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Challenges in adopting energy management systems by Brazilian companies: A fuzzy DEMATEL approach

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ABSTRACT

This paper investigates the relationships between challenges faced by Brazilian companies in adopting Energy Management Systems (EnMS). The fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodology is employed to examine the interdependencies between the challenges. The study involves assembling an expert panel to assess the causal relations between key challenges identified through a literature review. The findings reveal that challenges related to insufficient financial resources, deficiencies in competencies within the implementation team, and lack of support from top management are pivotal factors influencing the adoption of EnMS. These challenges are positioned as core factors, highlighting their critical role in EnMS implementation. Conversely, factors such as difficulty in determining appropriate performance indicators and justifying EnMS certification maintenance are categorised as impact factors, signalling their lower priority for resource allocation. The study contributes to research by providing a nuanced understanding of the challenges hindering EnMS adoption and their interdependencies. Additionally, the findings offer practical insights for organisations seeking to implement EnMS, guiding resource allocation and strategic planning efforts to overcome barriers effectively.

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Energy management systems; fuzzy DEMATEL; energy efficiency; barrier; sustainable management

1. Introduction

The significance of energy transition for achieving sustainable development is well-documented in the literature (Ahmad et al. 2023; Fitzgerald et al. 2023; Ullah et al. 2023). The considerable impact of the energy sector in this context justifies the focus of Sustainable Development Goal (SDG) 7 specifically on energy. SDG 7 (Affordable and clean energy) emphasises the necessity of ensuring access to reliable and sustainable energy for all people, which includes making energy affordable. To this end, five specific targets have been established. These targets reflect a balanced approach between environmental and social considerations, highlighting the importance of providing renewable and efficient energy to people and countries (UN 2015b).

Another aspect to highlight is the clear relationships that SDG 7 has with other SDGs. For example, when considering SDG 11 ('Sustainable cities and communities') (UN 2015a), studies linking sustainable urban development and renewable energy use are notable. Surya et al. (2021) demonstrated the potential positive effects that renewable energy could have on urban services in an Indonesian city. Regarding SDG 9 ('Industry, innovation and infrastructure') (UN 2015a), Ullah et al. (2023) emphasised the virtuous cycle that investments in technological innovations that are focused on sustainable development can have on economic growth, innovation investments, and the production and use of renewable energy. These authors also highlighted the crucial role of public policies in advancing energy transition.

It is worth mentioning that the process of energy transition also depends on reducing investments in fossil fuels (Sokołowski and Taylor 2023). In this context, the role of large oil and gas companies is emphasised, as they possess the necessary attributes to implement the required changes for this transition. However, these changes entail high costs for these companies (Berrêdo et al. 2024).

Moreover, while energy sector companies play a crucial role, organisations from other sectors also contribute significantly and stand to benefit from EnMS (Jovanović and Filipović 2016; Kobus, Mugge, and Schoormans 2015). The industrial sector bears substantial responsibility as it consumes a significant portion of the energy generated (Sola and Mota 2020). The manufacturing sector is a key example in this matter, where increasing energy efficiency is one of the most effective ways to reduce carbon emissions, considering the costs and benefits involved (Fitzgerald et al. 2023).

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An essential tool that companies of any size and sector can use to implement and manage an EnMS is ISO 50,001 (Pham 2015). Implemented management standards, such as ISO 50,001, can be audited and certified by independent third-party organisations (the certification body) to assess whether the corresponding management system complies with the applicable international standard requirements and the intended results are achieved (Fonseca et al. 2023).

According to the International Organization for Standardization (ISO 2018), an EnMS is designed to establish policies, goals, action plans, and processes related to energy management within organisations. Implementing ISO 50,001 has been shown to provide significant benefits, including improved energy performance and reduced carbon emissions (Fitzgerald et al. 2023). Additionally, positive effects of ISO 50,001 are observed in supply chain management (Zimon, Jurgilewicz, and Ruszel 2021).

Despite the advantages and contributions of ISO 50,001, the literature highlights several challenges that companies face with both the initial version published in 2011 (da Gonçalves and Santos 2019; Rampasso et al. 2019) and the updated version released in 2018 (Fuchs, Aghajanzadeh, and Therkelsen 2020). Studying these challenges is particularly important, considering the widespread adoption of the standard. The most recent data from ISO reveals that there were 27,631 valid certifications covering 53,569 sites worldwide in 2022 (ISO 2023).

Regarding the updated version of ISO 50,001, published in 2018, there is a need for more evidence and research about its difficulties, drivers, and positive impacts, especially in non-European countries (Fuchs, Aghajanzadeh, and Therkelsen 2020). In line with this argument, after an extensive literature review, Pandin et al. (2024) emphasised the need for more studies focusing on developing countries. This gap is particularly critical, considering the disparities in energy infrastructure and progress towards energy transition between developed and developing countries. The imbalance is evident in the number of ISO 50,001 certificates per country: China has 7,592 certificates, Germany 5,523, and Spain 3,326, while Latin American countries like Chile, Peru, and Brazil have only 167, 163, and 86 certificates, respectively (ISO 2023). One of the targets of SDG 7 is to reduce this gap (UN 2015b).

As argued by Caetano et al. (2023), the situation is even more critical when considering the negative impact that foreign direct investments can have on developing countries through increased consumption of non-renewable energies. Thus, to mitigate this impact, the authors recommend that developing countries pursue private investments in their energy infrastructure to reconcile economic growth with environmental sustainability.

Analysing the literature, it is evident that understanding the difficulties faced by companies in implementing ISO 50,001 and the need for more studies in developing countries is crucial. This issue is particularly concerning when examining the Brazilian economy. Despite being one of the largest economies in the world (International Monetary Fund 2024), Brazil has only 86 ISO 50,001 certificates (ISO 2023).

In this context, this study aims to analyse the relationships between the challenges faced by Brazilian companies in adopting EnMS. By identifying and addressing these challenges, the study seeks to provide actionable insights and strategies that can facilitate the adoption of EnMS. This, in turn, can significantly enhance energy efficiency, reduce carbon emissions, and contribute to broader goals of sustainable development and environmental stewardship in Brazil. Furthermore, the findings of this study can serve as a valuable reference for other developing countries facing similar challenges, thus promoting global efforts towards energy sustainability.

2. Background

2.1. Energy management systems (EnMS) and ISO 50,001

ISO 50,001:(2018) is structured into 10 sections, following the PDCA (Plan-Do-Check-Act) cycle logic. These sections cover various aspects, including the standard description, its delimitation, and its relationship with other ISO standards. The document also presents important terms related to EnMS and outlines the requirements for companies to implement an EnMS and achieve certification. Key requirements include analysing the organisation's context, defining the roles and responsibilities of leadership, planning, providing necessary support for the EnMS, managing operational aspects, conducting performance analysis, and carrying out improvement activities. Notably, ISO 50,001 is designed to apply to organisations of any sector and size (ISO 2018).

The versatility of an EnMS is evident in its wide range of applications. For instance, universities have effectively implemented EnMS on their campuses. These implementations vary in scale and approach. Kolokotsa et al. (2016) developed a web-based EnMS for a university campus, focusing on energy efficiency management, load analysis, and energy usage for individual buildings and the entire campus. Similarly, Shyr et al. (2018) applied an Internet of Things-based lighting control system on a university campus, demonstrating another innovative application of EnMS.

The construction sector has also been extensively studied concerning EnMS and energy transition. Jeong and Wi (2024) developed a building EnMS that integrates thermal and electrical energy control. Their system was tested and validated for its ability to enhance energy usage and reduce costs. Brem et al. (2020) explored the combination of ISO 50,001 and ISO 14,001, aligning this integration with two major building assessment methods: Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM). They found that implementing these ISO standards significantly improved project outcomes in both assessment methods, highlighting the benefits of such integration.

The implementation of ISO 50,001 alone can provide organisations with numerous advantages. According to ISO (2018), a well-designed EnMS can support and promote improvements in energy performance (such as energy efficiency and energy consumption), reduce energy-related costs, increase the use of renewable energy, and lower carbon emissions. The literature also reports various benefits from ISO 50,001 implementation. For instance, Pelser, Vosloo, and Mathews (2018) analysed the effects of ISO 50,001 in a cement factory and observed a 25% reduction in energy costs. Similarly, Fitzgerald et al. (2023) assessed the impact of ISO 50,001 in 83 manufacturing organisations, noting consistent improvements in their energy performance, cost reductions, and lower emission levels.

2.2. Challenges to the adoption of EnMS

Despite the benefits generated by an EnMS, several significant challenges must be considered (da Gonçalves and Santos 2019; Rampasso et al. 2019). Based on the evidence observed in the literature, Table 1 lists seven key challenges to the adoption of EnMS.

One of the primary challenges is the lack of financial resources to initiate projects related to EnMS implementation (IT1) (Johansson and Thollander 2018; Uriarte-Romero et al. 2017). This issue is particularly acute for small- and medium-sized enterprises (SMEs), which often struggle to secure the necessary capital (Jalo et al. 2021; Pereira et al. 2020).

Furthermore, even when financial resources are available, the return on investment (ROI) for EnMS projects can be uncertain and may take a long time to materialise (Genc and Sehgal 2014). There is also the challenge of ensuring that any observed increases in company value (Pham 2015), energy savings, or reductions in carbon emissions (McKane et al. 2017) are directly attributable to the implementation of an EnMS. This difficulty in demonstrating clear, measurable benefits can hinder the widespread adoption of EnMS (IT2).

Effective EnMS implementation requires training people and allocating resources (Păunescu and Blid 2016). An indicator of this need is the difficulty companies face in hiring workers with the necessary knowledge to support EnMS implementation and management (IT3). This challenge applies both to internal employees who require competencies, knowledge, and skills for implementation and to external consultants who support the process (Johansson and Thollander 2018). For SMEs, this challenge is even more pronounced, as finding workers with sufficient knowledge for implementation can be particularly difficult (Jalo et al. 2021). Moreover, the lack of support and commitment from top management in adopting EnMS (IT4) is another significant challenge observed in the literature, which can hinder adoption (Jovanović, Filipović, and Bakić 2017). Thus, establishing performance indicators to assess the effectiveness of EnMS can also pose challenges, as it requires the necessary knowledge to properly implement them at all levels of the organisation (IT5). Given the complexity involved in establishing such indicators (Jovanović and Filipović 2016; Velázquez et al. 2013), defining them can present a significant difficulty to be addressed, often requiring relying on external consultants to support the implementation process (IT6).

Another challenge related to the implementation of EnMS is the difficulty in justifying the maintenance of this type of certification over the long term (IT7). A sustainable energy strategy necessitates that employees, particularly top management, thoroughly understand the EnMS and remain committed to long-term strategic planning (Nakthong and Kubaha 2019). The extended period required to see a return on investment can jeopardise the ongoing maintenance of the certification, as companies may struggle to remain committed without immediate and visible benefits. This underscores the importance of fostering a deep organisational commitment to energy management and ensuring that the long-term benefits are clearly communicated and understood (Kobus, Mugge, and Schoormans 2015).

Table 1. Challenges to the adoption of EnMS.

Code	Description
IT1	Insufficient financial resources to initiate projects associated with EnMS implementation
IT2	Difficulty in determining the appropriate performance indicators for EnMS
IT3	Deficiency in competencies, knowledge, and skills within the implementation team
IT4	Lack of support and commitment from top management for EnMS adoption
IT5	Difficulty in demonstrating the benefits derived from EnMS adoption
IT6	Difficulty in relying on external consultants to support the implementation process
IT7	Difficulty in justifying the maintenance of EnMS certification to the market

Source: Authors' own creation.

3. Materials and methods

3.1. Research stages and procedures

To conduct the present investigation, the fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was used. This choice stemmed from a thorough review of existing literature and consultations with experts. DEMATEL offers a suitable framework for exploring the relationships among challenges in sustainability contexts (Rajak, Parthiban, and Dhanalakshmi 2021; Singh, Barve, and Shanker 2021), including applications in the energy sector (Gedam et al. 2021; Scholz 2024). Therefore, by utilising the fuzzy DEMATEL method, this study aims to analyse the interdependencies between challenges that impede the adoption of EnMS in Brazilian companies.

Building upon this, the research stages are illustrated in Figure 1, outlining the study's workflow.

A comprehensive literature review was initially conducted to grasp the existing knowledge landscape, which guided the formulation of the research question. This review also aimed to identify the challenges associated with the adoption of EnMS by companies. It involved an extensive exploration of existing research to discern the multifaceted obstacles encountered in this domain. Subsequently, an expert panel was assembled to corroborate and enrich the insights garnered from the literature, providing valuable perspectives and validating the identified challenges. With the challenges delineated, the fuzzy DEMATEL method was employed to evaluate the causal relations between them, offering a structured analysis of their interdependencies. Finally, the findings were synthesised and discussed, and conclusions were drawn, shedding light on the complexities and implications of EnMS adoption within the Brazilian business context.

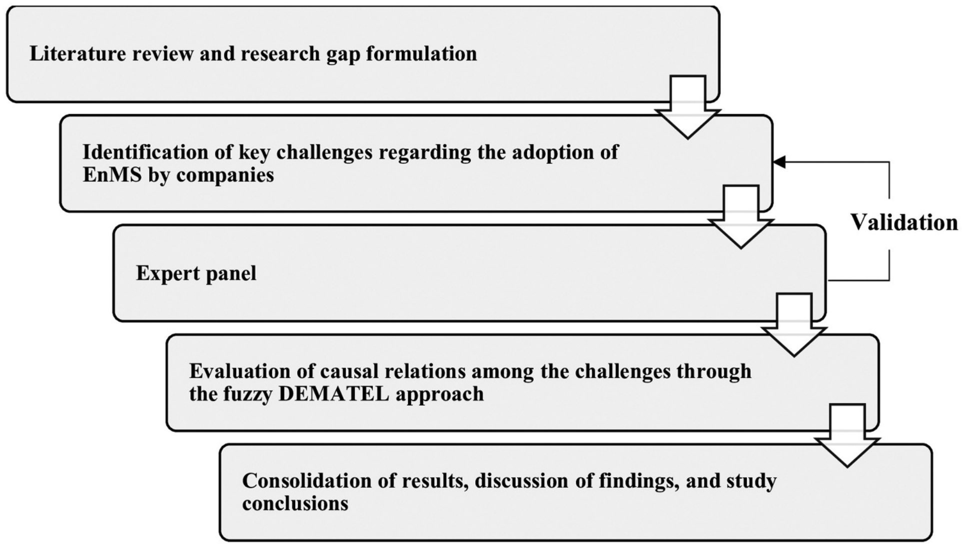

Figure 1. Research stages. Source: Authors' own creation.

3.2. Fuzzy set theory

Fuzzy set theory offers a robust framework for capturing subjective evaluations inherent in decision-making processes (Zanon and Carpinetti 2021). Linguistic variables, used to express these evaluations qualitatively, are transformed into quantitative representations through fuzzy sets within a discourse universe, employing membership functions – a methodological approach aligned with the principles of computing with words (Klir and Yuan 1995). This approach acknowledges subjectivity by allowing a single element to belong to multiple fuzzy sets simultaneously, a fundamental outcome of membership function parameterisation, as outlined by Zadeh (1978). By integrating linguistic variables and fuzzy numbers, decision-makers can navigate complex decision spaces while addressing inherent uncertainties and ambiguities (Jamali et al. 2023).

For a given universe $\rightarrow [0,1]$, a fuzzy set $\tilde{A}$ can be defined as: $\tilde{A} = \{x, \mu_A(x)\}, x \in X$, in which $\mu_A(x)$ is the membership degree function of the element x in $\tilde{A}$. The function $\mu_A(x)$ takes values in the interval $[0,1]$, where if $\mu_A(x) = 1$, x belongs totally to the fuzzy set $\tilde{A}$; otherwise, if $\mu_A(x) = 0$, then x does not belong to the fuzzy set $\tilde{A}$. Besides that, if $0 < \mu_A(x) < 1$, then x partially belongs to the fuzzy set $\tilde{A}$ (Dubois 1980). A fuzzy number can be defined as a fuzzy set with the membership function that satisfies the conditions of normality $(\sup \tilde{A}[x]_x \in X = 1)$ and convexity $(\tilde{A}[\lambda x_1 + (1-\lambda)x_2 \geq \min[A(x_1), A(x_2)]]$ $x_1, x_2 \in X$ and $\lambda \in [0,1])$ (Zimmermann 2010).

Fuzzy sets and, consequently, fuzzy numbers are characterised by their respective membership functions, which associate every $x_i \in X$ with its corresponding $\mu_A(x)$. One of the most commonly used types is the triangular fuzzy number (TFN). Let l, m, and u be real numbers. A TFN is typically represented as $\sim A = (l,\ m,\ u)$. Thus, the representation of the triangular membership function $\mu_A(x)$ is expressed by Equation 1.

$$\mu_{\tilde{A}}(x_i) = \begin{cases} 0 & \text{for } x_i < a, \\ \frac{x_i - a}{m - a} & \text{for } a \leq x_i \leq m, \\ \frac{b - x_i}{b - m} & \text{for } m \leq x_i \leq b, \\ 0 & \text{for } x_i > b. \end{cases} \quad (1)$$

3.3. Fuzzy DEMATEL

DEMATEL is a multicriteria decision method that focuses on understanding complex interrelationships among various factors within a problem domain. Through quantitative analysis of direct and indirect relationships, DEMATEL offers a comprehensive perspective informed by expert opinions on the degree of influence one element exerts over another (Kazancoglu and Ozkan-Ozen 2019). Notably, DEMATEL facilitates the visualisation of its findings through a two-dimensional diagram, positioning relevance relationships along the x-axis and cause-and-effect relationships along the y-axis (Si et al. 2018). This method excels in capturing multi-directional relationships, contrasting with techniques like AHP (Analytic Hierarchy Process) that typically assume uni-directional relationships and independence among factors (Chien, Wu, and Huang 2014).

While DEMATEL provides valuable insights into the interdependencies of complex systems, it falls short in addressing human subjectivity and data vagueness (Si et al. 2018). To overcome this limitation, the integration of fuzzy logic into the DEMATEL method emerges as a promising solution (Chien, Wu, and Huang 2014). This approach, known as fuzzy DEMATEL, accommodates imprecision and uncertainty inherent in real-world data, enhancing its applicability in scenarios characterised by subjective judgements and ambiguous information (Si et al. 2018).

Seven steps should be followed for the application of the fuzzy DEMATEL method (Luthra et al. 2016), as illustrated in Figure 2.

Step 1 – Conducting an expert panel

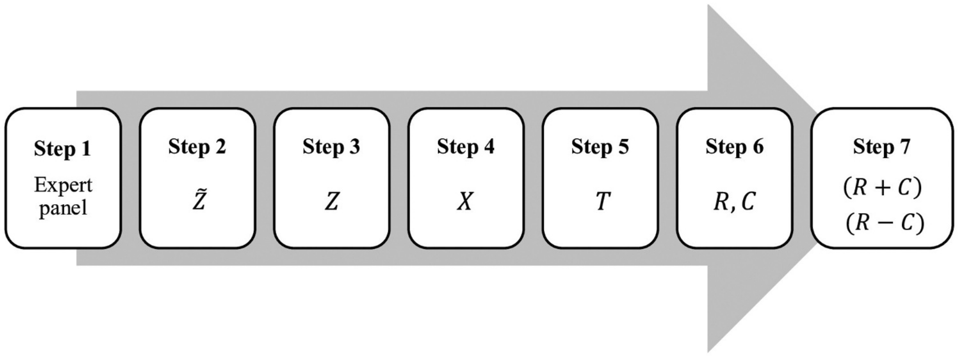

Figure 2. The fuzzy DEMATEL process. Source: Authors' own creation.

The initial phase involves assembling an expert panel and identifying the factors to be assessed for causal relations. In this study, the key challenges associated with the adoption of EnMS by Brazilian companies were identified. These challenges serve as the focal points for expert evaluation within the framework of the fuzzy DEMATEL technique.

Step 2 – Definition of the fuzzy direct assessment matrix $\widetilde{\boldsymbol{Z}} = \left[\widetilde{z}_{ij}\right]_{nXn}$

After identifying the analysed factors, pairwise comparisons should be conducted using expert panel regarding the influence level of element i over element j, using linguistic terms associated with TFNs, as shown in Table 2. Each expert generates one assessment matrix. These matrices should then be aggregated based on the arithmetic mean of judgements.

Step 3 – Definition of the initial direct assessment matrix $\boldsymbol{Z}$

Next, the defuzzification of the matrix $\tilde{Z} = \left[\tilde{z}_{ij}\right]_{nXn}$ is performed. In this study, the centre of area (CoA) method was used, as per Equation 2.

$$CoA = \frac{(u-l)+(m-L)}{3} + l \tag{2}$$

Step 4 – Normalisation of the initial direct assessment matrix $\boldsymbol{Z}$, generating matrix $\boldsymbol{X}$

This normalisation process is carried out using Equations 3 and 4.

$$X = \frac{Z}{s} \tag{3}$$

$$s = \max\left(\max_{1\le i\le n}\sum_{j=1}^{n} z_{ij}, \max_{1\le i\le n}\sum_{i=1}^{n} z_{ij}\right) \tag{4}$$

Step 5 – Definition of the total-relation matrix $\boldsymbol{T}$

This process involves using Equation 5, where I corresponds to the identity matrix.

$$T = X.\ (I-X)^{-1} \tag{5}$$

Step 6 – Definition of the vectors $\boldsymbol{R}$ and $\boldsymbol{C}$

This process entails calculating the sum of rows (R) and columns (C) of the total-relation matrix T, using Equations 6 and 7. In this study, 'R' symbolises the overall impact of one factor i on another factor j, while 'C' signifies the cumulative effects endured by factor j as a result of factor i.

$$R = [r_i]_{nx1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} \tag{6}$$

$$C = [c_i]_{1xn} = \left[\sum_{j=1}^{n} t_{ij}\right]_{1xn}^{T} \tag{7}$$

Step 7 – Definition of $(\boldsymbol{R}+\boldsymbol{C})$ and $(\boldsymbol{R}-\boldsymbol{C})$ and elaboration of the fuzzy DEMATEL causal diagram

In the final step, $(R+C)$ quantifies the significance of each factor and assesses its relationship with others. Conversely, $(R-C)$ determines the nature of the relationship between factors: a positive sign indicates influence on other factors, while a negative sign signifies being influenced by other factors. Figure 3 depicts each quadrant in the causal diagram, delineating the prominence and relation levels of factors. This

Table 2. Linguistic terms and respective triangular fuzzy numbers.

Linguistic terms	Code	l	m	u
No influence	N	0	0	0
Very low influence	VL	0	0	0.25
Low influence	L	0	0.25	0.5
Medium influence	M	0.25	0.5	0.75
High influence	H	0.5	0.75	1
Very high influence	VH	0.75	1	1

Source: Authors' own creation.

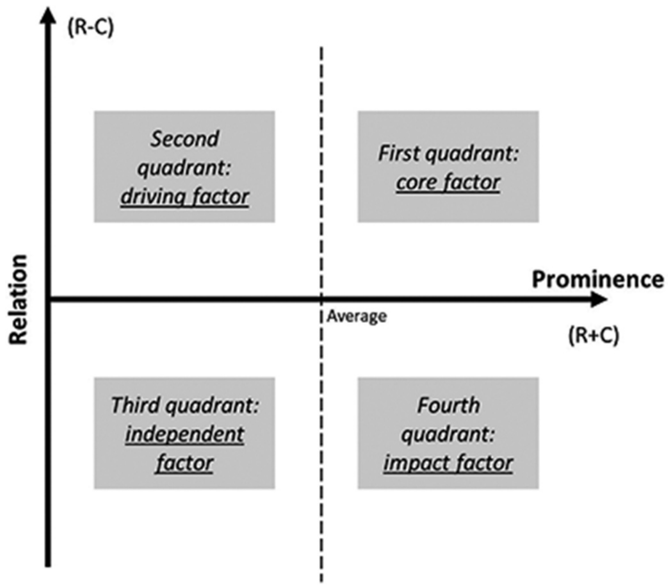

Figure 3. Causal diagram representation. Source: Elaborated based on Chien, Wu, and Huang (2014).

facilitates informed decision-making to effectively address problems. To optimise the efficient utilisation of management resources, progression should proceed from the first quadrant ultimately to the fourth one.

4. Results

Following the first step of the fuzzy DEMATEL method (Step 1 of Section 3.3), an expert panel consisting of seven specialists in the field of energy management was assembled. These specialists analysed each of the identified challenges, which served as the factors for the cause-and-effect assessments.

Subsequently, these assessments were conducted pairwise by each of the experts. The assessments were made using the linguistic terms (as previously presented in Table 2). To facilitate this process and minimise respondent fatigue, a data collection instrument in the form of an electronic spreadsheet was developed. An example of the data collection instrument is illustrated in Table 3.

As illustrated in Table 3, each expert conducted a pairwise assessment, i.e. they assessed the impact of each factor (IT) on each other.

For computational processing, the terms were converted to their associated fuzzy numbers. Consequently, seven fuzzy relationship matrices containing the influence level of element i over element j were obtained. These matrices were aggregated by calculating the arithmetic mean of judgements, resulting in the fuzzy direct assessment matrix $\tilde{Z} = [\tilde{z}_{ij}]_{nXn}$ (Step 2 of Section 3.3), as depicted in Table 4.

Then, the fuzzy DEMATEL method proceeds with the defuzzification of the matrix $\tilde{Z} = [\tilde{z}_{ij}]_{nXn}$. This process calculates the initial direct assessment matrix Z, which quantifies the causal relations between factors in an aggregated and crisp form (Step 3 of Section 3.3), as demonstrated in Table 5.

Thus, the initial direct assessment matrix Z is normalised to obtain matrix X (Step 4 of Section 3.3), as shown in Table 6. Then, the total-relation matrix T is calculated (Step 5 of Section 3.3), the result of which is displayed in Table 7.

The vectors R and C are then calculated, corresponding to the sum of rows and columns of the total-relation matrix T (Step 6 of Section 3.3). As previously explained, 'R' corresponds to the overall impact of one factor i on another factor j, while 'C' represents the cumulative effects endured by factor j as a result of factor i. Additionally, the values of $(R + C)$ and $(R - C)$ should also be determined (Step 7 of Section 3.3), quantifying both the significance of each factor and the polarity (positive or negative) of the relationship between factors. Table 8 presents the results.

Finally, the fuzzy DEMATEL causal diagram is developed. By calculating the average value of $(R + C)$, the central line can be established, forming the four DEMATEL quadrants (Figure 4).

5. Discussion

5.1. Analysis of cause-effect relationships

The fuzzy DEMATEL causal diagram facilitates the examination of relationships among the challenges encountered in the adoption of EnMS by Brazilian companies. Each challenge is plotted in the graph and located within one of the quadrants.

Analysing the cause-and-effect relationships, it is observed that IT1 (insufficient financial resources), IT3 (deficiency in competencies within the implementation team), and IT4 (lack of support from top management) are positioned above the $(R + C)$ axis, indicating that they are cause factors, while the others are effect factors. Additionally, factors to the right of the mean line are considered high-influence factors, whereas those to the left are considered low-influence factors. These findings shed light on critical areas that need to be addressed for

Table 3. Data collection instrument.

Which is the influence of IT factor *i* IT factor *j*?		*j* IT1	*j* IT2	*j* IT3	*j* IT4	*j* IT5	*j* IT6	*j* IT7
i	IT1	–	*	*	*	*	*	*
i	IT2	*	–	*	*	*	*	*
i	IT3	*	*	–	*	*	*	*
i	IT4	*	*	*	–	*	*	*
i	IT5	*	*	*	*	–	*	*
i	IT6	*	*	*	*	*	–	*
i	IT7	*	*	*	*	*	*	–

Source: Authors' own creation. *Note: Response provided by the experts.

Table 4. Matrix $\tilde{Z} = [\tilde{z}_{ij}]_{nXn}$.

	IT1			IT2			IT3		
TFN	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***
IT1	0.000	0.000	0.000	0.179	0.393	0.643	0.321	0.536	0.786
IT2	0.214	0.393	0.607	0.000	0.000	0.000	0.179	0.321	0.571
IT3	0.286	0.500	0.750	0.464	0.679	0.857	0.000	0.000	0.000
IT4	0.571	0.821	0.929	0.357	0.571	0.786	0.321	0.536	0.786
IT5	0.214	0.393	0.607	0.250	0.464	0.714	0.179	0.357	0.571
IT6	0.071	0.214	0.464	0.214	0.393	0.643	0.107	0.250	0.500
IT7	0.250	0.429	0.643	0.179	0.321	0.571	0.179	0.357	0.607
		IT4			**IT5**			**IT6**	
TFN	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***
IT1	0.357	0.571	0.750	0.250	0.464	0.643	0.179	0.393	0.643
IT2	0.143	0.357	0.607	0.286	0.464	0.679	0.107	0.214	0.464
IT3	0.393	0.643	0.893	0.464	0.679	0.857	0.143	0.286	0.536
IT4	0.000	0.000	0.000	0.286	0.500	0.750	0.393	0.607	0.857
IT5	0.357	0.607	0.786	0.000	0.000	0.000	0.107	0.250	0.500
IT6	0.214	0.429	0.679	0.143	0.321	0.571	0.000	0.000	0.000
IT7	0.179	0.357	0.571	0.214	0.393	0.643	0.143	0.321	0.571

	IT7		
TFN	*l*	*m*	*u*
IT1	0.357	0.571	0.750
IT2	0.143	0.357	0.607
IT3	0.393	0.643	0.893
IT4	0.000	0.000	0.000
IT5	0.357	0.607	0.786
IT6	0.214	0.429	0.679
IT7	0.179	0.357	0.571

Source: Authors' own creation.

Table 5. Initial direct assessment matrix *Z*.

Factors	IT1	IT2	IT3	IT4	IT5	IT6	IT7
IT1	0.000	0.405	0.548	0.560	0.452	0.405	0.476
IT2	0.405	0.000	0.357	0.369	0.476	0.262	0.440
IT3	0.512	0.667	0.000	0.643	0.667	0.321	0.571
IT4	0.774	0.571	0.548	0.000	0.512	0.619	0.500
IT5	0.405	0.476	0.369	0.583	0.000	0.286	0.500
IT6	0.250	0.417	0.286	0.440	0.345	0.000	0.310
IT7	0.440	0.357	0.381	0.369	0.417	0.345	0.000

Source: Authors' own creation.

Table 6. Normalised initial direct assessment matrix *X*.

Factors	IT1	IT2	IT3	IT4	IT5	IT6	IT7
IT1	0.000	0.115	0.155	0.159	0.128	0.115	0.135
IT2	0.115	0.000	0.101	0.105	0.135	0.074	0.125
IT3	0.145	0.189	0.000	0.182	0.189	0.091	0.162
IT4	0.220	0.162	0.155	0.000	0.145	0.176	0.142
IT5	0.115	0.135	0.105	0.166	0.000	0.081	0.142
IT6	0.071	0.118	0.081	0.125	0.098	0.000	0.088
IT7	0.125	0.101	0.108	0.105	0.118	0.098	0.000

Source: Authors' own creation.

Table 7. Total-relation matrix *T*.

Factors	IT1	IT2	IT3	IT4	IT5	IT6	IT7
IT1	0.429	0.540	0.520	0.583	0.548	0.452	0.545
IT2	0.453	0.356	0.407	0.459	0.474	0.354	0.460
IT3	0.623	0.665	0.446	0.669	0.663	0.486	0.634
IT4	0.689	0.656	0.592	0.528	0.641	0.564	0.628
IT5	0.501	0.522	0.452	0.553	0.401	0.399	0.518
IT6	0.381	0.425	0.357	0.435	0.407	0.256	0.392
IT7	0.461	0.449	0.413	0.460	0.461	0.374	0.349

Source: Authors' own creation.

Table 8. *R*, *C*, *(R+C)* and *(R-C)* calculation.

Factors	*R*	*C*	*R+C*	*R-C*
IT1	3.616	3.537	7.153	0.079
IT2	2.965	3.612	6.578	−0.647
IT3	4.186	3.187	7.372	0.999
IT4	4.298	3.688	7.986	0.611
IT5	3.345	3.595	6.940	−0.249
IT6	2.653	2.885	5.539	−0.232
IT7	2.966	3.527	6.493	−0.561

Source: Authors' own creation.

successful EnMS implementation. These challenges serve as focal points for resource allocation and strategic planning, guiding organisations in overcoming barriers to adoption.

This finding is in line with the literature, which points out that one of the primary challenges in adopting EnMS is the lack of financial resources to initiate projects (Johansson and Thollander 2018; Uriarte-Romero et al. 2017), critically affecting SMEs especially (Jalo et al. 2021; Pereira et al. 2020) due to lower financial capacity when compared to large companies. This adds up to another critical point, which is finding professionals with competencies, knowledge, and skills needed for the implementation of EnMS (Păunescu and Blid 2016). Faced with this challenging context, company leaders often do not provide the necessary support, attributing less importance to the actions and investments required to implement EnMS when compared to other company projects (Jovanović, Filipović, and Bakić 2017).

5.2. Analysis of quadrant positioning

A more detailed analysis can be conducted by considering factors and their respective quadrants, as proposed by Chien, Wu, and Huang (2014). Factors located in the first quadrant (core factors) exhibit high prominence and high relation. This reinforces the critical role of IT1, IT3, and IT4 in the adoption of EnMS by Brazilian companies and should be prioritised accordingly. Of particular significance within this quadrant is the factor IT3, which influences all other factors.

Factors positioned in the second quadrant, designated as driving factors, demonstrate low prominence but high relation. While these factors may impact only a limited number of others if left to operate independently, they are still significant and should not be overlooked. Notably, in this study, no factors were classified within this quadrant.

The third quadrant (independent factors) comprises those factors with minimal prominence and weak interrelations. These factors demonstrate limited interaction with others, indicating that a distinct control measure may be appropriate for this area, particularly given the definitions of IT2 (difficulty in determining the appropriate performance indicators), IT6 (difficulty in relying on external consultants to support the implementation process), and IT7 (difficulty in justifying the maintenance of EnMS certification to the market). Among these, IT2 warrants particular attention as the most affected factor of all.

Lastly, the fourth quadrant (impact factors) shows factors characterised by high prominence but low interrelation. This suggests that these factors, notably IT5 (difficulty in demonstrating the benefits derived from EnMS adoption), should be monitored and managed, although direct efforts for improvement may not be immediately necessary. Thus, these factors represent the lowest priority for resource allocation.

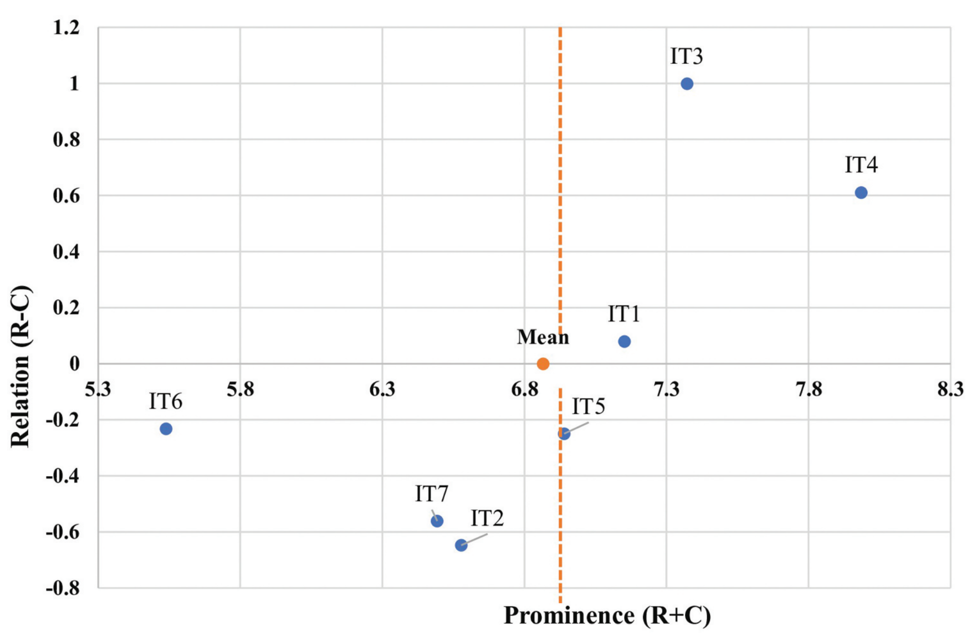

Figure 4. The fuzzy DEMATEL causal diagram for examining the relationships among the challenges. Source: Authors' own creation.

6. Conclusion

This research sheds light on the complex dynamics between factors that hinder the adoption of EnMS by Brazilian companies. It unveiled critical insights into the relationships among the challenges faced by companies, offering a comprehensive understanding of their interdependencies. Key findings reveal that challenges related to insufficient financial resources, deficiencies in team competencies, and lack of support from top management emerge as prominent cause factors, necessitating urgent attention for successful EnMS implementation. Moreover, challenges categorised as core factors underscore their pivotal role in driving the adoption of EnMS, highlighting their significance in resource allocation and strategic planning. Conversely, challenges classified as impact factors indicate areas requiring monitoring but may not necessitate immediate improvement efforts. Overall, these findings provide valuable guidance for organisations aiming to implement EnMS, fostering informed decision-making and facilitating progress towards sustainable energy management practices in Brazil.

While this study offers valuable insights into the challenges faced by companies in adopting EnMS, it is essential to acknowledge its limitations. Firstly, the research focused solely on the perspective of Brazilian companies, potentially limiting the generalisability of the findings to other contexts. Additionally, it relied on expert opinions and subjective assessments to construct the fuzzy DEMATEL causal diagram, which may introduce bias and variability in the results. In this sense, future research needs to strengthen its validity by incorporating more diverse data sources, such as quantitative data from case studies or surveys, to complement the expert assessments. Moreover, the analysis was conducted at a single point in time, overlooking the dynamic nature of organisational challenges and potential changes over time. Finally, the study did not delve into the specific nuances of individual industries or sectors within Brazil, which could provide valuable insights into sector-specific challenges and opportunities for EnMS adoption. Thus, researchers can use the conceptual and methodological framework of this study for replication in specific sectors, enriching the debate on EnMS implementation challenges and increasing practical relevance for companies.

In light of the findings and limitations identified in this study, several avenues for future research emerge. Firstly, longitudinal studies could be conducted to track the evolution of challenges and the effectiveness of mitigation strategies over time, providing a deeper understanding of EnMS adoption dynamics. Additionally, comparative studies across different countries or regions could offer insights into the contextual factors influencing EnMS adoption and the effectiveness of interventions in diverse settings. Furthermore, qualitative research methods, such as interviews or case studies, could provide a richer understanding of the underlying factors contributing to the challenges identified in this study. Finally, exploring the role of emerging technologies, regulatory frameworks, and organisational practices in facilitating EnMS adoption could offer valuable insights into strategies for overcoming barriers and promoting sustainable energy management practices globally.

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Ethics approval

This research was conducted in accordance with the ethical guidelines for research conduct of the State University of Campinas (Brazil) and approved by the Research Ethics Committee of this university under the Certificate of Ethical Appreciation number 72,963,123.40000.5404.

Consent

The informed consent was provided to and accepted by all participants.

Data, materials and/or code availability

Data will be made available on request.

Authors' contribution statements

Conceptualisation, R.C.G., J.S.P. and R.A.; Data curation, R.C.G., T.F.A.C.S, J.S.P., I.S.R., L.G.Z. and R.A.; Formal analysis, R.C.G., T.F.A.C.S, J.S.P., I.S.R., L.G.Z. and R.A.; Funding acquisition, T.F.A.C.S, I.S.R., M.P.S., W.L.F. and R. A.; Investigation, R.C.G., T.F.A.C.S, J.S.P., I.S.R., L.G.Z. and R.A.; Methodology, R.C.G.; Project administration, J.S.P. and R.A.; Resources, T. F.A.C.S, I.S.R., M.P.S., W.L.F. and R.A.; Software, R.C.G.; Supervision, J.S. P. and R.A.; Validation, T.F.A.C.S, J.S.P., I.S.R., L.G.Z., M.P.S., W.L.F. and R. A.; Visualisation, T.F.A.C.S, I.S.R., M.P.S., W.L.F. and R.A.; Writing – original draft, R.C.G., T.F.A.C.S, J.S.P., I.S.R., L.G.Z., M.P.S., W.L.F. and R.A.; Writing – review & editing, T.F.A.C.S, J.S.P., I.S.R., L.G.Z., M.P.S., W.L.F. and R.A. All authors have read and approved the final version of the manuscript.

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