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Industrial eco-productivity tool: A case study of industrial SMEs

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Abstract:

This paper presents a new, unified method to measure and increase production and environmental performance in industrial SMEs (Small and Medium Enterprises), which have very limited resources, by identifying areas to improve and forming related projects. This structured, easy-to-apply method is based on standard systems to measure waste production efficiency and eco-efficiency and unifies them in a single reference value. In addition, a case study is shown where the industrial eco-efficiency of the company is obtained with the developed tool

Key words:

Industrial eco-productivity, production sustainability, resource efficiency.

1. Introduction

Today, due to the legislative, economic and environmental pressure exacerbated by the Covid-19 health crisis, manufacturing industries are at the beginning of an industrial transformation, which constitutes a challenge as well as incentive to use resources efficiently and, accordingly, increase competitiveness and sustainability (Karmaker et al., 2021; Verma & Gustafsson, 2020). Most of the concepts and terms that link the Circular Economy (CE) and sustainability to manufacturing promote product life cycle management. This typically involves the four main stages of the life cycle: i) extraction, ii) production, iii) use and iv) end of life. Sustainable manufacturing addresses in particular the production stage of the product life cycle, albeit without neglecting the economic and environmental consequences of activities in the other stages. Sustainability in manufacturing can be achieved in several ways, including maximizing production efficiency, minimizing the use of resources and maximizing product production by replacing harmful and non-renewable resources, and reducing consumption by changing consumption patterns (Blume, 2020). In this sense, companies have traditionally used practices focused on eliminating activities that do not add value, increase production efficiency, and reduce environmental impact. To measure these processes, different metrics have been developed, such as Overall Equipment Effectiveness (OEE) (Singh et al., 2013) and eco-efficiency (Chenavaz et al., 2021). The aforementioned OEE and eco-efficiency are used independently and managed by different departments, though Domingo and Aguado have developed a unified metric. Despite this, Domingo & Aguado (2015) emphasized that indicators are still required that provide data to help make unified decisions and easily offer an overview of both production and environmental fields. This paper is part of the CircularTRANS research project supported by the Gipuzkoa region council (Spain's Basque region) to promote CE in the region's Small and Medium Enterprises (SMEs). More specifically, this paper presents a new method to measure and evaluate production and environmental performance in a simple, unified way in industrial SMEs, which have very limited resources.

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Sustainability in manufacturing, which implies the efficient use of resources in both economic and environmental terms, is an appropriate strategy for increasing industrial companies' productivity by increasing the productivity of the resources they use (Ma et al., 2015). Resource productivity is understood as the ratio between the input and output of a transformation process, thus making it possible to evaluate the process's degree of efficiency. In this sense, industrial performance metrics are increasingly considering both economic aspects and those related to environmental sustainability (Liedtke et al., 2014). Therefore, it is necessary for companies to use metrics that reference information and temporal and spatial patterns to continuously evaluate production and environmental performance, as well as be able to quantify them easily and usefully to identify areas for improvement. However, due to SMEs' traditional lack of resources or awareness of their own ecological footprint or responsibility to protect the environment, research on SMEs and the environment has often highlighted their poor environmental performance. Despite this, environmental concern among SMEs has increased in recent years. Even so, eco-efficiency and win-win opportunities are often considered irrelevant to SMEs, which may be more motivated by personal concerns for the environment focusing on their lack of management teams and dependence on but a few individuals and the flexibility, informality, immediate issues, and uncertainty of the environment in which they operate. Efficiency gains as well may not be significant for SMEs operating on a small scale, or initial investments may be unaffordable. SMEs thus need tools that allow them to measure and act on production and environmental performance in a simple way, and that enable the development of sustainable manufacturing processes (Millard, 2011). There are already researchers who have developed metrics applicable in production processes based on environmental and production aspects, including Sustainable Overall Throughput Effectiveness (SOTE) (Durán et al., 2018), Overall Greenness Performance (OGP) (Muñoz-Villamizar et al., 2018), Overall Environmental Equipment Effectiveness (OEEE) (Domingo & Aguado, 2015) and works where the eco-productivity is analyzed (Llanquileo-Melgarejo & Molinos-Senante, 2022; Ma & Cao, 2022; Nguyen et al., 2022). In some cases, SOTE, OGP and OEEE are not considered common management indicators, while in others, the method may be difficult to apply to SMEs, since it is necessary to use life cycle analysis software to obtain the eco-indicators' values. None of these methods measure production waste, however. This paper thus shows the development and application of a new metric called Industrial Eco-productivity (IE). Extant research has already analysed the concept of eco-productivity and define it as *"capacity of the system to transform energy, material, resources and information (without waste or squandering) into a product or service, without generating negative impacts on other interacting systems"* (Saravia-Pinilla et al., 2019). Based on this definition, green and lean aspects focusing on the elimination of production and environmental waste were integrated (Fercoq et al., 2016). The present metric was developed to encompass lean aspects related to the elimination of waste (Muda: *Toyota´s term to designate anything that takes time bus does not add value to customers*) (Liker, 2006), a production efficiency measurement and eco-efficiency indicator that measures processes' environmental impacts. IE is i) self-assessable for SMEs, ii) intended for internal use, iii) simple and easy to use and iv) does not require external tools. In addition, it provides instant results.

The remainder of this article is structured as follows. First, each of the concepts inserted in the new tool (productive waste, production efficiency and eco-efficiency) is analysed. Subsequently, the way IE is calculated is described. This is followed by a case study of IE's application in a metal stamping company. Finally, the study's conclusions are presented.

2. Manufacturing waste

Organizations widely practise lean, or the Japanese concept of manufacturing dynamics, to increase their productivity, reduce waste and address environmental impacts. Lean augments organizations by providing a toolbox of approaches to reduce waste, increase process productivity and advance organizational efficiency in industrial processes (Liker, 2006). The industry focus on waste reduction and process flow management causes organizations to adopt a lean methodology to improve efficiency (Baysan et al., 2019). Manufacturing waste forms the basis of lean, which pursues the reduction of non-value-added activities in organizational processes (Fercoq et al., 2016). Table 1 shows the specific synergies between the lean and green waste identified in a sample of US companies, demonstrating a close relationship between lean waste and the environmental impacts generated by industrial processes (Verrier et al., 2016).

Table 1. Lean muda and their associated green impacts (Verrier et al., 2016).

Lean Muda	Associated green impacts
Overproduction	Unnecessary use of energy and raw materials, further safety troubles where hazardous substances are involved, potential increase of direct output emis-sions
Inventory	Excessive power usage for heating/cooling/lighting, potential excess material use and rubbish production due to added packaging, possible product deterio-ration
Transportation	Energy use during transport (greater emissions, special risks with hazardous freight (e.g. spills), etc.)
Defects	Waste of raw materials and energy: management of re-treatments (energy, dis-posal, etc.)
Unnecessary movement	Potentially more space (energy) and packaging (materials) required for unnec-essary movement
Waiting	Spoiled energy and resources, potential material damage
Inappropriate processing	Unnecessary energy and raw material use, more rubbish and emissions, poten-tially hazardous processes
Lost people potential	Lost improvement potential

3. Production efficiency overall equipment effectivenees

OEE is commonly used as a performance indicator of equipment utilization. It calculates equipment-level efficiency and equipment productivity relative to its maximum capacity, which is assumed constant over the time period considered. It also determines the percentage of time spent producing defect-free products. As shown in Figure 1, OEE is the product of the availability index, performance index and quality index (Singh et al., 2013) in which to obtain these results it is necessary to know: i) the real working times of the machines and ii) the six major losses that they may have. These are related to each other and by obtaining these data the OEE percentage of the analyzed machine is obtained. OEE can be applied in different contexts: for instance, either as a benchmark to measure the initial performance of a manufacturing plant as a whole; to compare line performance across a factory, thus highlighting any poor line performance; or to identify which facility is underperforming and therefore where to concentrate resources (Muchiri & Pintelon, 2008). Accordingly, the term OEE has been modified based on its application, such as Overall Factory Effectiveness (OFE), Overall Plant Effectiveness (OPE), Production Equipment Effectiveness (PEE), Overall

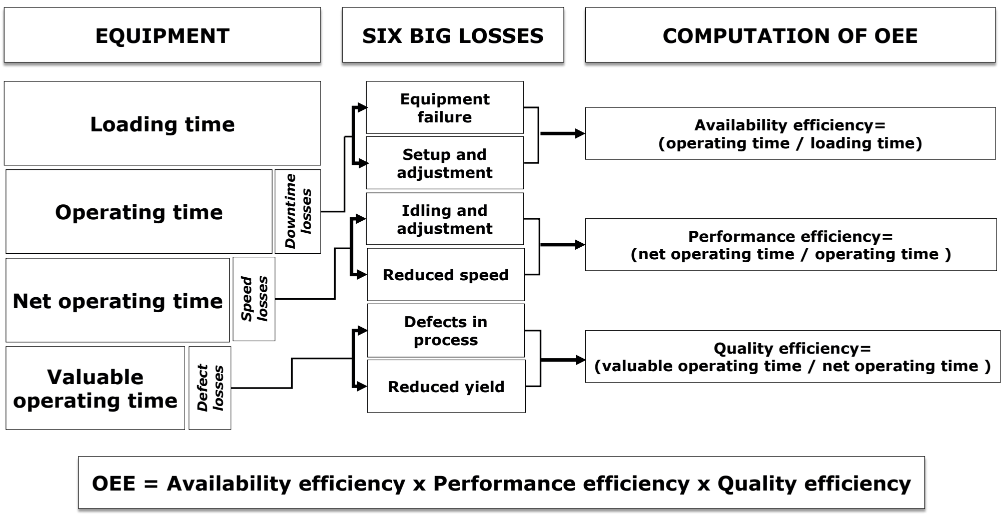


Figure 1. Overall equipment effectiveness (OEE) (Singh et al., 2013).

Asset Effectiveness (OAE) and Total Equipment Effectiveness Performance (TEEP). On the other hand, taking into account the green and lean vision, there are scholars like Muñoz-Villamizar et al. (2018) who have used OEE as a basis to develop other metrics through which they can evaluate the production and environmental behaviour of production processes, which they call Overall Green Performance (OGP). However, despite its widespread use and success, OEE does not provide a global view at the production system level, nor does it distinguish the impact of specific equipment on overall performance (Durán et al., 2018).

4. Eco-efficiency

Eco-efficiency is commonly defined as the relationship between the added value and aggregate environmental impact of a company's operational processes (Huppes & Ishikawa, 2007), and can be represented with the following ratio: economic performance / environmental performance (Thant & Charmondusit, 2010). Environmental impacts can be measured in terms of resource consumption, emissions or environmental damage, but these should be evaluated in a company's internal operations, excluding the stages related to the product and supplier (Hahn et al., 2010). Companies employ a set of practices to improve their eco-efficiency through different Life Cycle Assessment (LCA) based methods and other metrics to calculate their manufacturing environmental impact, such as Ecotasa, Ecovalue08, Ecoindicator-99, Ecoinvent and OEEE (Domingo & Aguado, 2015). Generally, their first objective is to reduce negative environmental impacts, but this is not enough: it is also necessary to promote value creation and produce economic value – in other words, to improve efficiency and performance. Consequently, it is necessary for organizations to implement green and lean practices simultaneously, through which they can improve their business performance while generating environmental and economic benefits (Duarte & Cruz Machado, 2017).

5. Industrial Eco-productivity tool

The IE evaluation method for SMEs is a proposed improvement process that can continuously identify all process failures. It is composed of five phases, as shown in Figure 2.

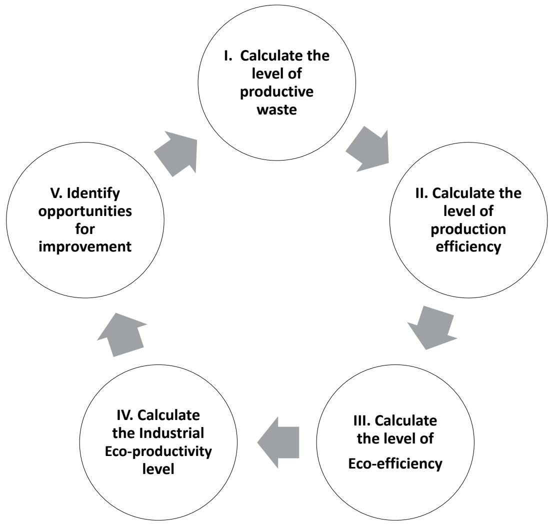


Figure 2. IE evaluation method for SMEs.

This process allows companies to self-assess and instantly know their eco-productivity performance without the need for complex tools. During the development of the tool it was concluded that: i) the tool should have an order to make it easier, ii) the data should be easy to enter, iii) the companies should not have to carry out any mathematical calculations, iv) it should be simple and intuitive, v) the results should be obtained instantly, vi) it should not imply an extra effort for the companies and vii) no help from external experts should be necessary.

The following sections further detail these steps.

5.1. Calculate the level of production waste

In this phase, a company's production waste is qualitatively evaluated. The calculation is based on the eight wastes described by Verrier et al. (2016). Figure 3 shows an extract of the questionnaire to calculate overproduction waste and correction waste. Each waste type consists of four levels, and based on the organization's waste levels, it receives a score to evaluate the waste analysed. Each level has a score of 1.25. Thus, if an organization is at level two, it has a score of 2.5/5. Based on the level of each waste type and that of the organization, as determined by the questionnaire responses, overall waste can be calculated (1, 2). If a company has a level of 100%, it means that, theoretically, it does not generate any productive waste.

PRODUCTIVE WASTE							
Type	**Desciption**	**Questions by level**	**Yes**	**No**	**Comments**	**Level**	**Objective**
Overproduction	This is the worst waste as it generates all the others. Producing more than demanded (more than customers need) or producing something before it is needed.	Level 1. Is a production management system in place?	☑	☐		2,5	5
		Level 2. Is there a standardized production system in place at the plant that links customer orders with the quantities to be manufactured, with a responsible person in charge and that is carried out through an ERP?	☑	☐			
		Level 3. Is there a standardized system that measures performance indicators and controls stocks?	☐	☑			
		Level 4. Is there an advanced management system that analyzes results to improve production management focused on minimizing production batches?	☐	☑			
Correction	Hidden (non-evaluated) reprocessing of a product to meet customer needs.	Level 1. Do you have a system for the identification and management of reprocessing?	☑	☐		3,75	5
		Level 2. Are corrections tracked in an ad hoc manner?	☑	☐			
		Level 3. Is there a system for collecting data on corrections and incidents, using standardized indicators?	☑	☐			
		Level 4. Is there a system of continuous improvement for the elimination of corrections?	☐	☑			

Figure 3. Extract of the questionnaire to calculate overproduction waste and correction waste.

$$Type=\sum\nolimits_{i=0}^{4} level_{(level=1.25)} \tag{1}$$

$$Waste=\frac{Level\ average}{5}\cdot 100 \tag{2}$$

5.2. Calculate the level of production efficiency

To obtain its production efficiency, a company must first determine the machine to be analysed. Then, it must collect information that reflects that machine's useful operating time. Accordingly, it is necessary to know the machine's calendar, loading time, operating time and net operating time (Durán et al., 2018). Once these times are obtained, the availability, throughput, quality rate and performance efficiency are calculated (Durán et al., 2018). If the company wants to calculate the efficiency of a production line, it must obtain the efficiency of each machine on that line and average the values. From there, if the company wants to obtain its complete organizational production efficiency, it must average the values of all its production lines.

5.3. Calculate the level of eco-efficiency

To obtain the level of production eco-efficiency, the company must determine the production system to be considered. As such, it needs to perform an inventory analysis that considers the inputs and outputs of the production system and the number of good parts manufactured per year. Once the inventory aspects have been identified, it is necessary to specify each consumption by defining a measurement system. Next, using the equations shown in Table 2, the utilization rates of the resources used are calculated. Once the utilization rates are available, production eco-efficiency is calculated at last, which involves averaging the equations' results.

Table 2. Equations to obtain eco-efficiency.

Items	Equations	Items	Equations
Materials (%)	$\frac{\text{Raw material-Raw material waste}}{\text{Raw material}}$	Water Output (%)	$\frac{\text{Water consumption}}{\text{Good manufactured parts per year}}$
Energy Input (%)	$\frac{\text{Energy consumption}}{\text{Good manufactured parts per year}}$	Air Emissions (%)	$\frac{\text{Consumption}}{\text{Good manufactured parts per year}}$
Energy Output (%)	$\frac{\text{Energy consumption}}{\text{Good manufactured parts per year}}$	Toxic Waste (%)	$\frac{\text{Consumption}}{\text{Good manufactured parts per year}}$
Water Input (%)	$\frac{\text{Water consumption}}{\text{Good manufactured parts per year}}$	Non-toxic Waste (%)	$\frac{\text{Consumption}}{\text{Good manufactured parts per year}}$

5.4. Calculate the level of IE

Based on the results obtained in the three previous sections, the company's level of IE is calculated with (3).

$$\text{IE}(\%)=\text{Waste}\times\text{Productive Efficiency}\times\text{Eco-efficiency} \quad (3)$$

5.5. Opportunities for improvement

Once its eco-productivity value is available, the organization must define an action plan to systematically improve it. To do this, the company sets improvement targets. These can be obtained from analyses of the eight types of waste and the six big losses (see Figure 1), and the eco-efficiency qualitative analysis.

6. Design, methodology and approach

The present work's methodology is based on case study research (Yin, 2013) as a variant of action research, which is particularly appropriate for the development of theories oriented to explain how and why organizations operate (Coughlan & Coghlan, 2002). For the case study itself, the present investigation adapted Blume's (2020) proposed process to create the following phases:

1. Modelling: Objectives, case definition and data acquisition.
2. IE modelling.
3. Identification, evaluation and selection of opportunities and improvement projects.

7. IE case study in SME

Forjas S.L. is a Gipuzkoa SME with 18 workers that supplies parts to the automotive auxiliary, food and pharmaceutical sectors. The company produces 600,000 bolts per year through a process of cutting, stamping and turning. To evaluate its eco-productivity, the company's production manager assesses production waste, production efficiency and eco-efficiency. In this case study, the production manager first decided to analyse the production efficiency of a stamping machine. Then, in collaboration with the researchers, he proposed some improvements to Forjas S.L.'s IE.

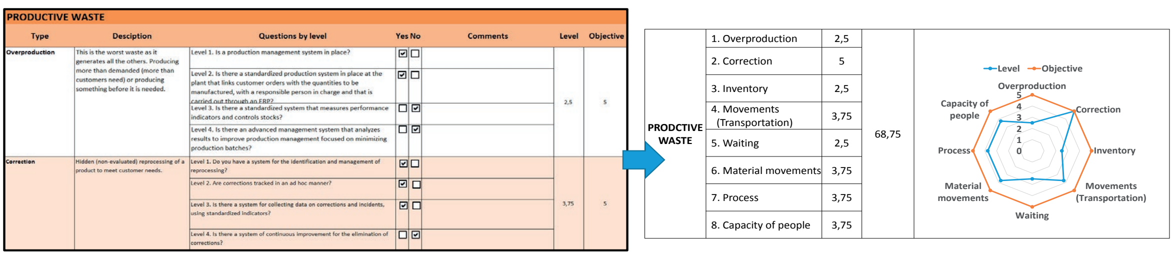
7.1. Level of production waste

To determine the company's productive waste, as shown in Figure 4, the production manager evaluated the levels of each production waste type using the evaluation questionnaire. After applying (1, 2), the organization's overall waste was 68.75%. The aspects to improve were identified as overproduction, waiting and inventories.

7.2. Production efficiency

To determine the percentage of availability, throughput, quality rate and the performance efficiency, the production manager next evaluated the collected waste information to calculate the chosen machine's useful operating time (Figure 5).

The calculated availability was thus 73.56%, the performance efficiency was 100%, the quality rate was 95% and the production system's efficiency was 69.88%. The areas to improve were related to increased availability by reducing changeover time and less breakdowns by reinforcing the facilities' maintenance management.



Productive waste questionnaire

Productive waste level

Figure 4. Evaluation of productive waste level.

Calendar Time (h)	4000,00		
Charging time (h)	3970,83	29,17	Scheduled stops
Operating time (h)	2920,83	3520,83	Changeovers (and waiting)
Net operating time (h)	2920,83	0,00	Micro-stops Speed losses
Useful operating time (h)	2774,79	146,04	Quality losses Start-up losses

Availability (%)	73,56	69,88
Performance Efficiency (%)	100	
Quality rate (%)	95	

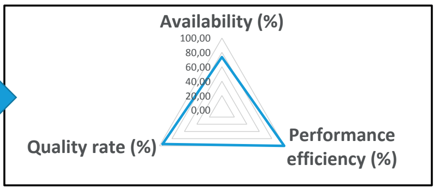


Figure 5. Evaluation of production efficiency levels.

7.3. Eco-effiency

As shown in Figure 6 to obtain the eco-efficiency results, the production manager identified the necessary information of the items shown in Table 2 and completed an inventory of natural resource use and emissions. As a result, the company's production eco-efficiency was 89.1%. The identified areas for improvement were related to reduced energy consumption.

ECO-EFFICIENCY (use per production unit)- ENVIRONMENTAL					
TYPE OF ASPECTS	ASPECTS	DESCRIPCTION	UNITS OF MEASUREMENT OF THE INDICATOR	QUANTITY	PIECES YEAR
MATERIALS	Raw Materials	Natural resources used for conversion into products or services, such as minerals, timber, etc.	tn/year	512	
	Auxiliary Materials	Materials needed for the manufacturing process but not part of the final product, such as lubricants for machinery	tn/year	0,000	
	Hydraulic oil		tn/year	0,50	
	Cutting oil		tn/year	0,00	
	Coolant Oils		tn/year	0,00	
	Tools		tn/year	0,00	
	Acids		tn/year	0,00	
	Gases		tn/year	0,00	
	Others		tn/year	0,00	
	Packaging	Materials used for packing and packaging	tn/year	0,00	
ENERGY inputs	Gas		m3 -> Kg CO2	0,00	
	Electricity		kw/h(year) -> Kg CO2	65.000,00	
	Fossil fuels (diesel)		l/year -> Kg CO2	0,00	
ENERGy outputs	Hot water		m3/year	0,00	
	Own generation		kw/year	0,00	

Materials (%)	98,33	89,10
Energy (%)	48,33	
Water (%)	99,68	
Air emissions (%)	100,00	
Waste (%)	100,00	

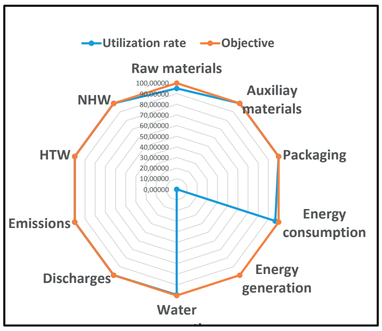


Figure 6. Evaluation of eco-efficiency level.

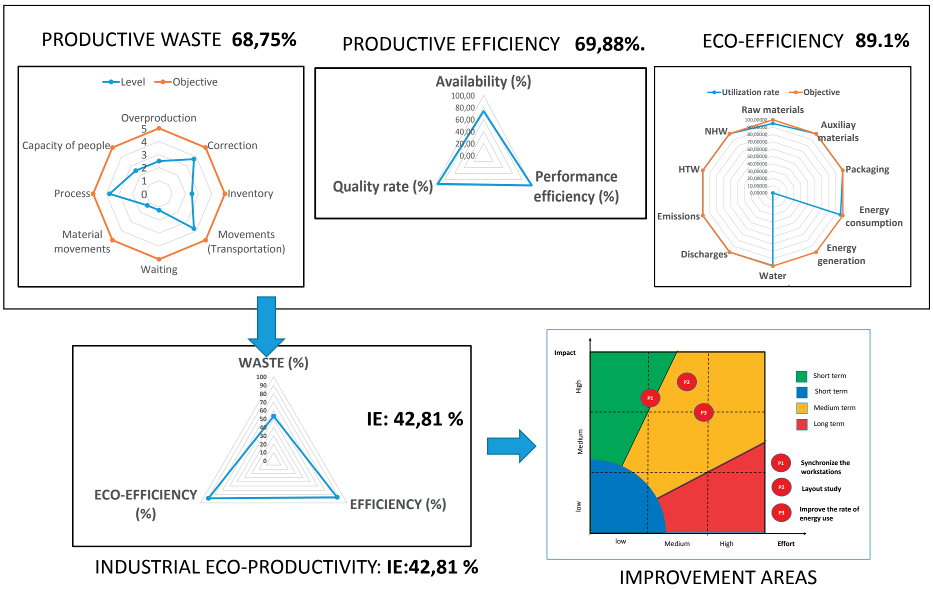


Figure 7. Industrial eco-productivity operator panel.

7.4. IE level

As shown in Figure 7 and based on the results from (3) obtained using the levels of production waste, productive efficiency and eco-efficiency, the company's IE was 42.81%. In view of these results, and as shown in Figure 7, the company identified the following projects for improvement. Each has a different time horizon based on the effort required and their individual impact.

7.5. Opportunities for improvements

For improvements of the company, following was proposed: i) synchronize the workstations, to improve waiting time, overproduction, and inventories, ii) SMED usage, to improve facility availability by reducing changeover time, and iii) preventive maintenances, to reduce breakdowns.

8. Conclusions

It is concluded that the IE tool allows companies to analyze their current situation, consequently propose improvements and thus bringing SMEs closer to working on CE and improving environmentally, as they can apply the measure easily and individually without the need for experts or specific tools.

The feedback obtained from the companies has been positive. They have emphasized the ease of use of the tool, the short time it has taken them to obtain the results. In addition, they have emphasized that since the tool is clear, intuitive and designed in such a way that everything has a logical order, have not required expert assistance.

One of the relevant aspects of this tool that helps to differentiate it from the rest is the possibility of using it without the help of experts and obtaining an immediate result with improvements to apply in the company. This means that companies do not have to dedicate extra resources and time to this application.

Likewise, mention that the results obtained allow companies to calculate aspects such as their carbon footprint and circularity indicators. IE is implemented in the CircularTRANS project.

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