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Industrial energy efficiency assessment and prioritization model: An approach based on multi-criteria method PROMETHEE

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ABSTRACT

In today's scenario of increasing energy prices, new legislations, and rising consumer concerns regarding environmental issues, industries face an unprecedented challenge of reducing their energy consumption without negatively impacting their profit and productivity. Based on this, companies are focusing on analyzing their energy efficiency, which has various criteria to be considered, and at least three organizational levels. To close this gap, this study developed an industrial energy efficiency assessment and prioritization model based on energy assessment literature. It utilized multi-criteria analysis for the prioritization of industrial energy efficiency measures. To achieve the goal, a literature review was conducted to map relevant energy efficiency practices from which an industrial energy efficiency assessment tool was developed through the lens of three organizational levels (plant, process, and machine). Subsequently, an energy-efficiency project prioritization tool was proposed using the multi-criteria PROMETHEE II method. The assessment and prioritization model was applied to an energy industry for refinement. It generated an overview of the company's energy efficiency maturity and a ranking of the most recommended measures for the optimal use of energy resources according to established criteria and their weights. Four subcategories (lighting, HVAC systems, compressed air, and motors) were analyzed for the organizational levels, and lighting presented the higher result of a maturity of 2.77 on a scale from 0 to 3, also the maturity of the company was 2.01, which means that is still space for improvement. The improvements were highlighted according to each subcategory studied, pointing to actions that needed to be developed to improve energy efficiency.

Keywords

Assessment and prioritization model;
Industrial energy efficiency measures;
Multi-criteria decision making (MCDM);
PROMETHEE II;

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1. *Introduction*

With new legislation and environmental policies such as the regulatory standard (NR) ISO 50.001-Energy Management System [1], the rising price of energy and increasing consumer concerns constitute a critical challenge within the context of manufacturing to reduce energy consumption without negatively impacting profit and productivity [2,3].

Given this challenge, there are a successive interest in energy efficiency (EE) measures and practices, both

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from the academic community and practitioners, as these solutions can reduce the economic and environmental impacts that plague energy consumption [4,5]. In a McKinsey report [6] stated that investments in EE technologies could reduce energy consumption by up to 50% against a possible reduction of 10 to 20% if the same investments were aimed at operational improvements. The EE is also studied by Perroni et al. [7], who investigated the relationship between EE practices of the US Department of Energy (DOE) and enterprise efficiency in resource use.

According to Erbach [8], despite this statistic and promises of interesting results for increasing sustainability and reducing costs, many investment opportunities for energy efficiency measures (EEMs) are often not implemented, creating what is called the "energy efficiency gap." Although there has been a continuous increase in EEM implementations in the industrial sector over recent decades, research indicates that considerable progress still needs to be made [9,10].

Backlund et al. [11] and Thollander and Palm [12] also discussed the energy efficiency gap. Backlund et al. [11] introduced the term as a discrepancy between the optimal and the current implementation of EE. Thollander and Palm [12] highlight that its full potential can be achieved by removing the barriers to EE. Lack of incentives and problems with information are some of the obstacles identified by these authors.

Numerous barriers to implementing an energy management system and optimizing EE are found in the literature. Trianni and Cagno [13] list the scarcity of information about opportunities and the lack of methods to prioritize EE projects as two main impediments. These problems highlight the need to identify investment opportunities in EE and determine how to prioritize them within an organization. Thus, assessment tools and multi-criteria models for decision-making support can be effective approaches to meeting these demands [14].

Energy management problems, generally, are complex problems due to their multiple's objectives, like social, technological, political, economic, and environmental [15]. Multi-criteria decision-making (MCDM) is an alternative to this problem because it systematically combines benefits or costs with the stakeholder's perspective to align options [15]. The MCDM is highly recommended for energetic planning and can be considered an adequate method to solve energy-related problems [16].

Efforts to improve EE within companies should be based on energy measurement and monitoring at three organizational levels: factory, process, and machine [17–19]. Although some assessment tools for energy management in manufacturing can be observed in previous studies [20–22], none of them have adopted the plant, process, and machine levels as model dimensions. Furthermore, the existing models focus on evaluating energy management systems. They do not emphasize methods to determine the most suitable actions for an organization to increase its energy performance considering its specific context.

The present study aims to fill this knowledge gap by proposing an industrial energy efficiency assessment and prioritization model from the three organizational levels mentioned above. Moreover, it suggests a tool for prioritizing the implementation of manufacturing energy efficiency measures using multi-criteria decision-making, precisely the PROMETHEE II method.

The remainder of this paper is structured as follows. Section 2 presents the theoretical basis for the research, in which key concepts of energy efficiency assessment tools are discussed. Subsequently, Section 3 describes the methodological approach proposed in this study. Section 4 presents the proposed industrial energy efficiency assessment and prioritization model. The application of the model through a case study can be found in Section 5, followed by the discussion in Section 6. Finally, the conclusions are presented in Section 7 of the article.

2. Literature review

The decision process is a key component in structuring and evaluating complex decisions regarding the energy sector [23]. So, multiple criteria force decision-makers to apply Multiple Criteria Decision Making (MCDM) methods in energy problems [24]. Decision-makers use MCDM techniques to organize and synthesize the information related to the problem, increasing confidence in the decision [15].

MCDM techniques are applied in different situations related to energy [24]. Büyüközkan and Güleryüz [25], for example, present an energy model of source selection with fuzzy preference relations. These techniques can also be applied in site selection problems for wind farms [26,27] or for solar power plants [28], geolocalization for photovoltaic farms [29], and for analyzing the energy efficiency of emerging economies [30]. Fossile et al. [31] present an energy selection for Brazilian ports using the Flexible and Interactive (FITradeoff) method, which was also utilized by Abreu Kang et al. [32] for power generation selection for the Brazilian electricity matrix.

Rigo et al. [23] divided the utilization of MCDM for energy problems into five classes: Source selection, Location, Sustainability, Technologies performance, Project performance, and Others. This article is included in the 'others' category since it focuses on process performance and developing measures. Mardani et al. [15] emphasize in their systematic review that energy management is one of the thirteen fields of research founded and that it is the second area of study, losing only to environmental impact assessment.

Rigo et al. [23] also identified the MCDM's methods in energy papers and in which step of the process they are applied. The authors utilized the PROMETHEE method during criteria weighting and evaluating alternatives. The PROMETHEE is also observed in the selection of energy sources for a city [33] and site selections for wind farms [34].

Based on this scenario, it is possible to observe that energy management is an exciting field of research for society and that MCDM techniques are applied to solve these complex problems.

Another topic of interest for this paper is the study of energy efficiency, which has several applications [35,36]. The utilization of EEMs in manufacturing is already discussed in the literature [37–39]. Worrell et al. [39] focus on the productivity benefits of applying energy efficiency improvement measures. Fleiter et al. [38] propose a classification of EEMs used in industry for investigating its adoption and design. Cagno and Trianni [40] evaluate the barriers to implementing EEMS in small and medium enterprises. So, it is possible to observe that adopting EEMs in the industry is a subject of investigation.

O'Sullivan [41] highlights the advantages of implementing an energy efficiency assessment tool to maximize the impact of EEMs. Lawrence et al. [42] presented a report that drew on the successful experiences of their partners to develop guidelines for an effective energy management program as part of the US government's Energy Star® project. Additionally, an evaluation matrix was designed to compare energy management practices described in the guidelines with those of the organization to be evaluated, thus allowing for self-evaluation.

The first step in developing the proposed industrial energy efficiency assessment and prioritization model was a review of the main EEMs available to organizations in the current manufacturing context. Consequently, the authors conducted a literature review to gather knowledge from articles that describe measures, practices, activities, or projects related to industrial energy efficiency.

Two primary documents were found to be a founding basis for the present study. The first is a guide proposed by the Energy Star® program, which aims to identify opportunities for energy savings in the industrial [42]; the second is the online database of the Industrial Assessment Centers (IACs) [43].

The U.S. Environmental Protection Agency and the US Department of Energy prepared the first guide through the Energy Star® program, which aims to promote the standardization of energy efficiency practices and provide information on the energy consumption of products and devices [44].

The IACs are research centers in several locations in the United States that seek to evaluate EEMs to reduce energy consumption and minimize waste. According to the data available on the website, the program has conducted more than 19,176 surveys, generating more than 144,604 recommendations from EEMs, with an average annual savings of USD 137,136 [43].

From the study and analysis of these two main sources, the industrial EEMs and their respective categories were raised; these components formed the basis for the assessment tool proposed in this study. The initial review of EEMs resulted in the listing of 168 measures. After excluding redundant measures, 107 unique efforts remained in the final model. More details on the tool construction process are presented in Section 4.

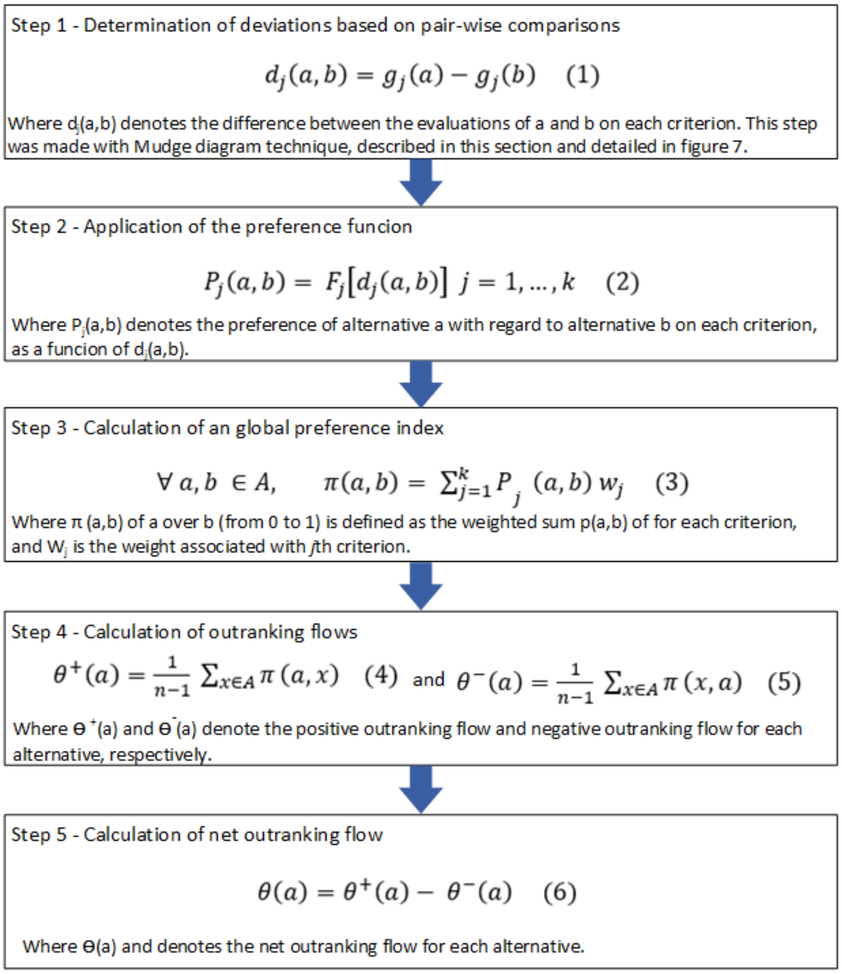
3. Methodology

MCDM methods aim to simplify complex decisions, specifically those arising from combinations of high volumes of information, by ranking possible choices to support decision-makers [45]. The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) is a methodology for the multi-criteria decision aid technique [46]. Within the known MCDM techniques, this study employed the PROMETHEE II method to select the most appropriate EEM within each factory category.

The choice for the PROMETHEE II method was based on its recommendation for problems where a limited number of alternatives are evaluated based on several conflicting criteria [47]. Also, the possibility for the decision-maker to consider the non-compensatory characteristics of the process and the opportunity to incorporate the incomparability relation in the analysis [46] are some benefits of choosing this method. In the present study, the range of EEM is limited, and ten criteria, sometimes conflicting, evaluate its choice. Two pieces of information are fundamental for constructing the PROMETHEE II method: (1) the pairwise comparisons of the criteria and (2) the choice of the preference function, which represents the difference in preference intensity between the alternatives.

The implementation of PROMETHEE II is conducted in five steps, as shown in Figure 1 [48]. In the first step, the criteria are compared pairwise, and a Mudge diagram was used for this purpose, which is described in more detail at the end of this section. In the next step, the preference function is chosen. In the third step, the global preference index is calculated. In the fourth step, both positive and negative outranking flows are calculated for each alternative. A positive outranking flow (ɵ+) quantifies how an alternative is globally preferred over all others, whereas a negative outranking flow (ɵ–) represents the contrary. Finally, the difference between positive and negative outranking flows is calculated by obtaining the net flow from which the alternatives are ranked.

In step one, the Mudge diagram was applied to calculate the weights of each criterion, which is a method of obtaining the degree of importance of particular criteria or numerical relations through a pairwise comparison between the alternatives [49]. The diagram is generated through this comparison, as shown in Figure 5 (section 5.2), with scores assigned to each alternative. Scores are based on a scale that generally has five levels [50]. The results allow the prioritization of each alternative based on its relevance and the analysis of its interrelations, as well as eliminating the alternatives dominated by others [51].



Step 1 - Determination of deviations based on pair-wise comparisons

$$d_j(a,b) = g_j(a) - g_j(b) \quad (1)$$

Where $d_j(a,b)$ denotes the difference between the evaluations of a and b on each criterion. This step was made with Mudge diagram technique, described in this section and detailed in figure 7.

Step 2 - Application of the preference funcion

$$P_j(a,b) = F_j\big[d_j(a,b)\big] \; j = 1, \dots, k \quad (2)$$

Where $P_j(a,b)$ denotes the preference of alternative a with regard to alternative b on each criterion, as a funcion of $d_j(a,b)$.

Step 3 - Calculation of an global preference index

$$\forall\, a, b \in A, \qquad \pi(a,b) = \textstyle\sum_{j=1}^{k} P_j\,(a,b)\, w_j \quad (3)$$

Where π (a,b) of a over b (from 0 to 1) is defined as the weighted sum p(a,b) of for each criterion, and W_j is the weight associated with *j*th criterion.

Step 4 - Calculation of outranking flows

$$\theta^+(a) = \frac{1}{n-1} \textstyle\sum_{x\in A} \pi\,(a,x) \quad (4) \quad \text{and} \quad \theta^-(a) = \frac{1}{n-1} \textstyle\sum_{x\in A} \pi\,(x,a) \quad (5)$$

Where $\Theta^+(a)$ and $\Theta^-(a)$ denote the positive outranking flow and negative outranking flow for each alternative, respectively.

Step 5 - Calculation of net outranking flow

$$\theta(a) = \theta^+(a) - \theta^-(a) \quad (6)$$

Where Θ(a) and denotes the net outranking flow for each alternative.

Figure 1: PROMETHEE II implementation steps [48].

4. Industrial energy efficiency assessment and prioritization model

The model proposed in this study consists of a combination of two methodologies: (1) Energy management assessment and (2) energy efficiency project prioritization. Figure 2 illustrates the composition of the model, the steps, the deliveries, and the tools employed.

4.1 Energy management assessment tool

To ensure the consistency of the energy assessment tool, only EEMs that would fit within the following categories were selected, as assigned by the Guide for Identifying Energy Savings in Manufacturing Plants from ENERGY STAR®: motors, compressed air systems, lighting, heating, ventilation, and air conditioning (HVAC) systems, pumps, boilers, furnaces, and steam distribution systems [42].

Within these eight categories, it was decided to deepen the research in four of them, which were considered of maximum interest in the literature owing to three factors: (i) wide diffusion in industries of different sectors [52], (ii) improvements in such categories are easily replicable [53], and (iii) Most are responsible for considerable energy not directly related to production processes [54]. These categories are:

a) **Motors:** Although responsible for 69% of energy consumption in Europe [55], they have the maximum potential for savings, from 11 to 18% [56];
b) **Compressed air systems:** Although considered the most expensive and inefficient way to obtain energy, these are responsible for 10% of the consumption of industrial electricity in Europe [57];
c) **Lighting:** Even though it represents a low percentage of industrial energy consumption, lighting still shows a significant absolute number that has several easy-to-apply measures [42];
d) **HVAC systems:** Playing a fundamental role because they participated in both production processes and thermal comfort at the workplace, these systems have several easy-to-apply measures [58].

In this scenario, it was decided that the PROMETHEE II multi-criteria decision-making model for prioritizing EEMs (explained in subsection 4.2) should be carried out for these four main categories.

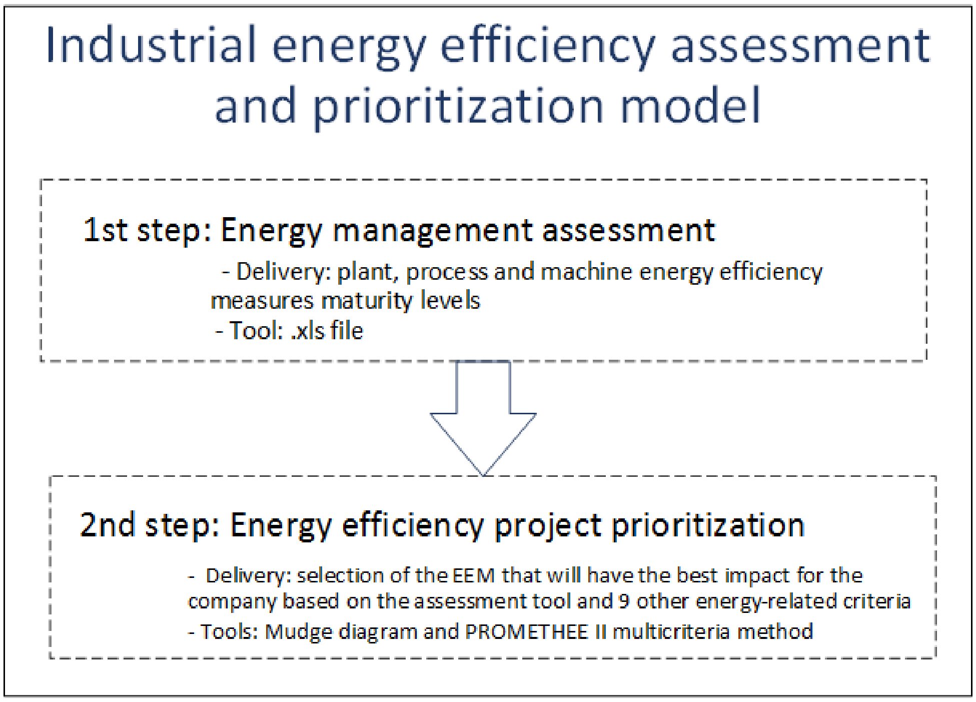


Figure 2: Proposed model composition, steps, deliveries, and tools.

The initial review of EEMs resulted in the listing of 168 measures. After excluding redundant measures, 107 unique measures remained in the final model. In this final version, the EEMs were categorized into four layers.

The first layer seeks to classify EE practices between plants, processes, and machines following the recommendation of Kara et al. [18]. The second layer concerns the energy efficiency categories (e.g., motors, lighting), whereas the third layer creates subcategories of the previous layer, grouping EE practices by affinity. The fourth and final layer presents the detailed EEMs themselves. The tool thus allows the evaluation of the overall energy performance of the factory and each specific layer. The distribution of these measures in the categories is shown in Table 1, and the complete assessment tool with all its layers and EEMs can be found in Appendix A.

In sequence, an attempt was made to define an adequate response scale for the assessment tool. For this purpose, the reference used was from the Energy Star® Evaluation Matrix [42], which performs the assessment based on three levels of implementation:

L1: Little or no evidence of implementation;
L2: Implementation in process or partial;
L3: Full implementation.

Table 1: Final count of the maturity model EEMs.

Level	Category	EEMs	%
Plant	• Lighting	• 14	• 13%
	• HVAC systems	• 32	• 30%
Process	• Compressed air	• 14	• 13%
	Steam distribution	7	7%
Machine	Pumps	11	10%
	• Motors	• 17	• 16%
	Boilers	9	8%
	Furnaces	3	3%
	Total	**107**	

From the assessment tool, a Microsoft Excel® spreadsheet was developed in which users could score the implementation levels of each EEM, and charts were automatically generated; this allowed for a visual representation of the assessment tool results through dashboards. More details of the visualization of the results are given in Section 5.

4.2 Energy efficiency project prioritization tool

Once the diagnostic evaluation of the EEMs is performed, the next step of the proposed model consists of applying the energy efficiency project prioritization tool. Consequently, an MCDM method was used, precisely the PROMETHEE II method. For the elaboration of the PROMETHEE II method, in addition to the maturity levels of each category collected in the previous step, some additional data was required, as shown in Table 2.

The literature played a supporting role in determining the evaluation criteria of the EE projects. From the literature review, the framework proposed by Trianni et al. [54] was of particular interest given its synthetization of attributes for choosing whether to implement an EEM according to the view of the managers responsible for such decisions. Owing to their relevance and suitability, nine attributes and their respective classifications of that study were used in the present study. In addition to the traditional criteria, the "maturity" criteria were adopted for this prioritization tool of EE projects, which in practice is the result of the implementation of the energy management assessment tool. All selected criteria are presented in Table 3.

It is understood that the lower the maturity of a given category, the greater its weight must be in the PROMETHEE II prioritization method. Thus, the maturity complement was used as a weight for the prioritization tool, and the objective of this criterion was to be minimized because a lower value indicates a higher

Table 2: Required information to PROMETHEE II analysis implementation.

Item	Determination
a) Definition of the criteria for the evaluation of the EE projects	Trianni et al. [54]
b) Objective of each criterion: maximization or minimization	Logical classification according to criteria
c) Definition of criteria weights	Mudge diagram
d) Definition of weight for each category (lighting, HVAC Systems, compressed air, motors)	Complementary value to the maturity of each category

Table 3: Attributes used in PROMETHEE II.

Criteria	Cluster	Scale	Objective
Payback period	Economic	Low | Medium | High	MIN
Costs of implementation	Economic	Low | Medium | High	MIN
Amount of energy savings	Energy	Low | Medium | High	MAX
Reduction of emission	Environment	Proven | Not proven	MAX
Reduction of waste	Environment	Proven | Not proven	MAX
Productivity	Production	Proven | Not proven	MAX
Costs of maintenance/operations	Production	Improved | Worsened	MAX
Easiness of implementation	Implementation	Easy | It depends | Difficult	MIN
Probability of success/acceptance	Implementation	Low | Medium | High	MAX
Maturity	Maturity	Low | Medium | High	MIN

maturity. The mathematical equation of the maturity criteria value is presented as follows:

$$Maturity\ of\ each\ category = 3 - \frac{1}{n}\sum x_{EEMs} \qquad (7)$$

Where n is the number of EEMs of each category and xEEMs is the maturity score of each EEM, ranging from 1 to 3. To prioritize the EEMs, four analyses were carried out using the PROMETHEE II method, each one of the main categories of EEM-lighting, HVAC systems, compressed air systems, and motors. Appendix B illustrates the decision matrix of the PROMETHEE II method for the compressed air systems category.

5. Implementation in a case study

The case study was conducted in a Norwegian multinational company that operates in the energy sector, supplying products, systems, and services to the oil and gas sector. For confidentiality reasons, the firm will be referred to as the company “Alpha” in this study.

5.1 Energy management assessment tool

Before the application of the energy management assessment tool, verification was made of which categories were present in Alpha. The authors interviewed three company employees: a maintenance manager and two other maintenance engineers. As a result, the categories “steam distribution systems” and “boilers” were removed because they were not present in Alpha’s operations. The tool evaluated all other categories, and 91 EEMs were identified. Notably, despite all EEMs being assessed, only the energy performances of 86 were considered for the calculation of the overall maturity score, which is the average of all EEMs identified; this is because the category “furnaces” did not reach 75% of EEM response completeness because of the lack of applicability of some measures within the reality of that specific industry.

Regarding the results of the analysis, the results were compiled into a dashboard with the following information: (1) The maturity levels of all EEMs regardless of their category, (2) the distribution of maturity levels for each organizational level, and (3) the distribution of maturity for each energy efficiency category of the plant; this information is presented in Figure 3.

Figure 4 shows in more detail the distribution for each subcategory for the four main categories considered in this study: lighting, HVAC systems, compressed air systems, and motors.

From the average maturity level of each category, the overall maturity score of Alpha was calculated, being assessed at “2.01” out of a total of 3 (67%), as shown in Table 4.

As previously mentioned, the weight of this criterion is calculated from its complement, ensuring that a category with low maturity has a high weight and vice versa. Based on this result, the categories “lighting” and “HVAC systems”, which compose the “factory” organizational level and have a maturity level greater than 2, require less scrutiny than the other categories because they have a high level of maturity. Thus, in the next step of prioritizing PROMETHEE II, these categories will have less weight in the maturity criterion.

In turn, the categories “compressed air system” and “motors,” had a greater weight within the prioritization tool because they were evaluated with a lower maturity level. The other categories, “pumps” and “furnaces,” were not considered in elaborating the PROMETHEE II

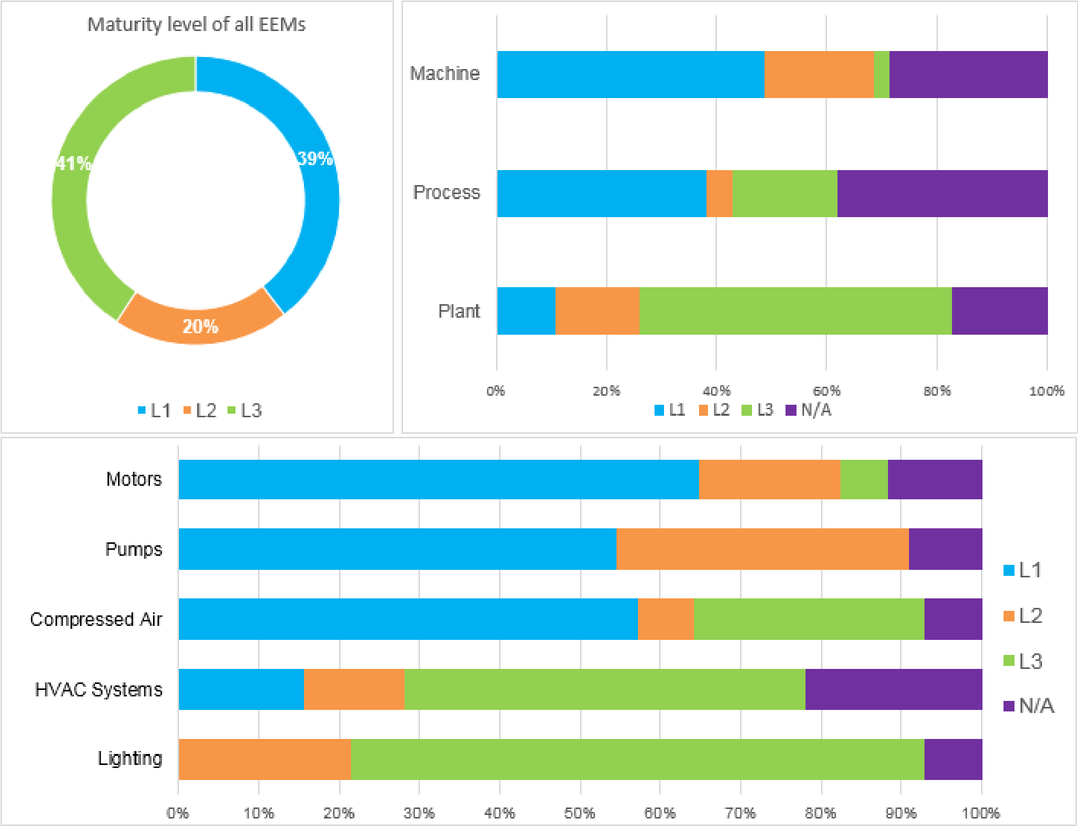


Figure 3: Dashboard of the EE assessment tool.

Figure 4: Subcategory level maturity results.

Table 4: Summary of maturity scores.

Category	Response Rate	Maturity
Lighting	13/14 (93%)	2.77
HVAC systems	25/32 (78%)	2.44
Compressed air	13/14 (93%)	1.69
Motors	15/17 (88%)	1.33
Pumps	10/11 (91%)	1.40
Furnaces	2/3 (67%) ▼	1.00
Organizational level	**Response Rate**	**Maturity**
Plant	38/46 (83%)	2.55
Process	13/14 (93%)	1.69
Machine	25/28 (87%)	1.36
Global	**Response Rate**	**Maturity**
Company Alpha	78/88 (86%)	2.01

method, as explained previously. However, the low maturity of "pumps" indicates that this category also requires additional focus from the company Alpha.

5.2 Prioritization of energy-efficient measures

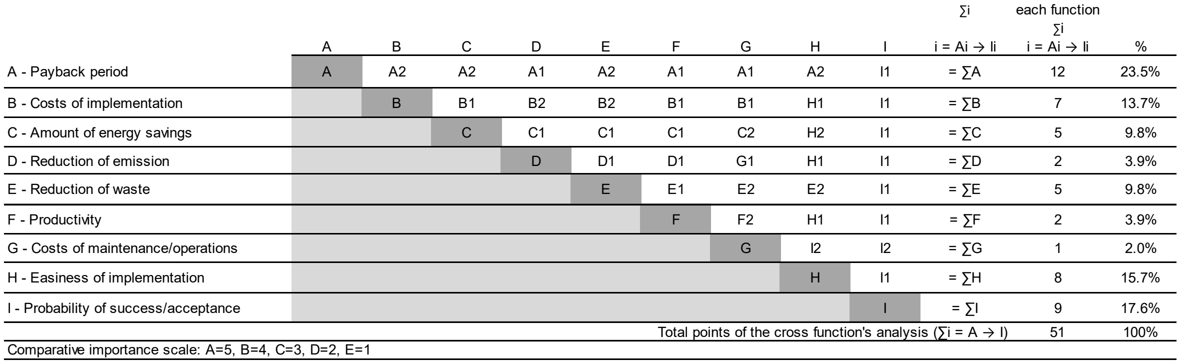
For the prioritization of these EEMs, the Mudge diagram (Figure 5) was first created to define the weights of each attribute related to energy efficiency projects in the company's specific context.

The goal of applying this tool is to prioritize the EEMs for the four main categories studied. With the calculation of the weights inputted into the PROMETHEE method, the prioritization analysis was customized for Alpha's context. Table 5 presents the ranking of the EEMs for the "motors" category.

Through the analysis of the four main categories considered in this study, a series of recommendations for prioritizing EEMs for each was possible, as summarized below:

- Motors (Maturity score: 1.33)
  3.2.17 Use optimally sized pumps and motors
  3.2.4 Refrain from rewind motors more than twice
  3.2.8 Prefer adjustable frequency drive over the throttling system
- Compressed air (Maturity score: 1.69)
  2.1.5 Detect and repair leaks on compressed air systems
  2.1.3 Adjust the compressed air pressure to the minimum demand
  2.1.10 Keep only compressed air lines that are strictly necessary
- HVAC Systems (Maturity score: 2.44)
  1.2.29 Establishes air ventilation to the minimum possible while respecting safety guidelines
  1.2.30 Evaluate and develop a guideline of air conditioning use during non-working hours
  1.2.23 Utilize heat pipes instead of electric reheat
- Lighting (Maturity score: 2.77)
  1.1.3 Install photocontrol devices
  1.1.5 Install automatic light timers in minimal utilized areas
  1.1.2 Use presence sensors

These analyses carried out by the PROMETHEE II method met the objective of providing the company a determination of which EEMs will provide the most significant benefit according to established criteria and weights.



	A	B	C	D	E	F	G	H	I	∑i i = Ai → Ii	Total points of each function ∑i i = Ai → Ii	%
A - Payback period	A	A2	A2	A1	A2	A1	A1	A2	I1	= ∑A	12	23.5%
B - Costs of implementation		B	B1	B2	B2	B1	B1	H1	I1	= ∑B	7	13.7%
C - Amount of energy savings			C	C1	C1	C1	C2	H2	I1	= ∑C	5	9.8%
D - Reduction of emission				D	D1	D1	G1	H1	I1	= ∑D	2	3.9%
E - Reduction of waste					E	E1	E2	E2	I1	= ∑E	5	9.8%
F - Productivity						F	F2	H1	I1	= ∑F	2	3.9%
G - Costs of maintenance/operations							G	I2	I2	= ∑G	1	2.0%
H - Easiness of implementation								H	I1	= ∑H	8	15.7%
I - Probability of success/acceptance									I	= ∑I	9	17.6%
Total points of the cross function's analysis (∑i = A → I)											51	100%
Comparative importance scale: A=5, B=4, C=3, D=2, E=1												

Figure 5: Mudge diagram for company Alpha.

Table 5: Ranking of EEMs for the category "motors" based on the PROMETHEE II method.

Rank	Alternatives	ɵ+	ɵ-	Net ɵ
1	3.2.17 Use optimally sized pumps and motors	0.3492	0.1429	0.2063
2	3.2.4 Refrain from rewind motors more than twice	0.3236	0.1416	0.182
3	3.2.8 Prefer adjustable frequency drive over the throttling system	0.3028	0.1807	0.1221
4	3.2.6 For inconstant loads on compressor, pump and blowers prefer adjustable frequency drive or multiple speed motors	0.3663	0.2674	0.0989
5	3.2.9 Prefer adjustable frequency drive over the mechanical drive	0.2479	0.2112	0.0367
6	3.2.15 Prefer energy-efficient belts and other components	0.2759	0.2491	0.0268
7	3.2.13 Develop a preventative maintenance plan	0.2857	0.2747	0.011
8	3.2.3 Refrain from rewind motors on unforeseen circumstances	0.2381	0.2357	0.0024
9	3.2.5 Catalog motors and their spare parts in a standardized way	0.2711	0.2698	0.0013
10	3.2.14 Develop a predictive maintenance plan	0.2308	0.3053	-0.0745
11	3.2.11 Establish a policy for motor or spare part replacement	0.1893	0.2772	-0.0879
12	3.2.16 Use ideal size of electric motors considering peak efficiency operation	0.1746	0.2991	-0.1245
13	3.2.10 Prefer adjustable frequency drive with an isolation transformer	0.2344	0.4176	-0.1832
14	3.2.2 Use a voltage controller on motors with low demand	0.2625	0.4799	-0.2174

6. Discussion

From the case study of the model, the adoption of the organizational lenses of "plant, process, and machine" was highly beneficial for several reasons:

- it ensured that EEMs from all perspectives were considered.
- it provided a precise classification of EEMs within the organization.
- it helped energy managers to assign responsibility in cross-functional EE project teams.
- it allowed analyses of energy management systems at different levels, from a macro level down to the detail of the EEMs.
- it facilitated the identification of imbalances in performance across organizational layers.

Another important aspect of the proposed model is the considerable level of the results' refinement as enabled by the combination of the assessment and prioritization tools. The delivered results can provide a more comprehensive understanding of a company's energy performance and support investment decisions in EE projects. Thus, this model reduces the barriers to energy efficiency and, consequently, the industrial energy efficiency gap.

Hasan et al. [59] highlight that energy management impacts the production resources like machinery and devices considered in this work. A similar classification of this paper is applied by Cagno et al. [60], but without the division according to the company's organizational levels. This scenario shows that the current work contributes to increasing the literature about how energy management impacts production resources. With the prioritization of the actions for improvement, it is possible to gain economy regarding the production costs and improve the company's productivity.

Demirel et al. [61] also analyzed energy efficiency using PROMETHEE. Still, the authors' model focuses on analyzing only industrial steam boilers, differently from the model of this study that considers organizational levels. Despite the differences, maintenance was an aspect that appeared in both models, showing that the machines must be in a good state of functioning not to affect energy efficiency.

Schulze et al. [62] mentioned that industrial energy performance could be highly complex because production systems and their related support process can vary widely between sites. This makes it challenging to create generalized solutions and requires each industrial site to develop a personalized energy assessment model based on the EEMs that are most suitable to its reality. This is a limitation of the proposed model as it must be adapted to every application.

Concerning the implementation of the model through the case of study, the three-level scale of maturity for each EEM was proven acceptable as it provided an adequate understanding to practitioners and offered a sufficient degree of detail for the generation of insights from the analysis performed. In addition, the model's applicability was considered appropriate as the process was conducted satisfactorily in approximately two hours. However, it should be noted that despite the literature on maturity models regarded as models of five levels [63–66], the model presented in this work with three levels can provide good results for the described situation.

The model, with its three maturity levels, gives more concrete objectives to be completed. Notably, the contribution of the present model is focused on the operational aspect of energy management systems. However, for comprehensive energy management, organizations should address other dimensions such as strategy, culture, control, and organization [62]. Finally, like the ISO 50.001 standard, the proposed model should be an ongoing process where, in each cycle, the company is expected to achieve better performance and learn new possibilities for improvement. The proposed model can be included during the implementation of ISO 50001 in enterprises since the standard does not present achievable goals.

7. Conclusions

With increasing global energy consumption, concerns arise about the sustainability of such an increase. For the industrial sector, which is the leading global consumer of energy, these concerns are of even greater proportions; any change in price or availability of energy significantly impacts competitive advantage, as competition occurs globally. Therefore, energy efficiency is fundamental to achieving cleaner production goals, governmental regulations, and compliance with stakeholders' needs.

The present research contributed to these objectives by proposing an industrial energy efficiency assessment and prioritization model focusing on the organizational levels of "factory, process, and machine." This focus was combined with a methodology for prioritizing EEMs in the industry through multi-criteria analysis tools. From applying the model in a case study, the present proposal offered several contributions to practitioners and the scientific community.

For practitioners, classifying energy efficiency into three organizational levels identifies a possible imbalance of efforts between levels. In addition, the model achieves an important amount of detail from the perspective of different corporate criteria with different weights, i.e., guidance through prioritization of EEMs.

Regarding the scientific community, the model provides a methodological contribution to (i) the combination of a traditional energy assessment tool with a prioritization of measures procedure, thereby enabling a high level of refinement of the results and (ii) to the authors' best knowledge, the unprecedented use of PROMETHEE II tool to prioritize EEMs in the context of manufacturing.

PROMETHEE II was the MCDM method utilized, but others should be considered regarding the non-compensatory nature of the problem. Despite its application, the model has some limitations, as the decision-maker interviewed during the research because they belong to the operational level, so their vision is limited to their current situation. Some managerial should be included during the analysis of the criteria. This model was general, so the list of EEMs considered this scenario a guideline for future models in the area. Some specialization is necessary for different types of industries.

Based on the results, further research is required in preparing energy management assessments and prioritization models tailored to different industry segments and their respective production processes. The model should include the managerial perspective to make it more viable at all organizational levels. Additionally, using other multi-criteria methodologies for the prioritization of EE projects is suggested, as this approach could potentially compare the results and analyze the advantages and disadvantages of each method, providing more literature for the MCDM methods.

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Appendix A

Energy Management Maturity Model Matrix

1st layer	2nd layer	3rd layer	Ref.	Energy efficiency measures	Maturity Score (1 to 3) or N/A
1. Plant	1.1 Lighting	Lighting Controls	1.1.1	Place more individualized switches that can be turned off when natural light is sufficient	
			1.1.2	Use presence sensors	
			1.1.3	Install photocontrol devices	
			1.1.4	Install light switches in external areas	
			1.1.5	Install automatic light timers in minimal utilized areas	
		Maintenance	1.1.6	Ensure regular cleaning of reflectors and lamps	
		Improvements	1.1.7	Use lamps with high energy efficiency	
		Conscious use	1.1.8	Keep only the necessary lamps	
			1.1.9	Get staff used to turning off unused lights	
			1.1.10	Reduce outdoor lighting to a minimum level of security	
			1.1.11	Avoid over-lighting areas	
			1.1.12	Whenever possible, give preference to natural light instead of artificial light	
			1.1.13	When the ceiling is too high, decrease the height of the fixtures	
			1.1.14	Utilize rooflight/skylight	
	1.2 HVAC Systems	Control	1.2.1	Make use of thermostats and/or timers	
			1.2.2	Enable manual shutdown of your HVAC equipment	
			1.2.3	Control humidity through a desiccant system	
		Management	1.2.4	Use air conditioning system to keep compressor pressure low	
			1.2.5	Keep the HVAC system free of hot, humid and dirty air as much as possible	
			1.2.6	Evaporate water from roofing to lower a/c load	
			1.2.7	Optimize multiple-source heating schedule and arrangement	
			1.2.8	Prioritize / install separate air handlers on HVAC systems	
			1.2.9	Optimize a/c efficiency by using water on a/c exchanger	
			1.2.10	Choose radiant heater for localized heating	
			1.2.11	Transfer heat through a heat pump for room conditioning	
			1.2.12	Supply air directly to exhaust hoods	
			1.2.13	Improve HVAC performance through optimizations softwares	
			1.2.14	Reduce the use of make-up airs to the minimum safe level	

		Maintenance	1.2.15	Perform maintenance and cleaning of refrigerant condensers and towers
			1.2.16	Smoke clean-up should be revised periodically
		Improvements	1.2.17	Improve or implement insulation on HVAC systems
			1.2.18	Control outside air volume flow with a damper on HVAC
			1.2.19	Utilize heat pipes to achieve setpoint temperature
			1.2.20	Implement different strategies to enhance air circulation such as under-ceiling air mixers
			1.2.21	Replace reheat coils to a variable air volume system
			1.2.22	If necessary, change old hvac system to a high energy efficiency model
			1.2.23	Utilize heat pipes instead of electric reheat
			1.2.24	Implement a pre-cooling system in air conditioning system
		Selection	1.2.25	Make sure HVAC equipment is properly sized
		Concious use	1.2.26	Lower the roof to decrease conditioned area
			1.2.27	Increase temperature in summertime and vice-versa
			1.2.28	Block the simultaneous use of heating and cooling systems
			1.2.29	Establishes air ventilation to the minimum possible while respecting safety guidelines
			1.2.30	Evaluate and develop a guideline of air conditioning use during non-working hours
			1.2.31	Ventilate only spaces that are being used
			1.2.32	Reuse air for warming, ventilation, and cooling
2. Manufacturing process	2.1 Compressed Air	Management	2.1.1	Eliminate blowdowns on air pipes by using suitable dryers
			2.1.2	Install filters on air compressors
			2.1.3	Adjust the compressed air pressure to the minimum demand
			2.1.4	Decrease the compressor entering air temperature through a heat exchanger
		Maintenance	2.1.5	Detect and repair leaks on compressed air systems
		Improvements	2.1.6	Place the compressor air entrances in coolest areas
			2.1.7	In safety systems, replace compressed air pressure systems with direct-acting units
			2.1.8	Improve controls on air compressors
			2.1.9	Standardized air compressors' header
		Usage Reduction	2.1.10	Keep only compressed air lines that are strictly necessary
			2.1.11	Use compressed air only for manufacturing purposes and not for cleaning or personal cooling
			2.1.12	Avoid using compressed air for drying, cooling and moving objects
			2.1.13	Whenever possible, use alternative cooling methods that do not use compressed air
		Selection	2.1.14	Make sure air compressor equipment is properly sized
	2.2 Steam Distribution Systems		2.2.1	Perform maintenance on steam traps regularly
			2.2.2	Make sure that steam traps are being monitored
			2.2.3	Make sure that the distribution system is thermally insulated
			2.2.4	Detect and repair leaks
			2.2.5	Upgrade/modernize the insulation of distribution system
			2.2.6	Upgrade/modernize steam traps
			2.2.7	Reuse flash steam

3. Machine	3.1 Pumps		3.1.1	Utilize high-efficiency pumps
			3.1.2	Use pump diameter size properly calculated
			3.1.3	Install properly sized pumps
			3.1.4	Use throttling valves as little as possible
			3.1.5	Install parallel system for variable loads
			3.1.6	Develop a maintenance plan for the pump system
			3.1.7	Make sure that pump system are being monitored
			3.1.8	If possible, limit or cut down pump system load
			3.1.9	Apply trimming impellers into pumps
			3.1.10	Periodically perform drive belts replacement
			3.1.11	Utilize adjustable-speed drives into pumps
	3.2 Motors	Management	3.2.1	Avoid unnecessary opening of the circuit protection device using soft-start
			3.2.2	Use a voltage controller on motors with low demand
			3.2.3	Refrain from rewind motors on unforeseen circumstances
			3.2.4	Refrain from rewind motors more than twice
			3.2.5	Catalog motors and their spare parts in a standardized way
		Adjustable frequency drive	3.2.6	For inconstant loads on compressor, pump and blowers prefer adjustable frequency drive (afd) or multiple speed motors
			3.2.7	Prefer afd over the motor-generator set
			3.2.8	Prefer afd over the throttling system
			3.2.9	Prefer afd over the mechanical drive
			3.2.10	Prefer afd with an isolation transformer
		Maintenance	3.2.11	Establish a policy for motor or spare part replacement
			3.2.12	Recruit certified repair shops exclusively
			3.2.13	Develop a preventative maintenance plan
			3.2.14	Develop a predictive maintenance plan
		Selection	3.2.15	Prefer energy-efficient belts and other components
			3.2.16	Use ideal size of electric motors considering peak efficiency operation
			3.2.17	Use optimally sized pumps and motors
	3.3 Boiler		3.3.1	Use optimally sized boiler systems
			3.3.2	Restrict air excess
			3.3.3	Restrict the amount of flue gases
			3.3.4	Perform control on Boiler process
			3.3.5	Perform regular maintenance on boiler
			3.3.6	Upgrade boiler insulation
			3.3.7	Recover heat from flue gases
			3.3.8	Improve the condensate return rates to the boiler
			3.3.9	Perform boiler blowdown regularly
	3.4 Furnaces		3.4.1	Monitor the air to fuel/power ratio
			3.4.2	Recover heat from flue gases
			3.4.3	Upgrade the heat retention and transferring on heaters

Appendix B

Compressed air systems decision matrix

Compressed Air Maturity Category weight: 1,31	**Payback period**	**Costs of implementation**	**Amount of energy savings**	**Reduction of emission**	**Reduction of waste**	**Productivity**	**Maintenance and operations**	**Easiness of implementation**	**Probability of success/ acceptance**	**Maturity**
Cluster	Economic	Economic	Energy	Environmental	Environmental	Production-related	Production-related	Implementation	Implementation	Maturity
Objective Min/ Max	Min	Min	Max	Max	Max	Min	Max	Min	Max	Min
Weight of each criterion (from Mudge diagram)	0.24	0.14	0.1	0.04	0.1	0.02	0.04	0.16	0.18	n/a
Eliminate blowdowns on air pipes by using suitable dryers	Medium	High	n/a	n/a	No	n/a	No	Depends	Medium	High
Install filters on air compressors	Medium	Low	Low	n/a	No	Decreased	No	Easy	Medium	High
Adjust the compressed air pressure to the minimum demand	Low	Low	Low	n/a	No	Decreased	No	Easy	High	Low
Decrease the compressor entering air temperature through a heat exchanger	Medium	Medium	Low	n/a	No	n/a	No	Hard	High	Low
Detect and repair leaks on compressed air systems	Low	Low	High	n/a	No	Decreased	Yes	Easy	High	Low
Place the compressor air entrances in coolest areas	Medium	Low	Low	n/a	No	n/a	No	Depends	Medium	Low

In safety systems, replace compressed air pressure systems with direct-acting units	Medium	Medium	n/a	n/a	No	n/a	No	Depends	Medium	High
Improve controls on air compressors	Medium	Medium	Medium	n/a	No	n/a	Yes	Depends	Medium	Low
Standardized air compressors' header	n/a	High	n/a	n/a	No	n/a	No	Depends	Medium	Low
Keep only compressed air lines that are strictly necessary	Low	Medium	n/a	n/a	No	n/a	No	Depends	Medium	Low
Use compressed air only for manufacturing purposes and not for cleaning or personal cooling	Low	Low	n/a	n/a	No	n/a	No	Easy	High	High
Avoid using compressed air for drying, cooling and moving objects	Low	Medium	High	n/a	No	n/a	No	Depends	Medium	Medium
Whenever possible, use alternative cooling methods that do not use compressed air	Low	Medium	n/a	n/a	Yes	n/a	No	Depends	Medium	n/a

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