on the top term. The performance depends on the contribution of the indicator to the overall operational result of the EIP. Results show that there is no need to reallocate or replace strategic resources among the constructs, but also show that the overall performance is only 59 % of the maximum possible. Two constructs, internal relationships, and energy recovery require control actions and further managerial improvement.

1. Introduction

In eco-industrial parks (EIP), solid waste and energy exchanges can contribute to reducing the carbon footprint and simultaneously increase the efficiency of manufacturing units (Gil et al., 2021). Some industries, such as power generation, cement, and steelmaking manufacturing use solid waste and energy leftovers from partner companies as raw material and secondary fuel to increase industrial efficiency (Sellitto et al., 2021). Waste from agri-food supply chains (Sellitto and Hermann, 2016) and municipal solid waste (MSW), including useless appliances (Sellitto and Hermann, 2019), can also route for industrial reuse.

One way to manage the strategic performance of EIPs and similar networks includes systematic assessments of economic and environmental aspects (Baierle et al., 2020). Such assessments consider practices such as industrial and energy symbiosis in managing the use of multiple renewable energy sources (Butturi et al., 2019). In the long term, an evaluation and control managerial system can help an EIP to achieve and maintain its economic, environmental, social, and institutional viability (Tudor et al., 2007).

Previous studies suggest considering drivers and barriers in the implementation (Sellitto et al., 2021) and maintenance (Abreu et al. 2020) of industrial symbiosis projects. Both studies qualitatively evaluate technical,

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commercial, and institutional relationships between companies in the same geographic region and listed influential factors such as communication, trust, logistics, reciprocity, and cooperation capacity. Ceglia et al. (2017) add factors that can limit or encourage favorable logistical solutions, such as common purpose, technological innovation, and mutual engagement in technological developments. Hewes and Lyons (2008) highlight the importance of trust in dyadic relationships and the relevant role of the integration of information systems in the management of waste and energy exchanges.

The purpose of this study is to propose an operational performance assessment system applied to EIPs. Such a procedure must include structural aspects related to the management (Sellitto et al., 2015) and the operation (Sellitto and Murakami, 2018) and technological aspects related to the efficiency of energy and materials recovery (Golev et al., 2015). The research method is qualitative modeling. The main contribution of the study is a tree-like structure formed by constructs and indicators. The structure was tested in an EIP that encompasses a focal, coordinator company, and five manufacturing companies that exchange, generate, reuse, or internally and externally route energy surplus, waste, and by-products recovered from internal and external sources. The top term is the overall operational performance, supported by four constructs: (i) internal relationships; (ii) external relationships; (iii) energy recovery; and (iv) materials recovery.

The internal relationships construct encompasses relationships between companies, communication, mutual trust, and technological exchanges. The external relationships construct encompasses government relations, communication with stakeholders, compliance, and social responsibility. The energy recovery construct encompasses the reuse of biomass, heat, fluids (water, gases, or steam), and the energy efficiency of facilities. The material recovery construct encompasses the reuse of MSW, by-products, efficiency in the logistical process, and efficiency in the manufacturing process. The first construct and second construct include social issues, while the third and fourth constructs include economic and environmental issues. The literature presents aspects related to the constructs that may help to assess the feasibility of industrial or energy symbiosis projects (Belaud et al. 2019). However, to the best of our knowledge, the previous literature review found no evaluation and control procedure applied to an EIP operation (Faria et al., 2021).

2. Theoretical Model: Relationships and Operation Efficiency in EIP

Internal relationship management among partners is an essential concern in symbiotic industrial networks (Sellitto and Murakami, 2018). The existence of previous, robust relationships among companies (King et al., 2020) and management systems (Ashton, 2008) can definitively facilitate the negotiation and management of critical factors that usually encourage or hinder symbiotic exchanges of materials and energy. The existence of a formal, institutional leadership may also boost performance (Faria et al., 2020), as well as mutual trust and technology advances exchange (Hewes and Lyons, 2008), communication (Ceglia et al., 2017), and integration of the information systems of partners (Hewes and Lyons, 2008).

The same is true regarding external relationships. Political, economic, governmental, and institutional aspects significantly influence decisions involving symbiotic companies (Fraccascia et al., 2017), mainly when there are regional policies to encourage the reuse of materials and fuels surplus (Yu et al., 2014). To take advantage of opportunities, communication with the various stakeholders must be fluid and transparent (Fraccascia et al., 2017). Besides avoiding penalties, which are usually severe, compliance with legal provisions many times generates additional benefits provided by legislation (Vimal et al., 2019), especially regional ones (Yamsrual et al., 2019). Finally, the relationship with neighboring communities and social responsibility actions can also encourage the active participation of these communities in offering materials still reusable, as occurs with waste picker cooperatives and municipalities administrations (Yamsrual et al., 2019).

As for energy recovery, the use of biomass such as sugarcane bagasse (Chantasiriwan, 2021), sludge (Loureiro et al., 2021), and rice husk (Sellitto et al., 2013) can typically reduce the use of primary fuel to a rate of 20 % to 30 % in most applications. Likewise, reusing refuse-derived fuel (RDR) (Brás et al., 2017), heat (Gil et al., 2021), and fluids such as hot water or steam can also reduce the generation of new heated fluids by up to a 25 % quote (Chantasiriwan, 2021). Finally, installations that are highly energy efficient or that take advantage of renewable energies, such as wind or solar panel farms, also contribute to increasing the strategic importance of energy recovery activities (Manaf and Abbas, 2021).

Finally, regarding materials recovery, the reuse of waste retrieved from various sources (Bain et al., 2010), the reuse of byproducts originated from manufacturing processes (Sellitto et al., 2021), the efficiency in the reverse logistics processes, which encompasses picking, warehousing, and distribution (Sellitto et al., 2013), and the efficiency in the manufacturing processes in the final destination are relevant aspects that should be managed in the operation of an EIPs (Yu et al., 2014).

Table 1 synthesizes constructs and indicators of the tree-like structure assessment.

Table 1: Tree-like structure of the operational performance assessment

Top term	Construct	Indicator: tag	Empirical reference
EIP performance	Internal relationships	Members relationships: A1	King et al. (2020)
		Institutional leadership: A2	Faria et al. (2020)
		Mutual trust and technology exchange: A3	Hewes and Lyons (2008)
		Communication: A4	Ceglia et al. (2017)
		Integration of information systems: A5	Yu et al. (2014)
	External relationships	Relations with governments: B1	Yu et al. (2014)
		Communication with stakeholders: B2	Fraccascia et al. (2017)
		Compliance: B3	Vimal et al. (2019)
		Social responsibility: B4	Yamsrual et al. (2019)
	Energy recovery	Biomass: C1	Loureiro et al. (2021)
		RDR: C2	Brás et al. (2017)
		Heat: C3	Gil et al. (2021)
		Fluids: C4	Chantasiriwan (2021)
		Energy efficiency: C5	Manaf and Abbas (2021)
	Materials recovery	Reuse of waste: D1	Bain et al. (2010)
		Reuse of byproducts: D2	Sellitto et al. (2021)
		Logistical efficiency: D3	Sellitto et al., (2013)
		Manufacturing efficiency: D4	Yu et al. (2014)

3. Methodology

The study adopted the following steps: (i) a literature review identified constructs and indicators in EIP management, which supported a tree-like structure for operational performance assessment; (ii) two managers of the focal company of the EIP evaluated, using a Likert scale [0 = strongly disagree ... 1 = strongly agree], the importance and performance of the indicators; (iii) an importance-performance analysis supported a strategic diagnosis of the EIP. Ordered pairs (importance, performance) formed a scatter diagram. Constructs near a positive diagonal forming a linear relationship are balanced (high importance, high performance; low importance, low performance). Far from the diagonal, there is some kind of imbalance: in high performance and low importance constructs, there is an excess of allocated strategic resources; in low performance and high importance constructs, there is a lack of allocated strategic resources (Slack, 1991). The joint analysis can indicate reallocations or even replacement of EIP strategic resources, which usually are scarce.
The methodology was applied to a network formed by a focal company and five secondary companies whose exchanges are synthesized in Table 2.

Table 2: Companies of the EIP

Company	Receives	Activity	Delivers
Focal	Metallic scrap	Steelmaking plant	Steel by-products, MSW
1	MSW	Waste processing plant	RDF
2	RDF	Cement plant	Soil pH corrective
3	Steel by-products	Foundry plant	Metallic slag to pavement service
4	Steel by-products	Machine manufacturer plant	Metallic scrap
5	Useless vehicles	Shredder plant	Metallic scrap

The steel by-products involved are electric-arc furnace and continuous casting dust, metallic swarf, mill scale, steel leftovers, and zinc sludge. The study of Sellitto et al. (2021) entails a complete description of the byproducts delivered by the steelmaking plant, a semi-integrated unit that includes refining (melt-shop) and conforming (rolling mills) stages. The study also describes how the fly ash generated by company 2 routes to the cement industry, acting as a fuller for pozzolanic cement products.

4. Results

Three managers of the focal company replied to two statements: (i) the importance for the overall operational result of the EIP of [*Indicator n*] is very high; and (ii) the EIP performance for [*indicator n*] is very good. The response options were: strongly agree (1), slightly agree (0.75), neither agree nor disagree (0.5), slightly disagree (0.25), and strongly disagree (0). The evaluation took into account the medians of the three replies, shown in Table 3. Table 4 synthesizes the evaluation.

Table 3: Evaluation by indicator

Indicator	Importance	Performance	Indicator	Importance	Performance
A1	4	3	C1	4	2
A2	2	2	C2	5	3
A3	5	3	C3	2	1
A4	5	3	C4	1	1
A5	4	2	C5	4	3
B1	4	4	D1	5	5
B2	4	5	D2	5	4
B3	5	4	D3	4	3
B4	5	4	D4	4	4

Table 4: Synthesis of the evaluation

Top term	Construct	Mean importance	Mean performance	Gap	Order
EIP	Internal relationships	4.00	2.60	1.40	first
performance	External relationships	4.50	4.25	0.25	fourth
	Energy recovery	3.20	2.00	1.20	second
	Materials recovery	4.50	4.00	0.50	third

4.1 Discussion

The discussion entails two main issues. The first is the analysis of how the allocation of strategic resources, such as labor, capital, management, and intangible assets, fits with the importance of the constructs. Eventually, replacements or reallocation of resources among constructs may be necessary when imbalances exist. The second issue is to control the performance. Eventually, control actions focusing on increasing performance may also require managerial improvement in procedures, not only in resources. The scatter diagram of Figure 1 plots the ordered pairs [importance, performance] for the constructs, which helps afford the first issue.

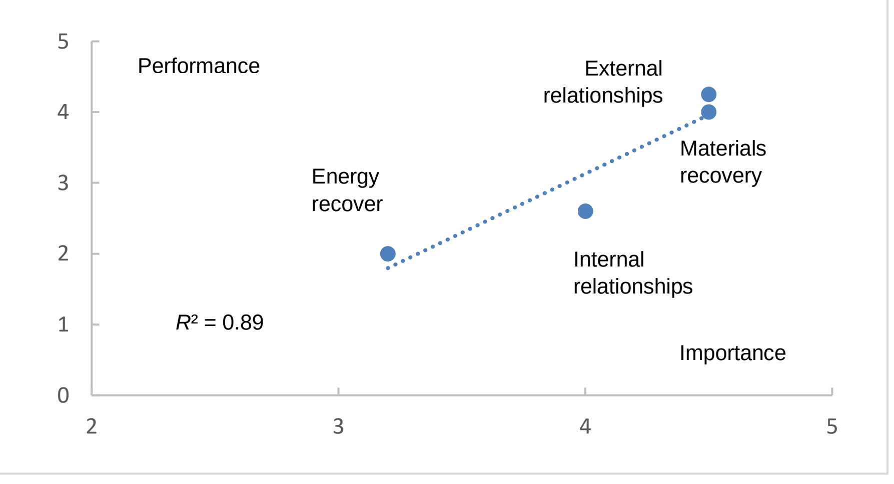

Figure 1: Relationship between importance and performance for the constructs

The diagram shows a high likelihood (R^2 ≈ 90 %) for a linear relationship among constructs, meaning no imbalance: the higher the importance, the higher the performance. It means that the current strategy coherently allocates more resources (which imply a higher performance) to the more important constructs. Therefore, there is no need for the replacement or exchange of strategic resources among constructs. Regarding performance improvement, equation 1 provides an overall operational performance of 59 % for the EIP.

$$P\,\% = \frac{\frac{\sum_{i=1}^{18} Imp_i Perf_i}{\sum_{i=1}^{18} Imp_i} - Min_{perf}}{Max_{perf} - Min_{perf}} = \frac{3.35 - 1}{5 - 1} = 59\,\% \qquad (1)$$

In which:

- P % = overall relative performance of the EIP, ranging from 0 to 100 %;
- Imp_i = importance of the i_{th} indicator, $i \in [1, 2, \ldots, 20]$;
- $Perf_i$ = performance of the i_{th} indicator, $i \in [1, 2, \ldots, 20]$;
- Max_{perf} = maximum possible individual performance = 5; and
- Min_{perf} = minimum possible individual performance = 1.

Such a result means that, although balanced, the overall operational performance barely overcomes half of the top, leaving room for improvement. In tree-like structures, a usual assumption is to admit high correlation among indicators of the same construct and low correlation otherwise (Sellitto et al., 2015). For example, recovering hot water from a process improves simultaneously the performance of both heat and fluids indicators but has little or no effect in other constructs. The same would be true regarding the implementation of a communication channel with the stakeholders. It may improve the performance of more than one indicator in the second construct, such as compliance or social responsibility, but would have no effect outside the construct.
Since actions targeting one indicator may influence others in the same construct, it is useful to focus on the constructs with the major gaps. In the EIP, those constructs are internal relationships and energy recovery. For the same managerial effort, technology development, or financial investment, strategic actions outside these two constructs may produce fewer effects on the overall operational performance. Some examples of strategic actions that the management body should immediately start to boost internal relationships are a structured program to stimulate communication and technology development and exchange among members, a systematic schedule of manager meetings to exchange experiences, and the implementation of an integrated information system able to exchange and update information in real-time. To boost energy recovery, management should implement a systematic program to receive larger volumes of MSW from local, nearby communities, not only from the local industrial activity of the region, and biomass from the rural activity, which is intensive in the region. Such actions immediately increase performance with a low managerial implementation effort.

5. Conclusions

The main conclusion is that even if a balance exists in the strategic resources allocation in the EIP, the overall performance is not satisfactory. The procedure pointed out that the EIP achieves only 59 % of the maximum performance it should achieve. Therefore, control actions are due mainly to the constructs with larger gaps (mean importance – mean performance). Internal relationships and energy recovery are the constructs with larger gaps and should be priorities for control actions aiming at increasing performance.
The study opens room for more research. Further research should include multicriteria decision methods for evaluating the importance and more respondents, which will allow the refinement of the metric, mainly regarding multivariate analysis and multicollinearity in indicators. Multicollinearity should be verified by cross-loading (correlation with more than one construct), wrong-loading (correlation with the wrong construct), and weak-loading (no correlation) and whenever possible forewarned. The solution may require relocation, reconfiguration, or elimination of indicators. These actions lead to a more robust assessment procedure that can serve as a strategic feedback link for the performance management of eco-industrial parks.

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