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Greenhouse gas Emissions Deployment (GED): A novel Lean method for mitigating greenhouse gas emissions in industrial environment

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ABSTRACT

This paper presents a novel methodology specifically developed for measuring and reducing Greenhouse gas (GHG) emissions in production systems and logistics, named Greenhouse gas Emissions Deployment (GED). Thanks to its step-by-step procedure, it enables industries to systematically identify GHG emissions caused by organizational losses, ineffective usage losses, and design losses that need to be tracked and removed in order to operate in the most efficient and environmentally sustainable way. By customizing the Manufacturing Cost Deployment structured use of matrices, GED can detect losses, evaluate cause-effect relations, and support improvement prioritization. First, the losses affecting emissions are identified and their relationship is analysed to identify the underlying causes. Each causal loss is then evaluated according to the total amount of emissions it generates, which are also converted into appropriate economic terms. Finally, to select the correct improvement actions, a cost/benefit analysis is performed based on technical and economic factors that include both cash flows and the marketing impact on the end customer due to the commitment to sustainability. The proposed approach was applied to a major company operating in the plywood production sector in order to demonstrate its validity and effectiveness in production systems.

1. Introduction

In December 2015, representatives from the member countries of the United Nations Framework Convention on Climate Change (UNFCCC) convened in Paris for the 21st Conference of the Parties (COP21). This historic Paris conference culminated in the world's very first legally binding global climate accord. This significant agreement, which came into force in 2020, established an ambitious target to limit the increase in global temperatures to below 2 degrees Celsius, and preferably to keep it to within 1.5 degrees Celsius compared to pre-industrial levels. Achieving this goal is a long-term objective. Despite the mounting recognition of the urgency surrounding climate action, integrating the principles of the Paris Agreement within various organizations (Intergovernmental Panel on Climate Change (IPCC), 2023a) remains challenging. As of 2019, approximately 23 % (equivalent to 13.6 Gt CO_2-e) of the world's cumulative net anthropogenic Greenhouse gas (GHG) emissions were attributed to the energy supply sector, with industry accounting for 24 % (14 Gt CO_2-e), agriculture, forestry, and other land use contributing 22 % (13 Gt CO_2-e), transportation making up 15 % (8.7 Gt CO_2-e), and buildings representing 6 % (3.3 Gt CO_2-e) (Intergovernmental Panel On Climate Change (Ipcc), 2023b). If emissions related to electricity and heat production are attributed to the end-use sectors, a staggering 90 % of these emissions are allocated to the industrial and building sectors. This reallocation significantly elevates their relative contributions to GHG emissions, increasing industry's share from 24 % to 34 % and buildings' share from 6 % to 16 % (Intergovernmental Panel On Climate Change (Ipcc), 2023a).

To achieve the goal of the agreement, industries should drastically reduce their current emissions. Although the topic has been studied and is currently part of an important research strand, the scientific literature highlights the need for operational methods and tools that can assess and help mitigate emissions for industrial companies (de Sousa Jabbour et al., 2019; Er Kara et al., 2021).

Embracing sustainability entails the effective long-term management of processes and resources. Irrespective of their specific industry, all companies share a common goal: reducing costs and maximizing profits. However, it is worth noting that many managers still view the

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Nomenclature

Variable	
C	Cost factor
CP	Cost Permits price
CO_{2-e}	Equivalent Carbon Dioxide
DE	Direct Emission
E	Total Emissions
Ea	Easiness factor
Ef	Efficacy factor
$F(t)$	Operational cash flow at year t
GHG	Greenhouse gas
GPN	Greenhouse emissions Priority Number
GWP	Global Warming Potential
IE	Indirect Emission
ImE	Improvement implementation Emissions
NPV	Net Present Value
Sa	Improvement implementation cash flow
T	Investment lifetime
TEC	Total Emission Cost
α	Appealing factor
β	Interest rate

minimization of environmental impacts as an unfortunate necessity, driven primarily by the need to avoid legal penalties. They may not be fully aware of the compelling evidence that demonstrates how the benefits of sustainability far outweigh the associated costs. Consequently, some managers are still reluctant to adopt proactive environmental measures. In reality, given that emissions are closely linked to energy consumption, raw material usage, and waste disposal, focusing on carbon management and its reduction offers a substantial opportunity. This approach not only helps in curbing emissions but also simultaneously trims operational expenses.

In this context, numerous studies have highlighted the significance of Lean manufacturing as a key component of enhancing environmental performance (Cherrafi et al., 2017; Manikas et al., 2021). Lean manufacturing is a widely acknowledged approach employed by manufacturing organizations to achieve optimal productivity and quality. It encompasses a range of standardized tools and methods that are consistently employed to identify and eliminate waste.

In recent years, there has been a growing body of research focused on quantitative approaches in relation to both Lean manufacturing and sustainability. For example, a value-load diagram was proposed by Thanki and Thakkar (2016) in order to evaluate the operations and the impact on the environment of manufacturing systems. Fercoq et al. (2016) conducted a quantitative analysis of the incorporation of lean and green principles with a specific emphasis on the implementation of waste reduction methods in manufacturing procedures. Additionally, Lim et al. (2022) introduced an innovative methodology for seamlessly incorporating green-lean practices with the principles of the circular economy. The latter study underscores the effectiveness of integrating circular economy strategies into the optimization of production operations.

What is clear from these studies is that process optimization is key in the mitigation of emissions. Thanks to its logic and schematic framework, Lean Manufacturing can offer companies tools and methods aimed at identifying losses that cause GHG emissions. By reducing the energy demand and material waste, companies can cut costs, increase efficiency, and reduce their GHG emissions. Lean Manufacturing thus provides a win-win situation for ecological improvement and economic development (Inman and Green, 2018). By collecting data from over 180 industrial plants in the U.S, the latter authors found that Lean Manufacturing practices were positively associated with environmental and operational performance. Hao et al. (2021) demonstrated that the complementarity of servitization and lean bundles significantly enhance sustainable performance. Bai et al. (2019) developed a multi-criteria decision-making model to incorporate environmental aspects as decision factors for lean implementation in order to better exploit their synergy.

Between lean tools and methods, Manufacturing Cost Deployment (MCD) is a systematic method based on a specific implementation which enables the development of a cost-reduction program (Yamashina and Kubo, 2002). The implementation of MCD offers numerous benefits: (i) it presents all production process inefficiencies in a clear and structured manner, (ii) it focuses on identifying the main areas where inefficiencies exist and can be rectified, thereby improving efficiency and effectiveness, and (iii) it facilitates the identification and execution of specific enhancements to eliminate the root causes of these losses.

In this paper, a new lean method named Greenhouse gas Emissions Deployment (GED) is introduced. Similarly to the MCD, the GED method follows a five-step procedure, and each step is accompanied by a dedicated matrix:

- identification of GHG emissions due to losses
- classification into causal and resultant losses
- quantification of the emissions associated with the losses
- definition and evaluation of the improvement actions
- selection of the best improvement projects thanks to cost/benefit analysis.

MCD and GED follow the same path with operational and simple implementation. However, MCD cannot directly address the identification and mitigation of emissions, as it was created to detect production losses in serial production environments. It therefore needs to be appropriately modified to develop a more suitable method for identifying, quantifying and reducing GHG emissions. GED is thus conceived as an innovative version of the MCD for the GHG mitigation of factory emissions.

GED also employs a distinct decision-making approach for the selection of improvement projects, moving beyond a simple cost/benefit analysis. In identifying projects that generate the greatest advantages, measured in terms of positive cash flows, while also effectively managing the total investment costs, GED also considers relevant "marketing" factors. Companies that express interest in adopting sustainable practices stand to gain numerous advantages (Carvalho et al., 2017). These benefits include the potential to command higher prices for environmentally conscious products, an enhanced corporate image, the opening up of new market opportunities, and a competitive edge. Consequently, the GED method enables the implementation of interventions, even in cases where direct financial returns are not the sole driving factor.

The paper is organized as follows. Section 2 highlights the research perspectives and the novel contribution of the paper. Section 3 then presents a new loss classification and describes the GED method in detail. The method is applied in a company that produces plywood. The results of the industrial application are reported in Section 4, while the conclusions and future remarks are reported in Section 5.

2. Literature Review

This theoretical section is divided into three parts. In the first subsection, we discuss studies and results related to GHG mitigation in order to analyze which measures have achieved the most significant improvements. In the second, we show different applications of MCD in different contexts. Finally, in the last subsection, we highlight the research gaps to be addressed in this work.

2.1. Greenhouse Gas Mitigation Measures

Several useful reviews on GHG mitigation can be found in the literature (Gerres et al., 2019; Zhang et al., 2021). Reviewing a large number of studies, Lewandowski and Ullrich (2023) classified measures according to their frequency of implementation and effective mitigation. In their overview, they reported that energy and process efficiency was the most frequently applied measure. However, they do not provide specific tools for achieving this goal. Seeking strategies for the steel sector, Axelson et al. (2021) reviewed the literature on industrial decarbonization. They found that improving process efficiency and reducing virgin material requirements play a significant role in reducing carbon emissions. Also, according to Wei et al. (2022), improving process efficiency plays a crucial role in carbon emission mitigation. They highlighted the need for standardized planning, organization, progress, and technical management together with risk management tools to reduce GHG emissions. Korczak et al. (2022) investigated what decarbonization measures have been applied in the non-metallic minerals sector. They found that carbon capture, use and storage (CCUS) are considered the most promising decarbonization measures for industry. Unfortunately, they pinpointed that more research is needed for full-scale implementation.

Carbon management is one approach that addresses GHG emissions of industrial companies (Zhou, 2020). This encompasses a diverse set of tactics that enable companies to reduce their documented CO_2 emissions. These tactics include enhancing energy efficiency, substituting low-carbon fuels, using renewable energy certificates, conducting Life Cycle Assessments (LCA), and implementing innovative technologies such as carbon capture, also referred to as direct air capture. Although this approach can mitigate GHG emissions, it is not a method of process optimization. For instance, carbon management cannot identify those processes that are carried out incorrectly and thus consume more materials than necessary. Simply replacing fossil fuels with low-carbon ones enables companies to reduce emissions, but completely misses the opportunity for further mitigation through reduced fuel consumption, which could also lead to economic savings.

Lean Manufacturing offers a suite of tools aimed at mitigating the environmental footprint of industrial operations. Ng et al. (2015) introduced a lean metric tailored at gauging the impact of lean implementation on carbon emissions. This metric seeks to establish a clear linkage between production activities and their associated carbon footprint. Adhering to lean principles, the authors categorized activities into two distinct groups based on their contribution to the carbon emissions of the final product. Activities adding value, such as physical transformation, were associated with value-added carbon, whereas those that did not add value, such as transportation, were linked to non-value-added carbon. The objective is to demonstrate the positive environmental outcomes resulting from the adoption of lean practices.

While the Carbon-Value Efficiency metric is a robust tool for integrating lean and green initiatives, it falls short in pinpointing and addressing industrial inefficiencies leading to GHG emissions. Moreover, its reliance on a traditional loss classification may be inadequate.

Faulkner and Badurdeen (2014) innovatively applied Value Stream Mapping (VSM) to assess environmental and societal impacts within industrial settings. They introduced a methodology termed Sustainable VSM, which integrates environmental and social metrics into the conventional analysis framework. However, given its foundation in VSM, this approach has inherent limitations, such as the difficulty in accurately representing complex processes and the inability to comprehensively capture interactions among multiple value streams. Additionally, Sustainable VSM falls short in providing a tailored loss classification system aimed at effectively reducing GHG emissions, which is crucial in achieving sustainability goals.

Domingo and Aguado (2015) introduced an innovative lean metric known as Overall Environmental Equipment Effectiveness (OEEE), which merges the principles of Overall Equipment Effectiveness (OEE) with sustainability considerations. By augmenting traditional equipment use parameters (availability, quality, and performance) with a sustainability factor, they aimed to assess the environmental impacts associated with industrial products. This metric serves as a valuable tool for evaluating performance while also taking environmental factors into account. However, it adheres to the conventional OEE loss structure, potentially overlooking specific opportunities for improvement tailored to environmental sustainability objectives.

2.2. Adaptation of Manufacturing Cost Deployment

MCD is one of the fundamental pillars of World Class Manufacturing Its application in a serial production environment can bring several advantages, including the immediate visualization of inefficiencies where they occur and the selection of the most suitable solutions in an economic and quantitative manner (Carlos et al., 2013).

As a result of the aforementioned advantages, this approach has been implemented in production settings other than the automotive industry, where it was originally developed. Bertolini et al. (2022) introduced Project Time Deployment for identifying crucial losses in an Engineer-to-Order (ETO) project. Braglia et al. (2019) examined a customized tool derived from the MCD approach to address inefficiencies in manual assembly tasks within ETO projects. Braglia et al. (2020b) created Energy Cost Deployment (ECD) by modifying MCD with an 'energy diagnosis' approach to detect energy wastage in a manufacturing process. However, ECD can only assess energy losses and does not take energy related GHG emissions into account. Another interesting adaptation of MCD concerns material losses in the production process Braglia et al. (2021). As with ECD, this only deals with material consumption and does not provide material related GHG emissions. Although the combined application of these two methods could lead to a reduction in emissions, it is important to note that several problems remain. First, a new and specific decomposition of industrial losses is needed to correctly identify which and where losses occur. Next, the combination itself is quite tricky. In fact, implementing measures to reduce material consumption could lead to increased energy consumption and vice versa. Finally, there is a shortage of ways to quantify economic losses due to GHG emissions. In the light of these considerations, we conclude that a new adaptation of the MCD from a GHG perspective presents an important opportunity to simultaneously reduce emissions and save costs.

2.3. Research Gaps

The following issues thus arise from the analysis of the literature:

- Industries have a plethora of measures to reduce their GHG emissions. Of these, increasing process efficiency is one of the most effective measures. However, there is a lack of management tools and methods that are able to successfully support the implementation of GHG reduction programs which consistently identify where and how to act without wasting the already limited resources available.
- While Lean Manufacturing methodologies have been extensively employed to improve the environmental performance of industrial processes, a notable research gap remains in the development of a customized lean approach specifically aimed at identifying and addressing industrial losses responsible for GHG emissions. Existing lean methods have primarily focused on enhancing overall operational efficiency and reducing waste, but a dedicated framework tailored to pinpointing and mitigating GHG emissions-related losses is currently lacking.
- MCD has been extensively developed in different contexts to meet different challenges, demonstrating its operability and effectiveness. To the best of our knowledge, no adjustments/changes have been

made to the MCD with regard to the assessment of GHG emissions from industrial losses and their mitigation.

Based on these considerations, we present a new lean method called GED which is specifically designed to address the environmental challenges that Climate Change has placed on production systems. GED enables companies to systematically identify industrial losses that cause GHG emissions and eliminate them in the most efficient and ecologically sustainable way. The most striking feature, which distinguishes the method, is its ability to economically evaluate all emissions attributable directly and indirectly to the plant, also considering Scope 3 emissions (World Business Council for Sustainable Development and World Resources Institute, 2004). The evaluation of Scope 3 emissions enables companies to highlight the most significant prospect for reducing GHG emissions. As a result, it empowers them to make more environmentally conscious decisions regarding their operations and the procurement, production, and sale of products. Further details on this topic can be found in Section 3.

3. Methods

As shown in the previous sections, the GED is a novel lean method based on the MCD structure but specifically oriented towards GHG mitigation. More generally, as with other lean tools and traditional methods, it identifies and removes no-value added activities which according to Lean Manufacturing principles, are referred to as Muda. This refers to any activity that consumes resources but adds no value to the costumer. Traditionally, there are seven types of Muda: overproduction, waiting, transportation, overprocessing, inventory, unnecessary movement and defects (Ohno, 1988). The final goal of Lean Manufacturing is to eliminate such activities that do not directly contribute to what the customer considers as valuable in the final product. By doing so, a company can achieve greater efficiency, reduce costs and enhance overall production flow.

Examples of lean tools that are usually implemented first are OEE (Nakajima, 1988) and VSM (Rother, 1999). OEE is a key lean metric used to understand, measure, and improve current performance. It was originally developed for machine use assessment from a maintenance perspective. Later, its logical framework was extended to measure effectiveness in labour (Braglia et al., 2020a), materials (Braglia et al., 2018), energy (May et al., 2015), and space use (Braglia et al., 2024). VSM is a comprehensive analysis and visualization tool used to illustrate the main processes and their operations, together with the lead times, buffers, and information flows. VSM provides a clear distinction between value adding and non-value adding activities in time units. As with OEE, VSM has been extended to evaluate environmental impact and social well-being (Garza-Reyes et al., 2018) and energy efficiency aspects (Cosgrove et al., 2018).

The power of GED lies in its two key features: a structured, step-by-step approach and a novel classification system for industrial losses. This combination aligns perfectly with Lean Manufacturing's core principle of waste elimination, ensuring the targeted removal of losses that directly generate GHG emissions.

3.1. *Definition of System Boundaries and Classification of Emissions Losses*

Before depicting categories and kinds of emissions losses, it is important to describe the underlying logic of the GED method. Here, the factory under investigation needs to be broken down into functional areas identifying losses that account for GHG emissions. Obviously, the number and the kind of functional areas are strictly associated with the case under investigation. In each functional area, several activities take place, each involving the use and manipulation of energy and/or materials. Consequently, each functional area is characterized by GHG emissions.

By collecting each GHG emission of each functional area, it is possible to assess the total amount of GHG Emissions, i.e., Actual Emissions of the factory (Fig. 1). According to guidelines of IPCC, the total GHG emissions produced are evaluated by summing the multiples of GHGs in their Global Warming Potential (GWP) factors, and it is measured in CO_2 equivalent (CO_{2-e}) per year:

$$CO_{2-e} = \sum_{i=1}^{n} GWP_i \bullet GHG_i \tag{1}$$

GWP is a measure of how much a given mass of GHG contributes to global warming compared to the same mass of CO_2. In this paper, according to ISO 14064 – 1(The International Organization for Standardization, 2018), seven GHGs are considered: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), nitrogen trifluoride (NF_3), perfluorocarbons (PFC_x), hydrofluorocarbons (HFC_x), and sulfur hexafluoride (SF_6). GWP is determined by two contributing factors (Zhou, 2020): radiative efficiency (i.e., heat-absorbing ability) and decay rate (i.e., the amount removed from the atmosphere over a given number of years). This paper adopts the latest GWP values reported in Intergovernmental Panel on Climate Change (IPCC) (2023a).

According to Fig. 1, the disparity between the Ideal and Actual Emissions can be attributed to various losses, which incrementally contribute to emissions while conducting activities. GED aims to eliminate/reduce emissions due to losses by pursuing process optimization. Three loss categories are delineated here, each intended to underscore the characteristics of these losses: (i) Standard Deviation Losses, (ii) Ineffective Usage Losses, and (iii) Design Losses. Standard Deviation Losses are related to erroneous planning and scheduling of activities, such as lighting areas where no tasks are carried out and heating/cooling items that should not be heated/cooled. Ineffective Usage Losses encompass erroneous performance of activities, such as damaged pipe insulation, lubricant leakage, or equipment failures. In fact, repairing failures requires the consumption of energy and materials such as welding operations, or the purchase of new items, the production of which is associated with additional emissions. Finally, Design Losses would occur even if the equipment was used correctly, as they are linked to design shortcomings. Examples are insufficient thickness of pipe insulation, excessive packaging thickness, or gears with low-performance ratings.

The remainder of emissions, called Ideal emissions, provide the objective of this lean method. It is important to emphasize that Ideal Emissions should be evaluated based on the technology available for the factory under consideration. We define Ideal Emissions as emissions associated with carrying out technologically and methodologically optimized activities, currently considering the State-of-Art. Hence, today, Ideal Emissions cannot be zero. From this viewpoint, the purpose is not to eliminate all emissions, because a certain amount of emissions will remain, but they can be progressively reduced with the introduction of future technological enhancements. For instance, the purchase of new plants capable of carbon-free operations is possible, but whenever possible in accordance with a life cycle approach, emissions related to

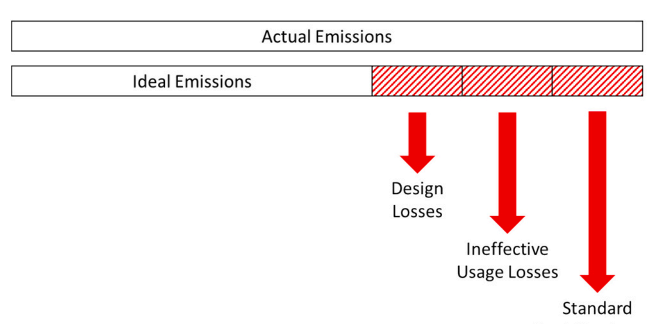

Fig. 1. Structure of emission losses.

the production, operations, and disposal of the plants themselves should be considered. Ideal Emissions also include the proportion of emissions that cannot be managed by the company, such as methane leakages that occur in external pipelines.

Table 1 shows examples of loss types that fall into each subcategory. In order to support company's reporting of emissions, each loss type is associated with the scope of the emissions that are caused by the loss itself. Specifically, GHG emissions are classified into three scopes (World Business Council for Sustainable Development and World Resources Institute, 2004).

Scope 1 emissions result directly from the activities and assets under the ownership and control of a company. In simpler terms, these emissions result from activities within the firm and are released directly into the atmosphere. Scope 1 emissions can be categorized into four main groups:

1. **Stationary Combustion:** This category encompasses all GHG emissions generated by the burning of fossil fuels. The fuels considered within this category include oil, gasoline, natural gas, liquefied petroleum gas, and propane. These emissions are often associated with heating sources and stationary machinery.
2. **Mobile Combustion:** Mobile combustion refers to GHG emissions produced by the combustion of non-biofuel fuels in vehicles owned or leased by the organization. This includes emissions from gasoline and diesel-powered cars, trucks, and vans. Fully electric vehicles and plug-in hybrids are categorized as Scope 2 emissions, which are considered as indirect emissions.
3. **Fugitive Emissions:** Fugitive emissions pertain to the unintentional leakages of GHGs, often associated with equipment such as refrigeration and air conditioning units. These emissions result from the escape of GHGs during their storage or use.

Table 1
Emission loss types.

Loss category	Loss type	Scope 1	Scope 2	Scope 3
	Missing procedure		•	
	Mistakes in production planning	•	•	•
	Missing/mistake in documentation		•	
Standard deviation losses	Erroneous process parameter	•		
	Unrequired start-up or shutdown		•	
	Unrequired heating/cooling	•		
	Unrequired use of lighting system		•	
	Leakages of fluids (fuel, vapor, oil, air, refrigerant, etc.)	•		
	Failure			•
	Scrap disposal			•
	Degradation of thermal insulation	•		
Ineffective usage losses	Rework		•	
	Inefficient use of equipment		•	
	Inefficient use of air conditioning		•	
	Performance degradation of equipment		•	
	Inefficient material handling system	•	•	
	Thickness of insulations	•		
	Unsustainable packaging			•
	Oversized lighting/air conditioning system		•	
Design losses	Low nominal equipment performance	•	•	
	Use of non-renewable energy		•	
	Inefficient lighting/air conditioning system		•	
	Fossil fuel consumption	•		

4. **Process Emissions:** Process emissions occur during industrial processes and on-site production activities. Examples include the release of CO_2 during cement manufacturing, emissions from factory operations, and the release of chemicals during various industrial processes.

Understanding and managing Scope 1 emissions is essential for companies looking to measure and mitigate their environmental impact and promote sustainability.

Scope 2 emissions stem indirectly from the production of energy purchased from an external provider. In simpler terms, these emissions encompass all GHG emissions released into the atmosphere resulting from using purchased sources of electricity, steam, heat, and cooling. For most organizations, electricity consumption is the primary and often only source of Scope 2 emissions. Scope 3 emissions cover all other indirect emissions, except for those included in Scope 2, which are linked to activities along the entire value chain of the reporting company. This includes emissions both upstream and downstream in the production and consumption process. In essence, Scope 3 emissions are connected to the activities carried out by the company but occur outside of its immediate control or ownership. Specifically, Scope 3 emissions involve the energy consumed by utilities during the transmission and distribution of electricity and extend to various other indirect emissions associated with the company's business activities. These emissions can result from a wide range of sources, including suppliers, transportation, waste management, and other components of the supply chain.

It is important to note that some kinds of loss may generate emissions that could fit in several scopes according to the specific case under analysis such as a gear with low nominal performance and mistakes in production planning (Table 1). Gears with a low nominal yield may be powered by direct fossil fuel consumption (Scope 1) or by purchased electricity (Scope 2). Alternatively, mistakes in production planning may involve energy consumption (Scope 1 or 2) and/or material consumption (Scope 3).

To assess the performance of a plant from an environmental perspective, a well-defined spatial and temporal domain needs to be defined. The determination of the spatial domain is fundamental in order to categorize emissions. For example, setting the spatial domain to coincide with the physical boundaries of the plant means counting all the emissions due to company-owned resources that are external to the plant but internal to the factory as indirect, while a physical domain coinciding with the factory means considering them as direct. Typically, the time horizon of a corporate environmental report is one year. In such cases, the report can relate to the previous year or any other specific period that the analysis team considers significant.

Current legislation requires Scopes 1 and 2 to be reported, while Scope 3 is still voluntary and the most difficult to assess. GED offers a holistic view which in accordance with lean principles aims to consistently identify and eliminate all kinds of inefficiencies. Consequently, a sustainable competitive advantage will be gained by companies that manage to report in all three areas. It is critical to stress that the traditional scope classification is not effective in tackling emissions-related losses from a practical viewpoint and thus, a more operation-oriented classification is necessary. For instance, Scope 2 emissions (electricity consumption) themselves do not provide any information on inefficiency within the factory.

3.2. *Greenhouse Gas Emissions Deployment*

GED is an operational method that focuses on identifying and evaluating GHG emissions-related losses and supporting decision-making for the implementation of GHG mitigation measures within factory boundaries. The application of GED is articulated in five sequential steps. Each step is related to a specific matrix.

3.2.1. A-Matrix: Identification of Greenhouse Gas Emissions Due to Losses

The first step of the GED method involves building the A-Matrix (Fig. 2). This matrix classifies losses by highlighting where they are located within the factory. Loss types are shown in the rows, while the functional areas are shown in the columns. To better understand the emissions involved, losses are grouped according to the emissions they cause (Scope 1,2, and 3). In order to create the matrix, a thorough investigation and census of all company activities needs to be carried out. This survey should be carried out by a team, which in accordance with the principles of lean thinking, includes people with various backgrounds (environmental sustainability, design, production, maintenance, etc.)

The presence of a loss is indicated in the corresponding cell in the A-Matrix. To provide an initial qualitative assessment of the significance of the loss, a three-color system can be employed: red signifies a highly significant loss, yellow indicates a significant loss, and green represents a minimal loss. Each identified loss should be investigated to document its potential impact on the total amount of GHG emissions, however this qualitative classification provides an initial priority order of which losses should be addressed first. Red losses are tackled first then, according to Lean Manufacturing principles, the other coloured losses are subsequently addressed with the final aim of eliminating them all. Due to the versatility of the method, the analyst has the flexibility of using a different qualitative ranking system with a greater variety of coloured classes and can also modify the number of classes without affecting the effectiveness.

3.2.2. B-Matrix: Classification into Causal and Resultant Losses

GED also clarifies the cause-effect relation, which in this section is illustrated in the B-Matrix (Fig. 3). In fact, a loss that occurs in one

Loss category	Scope	Loss type	Functional Area 1	…	Functional Area s	…	Functional Area S
Standard Deviation Losses	Scope 1	Loss i					
		Loss i+1					
		…					
		Loss I					
	Scope 2	Loss j					
		Loss j+1					
		…					
		Loss J					
	Scope 3	Loss k					
		Loss k+1					
		…					
		Loss K					
Ineffective Usage Losses	Scope 1	Loss l					
		Loss l+1					
		…					
		Loss L					
	Scope 2	Loss m					
		Loss m+1					
		…					
		Loss M					
	Scope 3	Loss n					
		Loss n+1					
		…					
		Loss N					
Design Losses	Scope 1	Loss p					
		Loss p+1					
		…					
		Loss P					
	Scope 2	Loss q					
		Loss q+1					
		…					
		Loss Q					
	Scope 3	Loss r					
		Loss r+1					
		…					
		Loss R					

Fig. 2. The A-Matrix.

			Resultant losses											
			Loss r_1						Loss r_k					
		Where	Functional Area 1	…	Functional Area s	…	Functional Area S	…	Functional Area 1	…	Functional Area s	…	Functional Area S	…
Causal losses	Loss c_1	Functional Area 1	●						●					
		…												
		Functional Area s												
		…												
		Functional Area S												
	…													
	Loss c_h	Functional Area 1			●									
		…												
		Functional Area s	●								●			
		…												
		Functional Area S												
	…													

Fig. 3. The B-Matrix.

functional area can lead to other losses in the same area or elsewhere. For instance, an incorrect setting of a process parameter (causal loss) can generate emissions in one place and then affect another process which consequently produces parts that must be reworked (resultant loss), adding further emissions. In this case, a loss is defined as *resultant* if it is caused by one or more losses, otherwise it is *causal*. For an effective plan to reduce emissions, companies should not overlook the cause-effect relationship. In fact, to be effective in accordance with lean thinking (Cocca et al., 2019; Ramesh and Kodali, 2012), a loss reduction program should address causal losses. Action on resultant losses is also an option, but this would be a temporary solution that mitigates emissions locally and for a limited period. The only way to permanently eliminate resultant losses is to directly address the underlying causal losses.

It is important to highlight that a resulting loss, stemming from a causal loss in a specific functional area, can trigger another loss either within the same area or in different areas. For instance, a steam spill resulting from a poorly fixed flange might lead to the wetting of thermal insulation on an adjacent pipeline, leading to a decrease in the temperature of the process fluid. Consequently, this could then result in the production of out-of-standard products. This chain of losses, in turn, contributes to emissions due to increased energy consumption for steam generation, replacement of insulation, and the production of non-compliant products (involving all three Scopes). Analysing such loss chains requires investigating the root cause and accounting for all the related emissions, as in simpler cases.

After the A-Matrix has identified losses and their respective functional areas in the factory, the B-Matrix assigns causal losses and their positions in the rows. The columns on the other hand show resultant losses and their corresponding locations. It is important to stress the cause-effect relation because by identifying losses, the company can then effectively manage those whose effects exist in multiple functional areas. A non-empty cell indicates which resultant loss originates from which causal loss and the specific functional areas in which they occur. Note that a single causal loss may be related to multiple resulting losses, and that a resultant loss in a given location can be a causal loss in another location and hence, this loss can appear in both rows and columns.

3.2.3. C-Matrix: Quantification of Emissions Associated with the Chain of Losses

By using matrices A and B, it is possible to visualize what the losses are and where they occur, thus highlighting the cause-effect relation. The next step consists of quantifying the emissions of all the resultant-causal loss chain. The C-Matrix (Fig. 4) converts the losses into the associated amount of GHG emissions. The rows report the causal losses and where they occur, while the columns report the resultant losses and where they were observed.

The corresponding amount of GHG emissions is reported for each combination of causal-resultant loss in the C-Matrix. For each causal loss, two different emissions are evaluated: the emissions generated where that loss is caused by the loss itself (i.e., column “direct emission”), and the total amount of emissions caused elsewhere (i.e., “indirect emission”). The total emissions associated with the whole resultant-causal loss chain are the sum of the two contributions.

In the C-Matrix, $DE_{c_1}^{(1)}$ refers to the direct emissions occurring in functional area *1* due to the causal loss c_1 itself. The notation $IE_{c_1,r_k}^{(1,s)}$ is used to refer to indirect emissions in the functional area *s* that are caused by the resultant loss r_k due to causal loss c_1, which occurs in functional area *1*. The total amount of emissions related to the losses chain caused by causal loss c_1 occurring in functional area *1* is given by the sum of direct and indirect emissions due to causal loss c_1 as follows:

$$E_{c_1}^{(1)} = DE_{c_1}^{(1)} + \sum_{i,j} IE_{c_1,r_j}^{(1,i)} \tag{2}$$

Finally, the last column of the C-Matrix, also provides an economic quantification of the total amount of the emissions chain by multiplying the total emissions by the European Union (EU) Carbon Permits (CP) according to the Cap-and-Trade system (Aldy and Stavins, 2011) that EU nations apply to price carbon emissions. Specifically, the total emission cost related to the loss chain caused by causal loss c_1 occurring in functional area *1* is obtained as follows:

$$TEC_{c_1}^{(1)} = \left(DE_{c_1}^{(1)} + \sum_{i,j} IE_{c_1,r_j}^{(1,i)} \right) \bullet CP \tag{3}$$

The Cap-and-Trade system is a widely adopted market-based approach used worldwide. It involves establishing an annual limit (Cap) on the total GHG emissions allowable, and companies have the option to buy emission allowances from the market (Trade) to comply with these emission standards. This cap is reduced each year. Companies are required to submit sufficient allowances to offset all their emissions, otherwise they will incur substantial fines. Approximately 43 % of allowances are given for free and the rest is auctioned. Virtuous companies that remain within their free emissions allowances can sell the difference

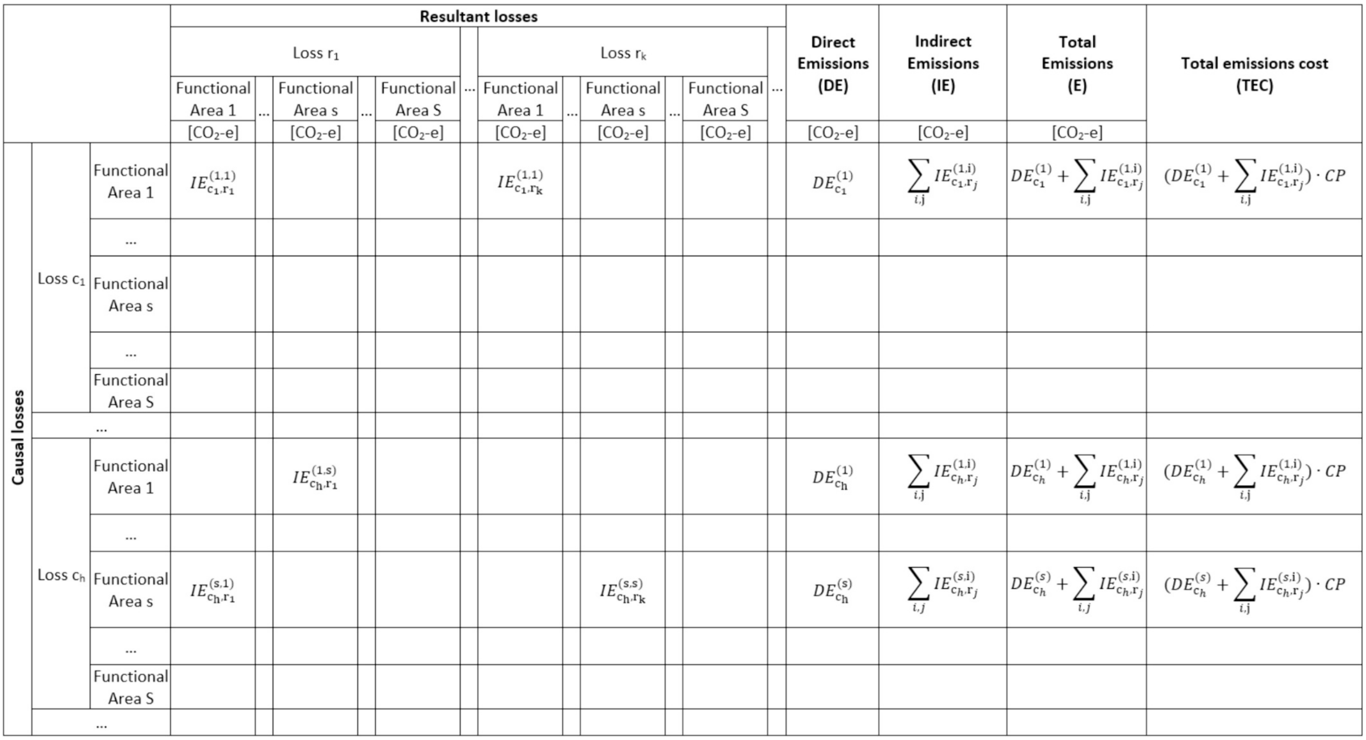

Fig. 4. The C-Matrix.

on the market, while other companies that exceed their free allowances need to purchase them on the market.

The cap-and-trade system is obliged to cover emissions from Scope 1 and 2. However, the new approach presented in this paper aims, whenever possible, to economically evaluate all emissions attributable directly and indirectly to the factory, and therefore Scope 3 emissions are also considered.

3.2.4. D-Matrix: Definition and Evaluation of Improvement Techniques

After quantifying loss chains in terms of emissions produced and their associated costs using the C-Matrix, appropriate improvement techniques need to be selected and put into practice. The particular benefit of GED is that the method supports the decision-making process. The D-Matrix is built for this purpose (Fig. 5). Causal losses are reported in the rows, while the columns show potential improvement techniques. Depending on the specific case at hand, it is possible to widen or narrow the set of corrective actions described here. We have identified two kinds of improvement techniques: Engineering techniques that involve the redesign of plants; *ii*) Management techniques which include plant management modifications such as the implementation of lean management tools.

The first step in dealing with a loss is to determine the corrective action, while the second step is to determine which are the most suitable tools to used (see 3.5). The D-matrix plays a crucial role in guiding the decision-making process by identifying the most suitable set of techniques for addressing each specific causal loss. This set is then used to

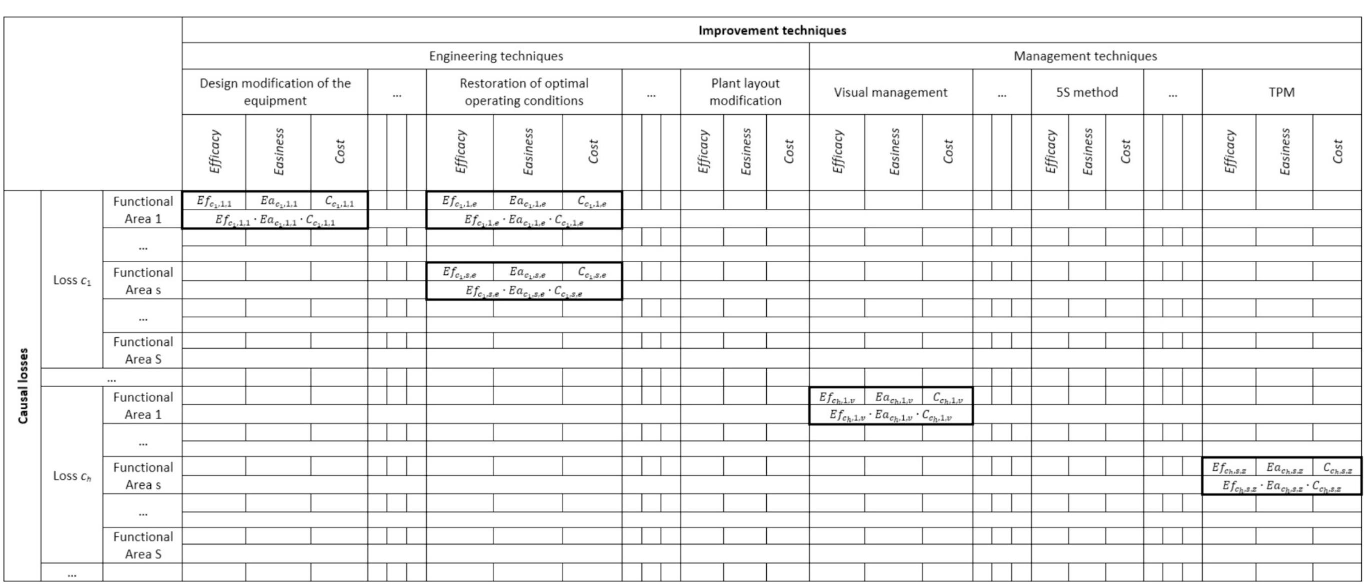

Fig. 5. The D-Matrix.

inform the next step in determining how to tackle a particular loss with the corresponding technique. Since economic resources and time are usually in short demand, simplifying, and speeding up the selection process is very beneficial and prevents time waste or downtimes.

The Greenhouse gas emissions Priority Number (GPN) has been designed for this purpose. It simplifies the decision process via three parameters: efficacy, easiness, and cost of the improvement technique. Efficacy (*Ef*) addresses the ability to reduction emissions that the action can achieve. Easiness (*Ea*) concerns the action in terms of time and personal resources. Cost (*C*) represents the economic effort required for implementing the action.

For each causal loss, team members score these criteria on a scale of 1 to 5 to for each improvement technique. The closer the parameter score is to 5, the greater the suitability of the technique according to the parameter. GPN is the product of these three scores. It provides a qualitative assessment of how well an improvement technique can reduce or address a particular causal loss. When dealing with a causal loss (c_h) that occurs within a specific functional area (s) and applying a relevant improvement method (d), the corresponding metric $GPN_{c_h,s,d}$ is:

$$GPN_{c_h,s,d} = Ef_{c_h,s,d} \times Ea_{c_h,s,d} \times C_{c_h,s,d} \tag{4}$$

where,• The Efficacy factor ($Ef_{c_h,s,d}$) quantifies the effectiveness of improvement technique d in reducing the causal loss c_h within the functional area s. An efficacy factor of Ef = 1 indicates a low impact, while an efficacy factor of Ef = 5 signifies a high impact. In other words, it measures how well the improvement technique can mitigate or address the specific causal loss, with higher values indicating a more significant impact.• The Easiness factor ($Ea_{c_h,s,d}$) quantifies the simplicity of implementing improvement technique d in terms of the required resources and time required to reduce or eliminate the causal loss c_h in the functional area s. An easiness of 1 indicates low ease. Whereas an easiness equal to 5 indicates high easiness. In other words, it measures how easy or straightforward it is to apply the improvement technique to address the specific causal loss, considering the resources and time needed for the implementation. A higher easiness factor suggests that the technique is relatively simple and efficient to put into practice.• The Cost factor ($C_{c_h,s,d}$) quantifies the economic burden or expense associated with adopting improvement technique d to address the causal loss c_h within the functional area s. A cost of 1 indicates a high cost. On the other hand, a cost equal to 5 means a low cost. In essence, it measures the financial costs incurred in implementing the improvement technique and mitigating the specific causal loss. A lower cost factor implies a more significant economic investment or burden required in the adoption of the technique.

The GPN, which ranges from 1 to 125, measures the suitability of improvement technique d to manage causal loss c_h in the functional area s. Based on their respective GPN values, corrective actions for a given causal loss are ranked, with technique A considered superior to technique B if the GPN value of technique A is higher. To focus on the improvement activities that hold the most promise (the first n), the next step entails selecting, for each causal loss, the technique with the highest GPN. Since the effort needed to manage several improvement activities simultaneously is closely related to the case at hand, the number n can vary widely from case to case.

A non-empty cell of the D-Matrix reports the score of each evaluation criterion and the corresponding product (i.e., the GPN) associated with the technique applicable to the specific causal loss. On the other hand, an empty cell means that the improvement technique is unable to address that loss.

3.2.5. E-Matrix: Selection of Improvement Projects Resulting from a Cost/Benefit Analysis

The preselected subset of improvements is a preliminary solution which needs to be investigated to establish whether the techniques are economically viable and, consequently, which improvements should be implemented first. D-Matrix provides a list of techniques ranked by their suitability to tackle each causal loss, but it does not include possible constraints such as budget. Hence, a restricted number of improvements (i.e., first n) needs to be analysed and ranked.

The last step of the GED method is to select the best sequence of improvements through the creation of the E-Matrix (Fig. 6). An investment efficiency measure is also provided for each improvement project. Typically, NPV is the valuation criterion applied in engineering economics (Campuzano-Bolarín et al., 2019; Sarkis and Dhavale, 2015). Obviously, other financial metrics can be used to determine whether an investment will be profitable in the long run, such as the internal rate of return (IRR) and the return on investment (ROI).

The E-Matrix reports the causal losses with their locations in the rows, while preselected improvement techniques, with their NPV, are given in the columns. For each technique, the GPN and the initial investment $F(0)$ are also reported. $NPV_{c_h,s,d}$ is evaluated as follows:

$$NPV_{c_h,s,d} = \sum_{t=1}^{T} \frac{F_{c_h,s,d}(t)}{(1+\beta)^t} - F_{c_h,s,d}(0) \tag{5}$$

The term $F_{c_h,s,d}(0)$ represents the initial cash outflow at time 0, which corresponds to the initial investment required (Capex) to start to project. β represents the discount rate, and T is the time period over which the investment will be made. $F_{c_h,s,d}(t)$ represents the projected operational net cash flow at time t, which is determined by adding together two different components. The first one is net Total Emission Cost multiplied with the *appeal coefficient* ($\alpha_{c_h,s,d}$). The net Total Emission Cost is obtained by evaluating the difference between the emissions due to losses assessed in the C-Matrix, and emissions due to the implementation of improvements such as the purchase of new plants and materials ($ImE_{c_h,s,d}$) multiplied by the CP value. The higher net effectiveness of improvement actions directly translates into a higher operational cash flow through the reduction of emissions, ultimately leading to a greater NPV and improved profitability. The second component considers the cash flow associated with the implementation of the improvement technique ($Sa_{c_h,s,d}$). This cash flow comprises all benefits derived from implementing the selected actions such as reducing energy and material consumption and possibly their cost. This is expressed analytically as follows:

$$F_{c_h,s,d}(t) = \alpha_{c_h,s,d} \bullet \left(DE^{(s)}_{c_h} + \sum_{i,j} IE^{(s,i)}_{c_h,r_j} - ImE_{c_h,s,d} \right) \bullet CP + Sa_{c_h,s,d} \tag{6}$$

Here, the *appeal coefficient* ($\alpha_{c_h,s,d}$), which concerns the causal loss c_h occurring in the functional area s under the mitigation dth technique, accounts for the marketing impact that emissions mitigation has on the end customer. In fact, as highlighted by Sherif et al. (2022), companies that implement sustainable practices can not only improve quality but also gain a larger market share due to the desire of customers to receive clear messages about sustainability. Hence, the company may be pushed to implement interventions regardless of the direct remuneration directly attributable to the intervention itself. This coefficient, which is positively oriented and is a minimum of 1 (i.e., the condition of no marketing impact), can be evaluated by converting judgment tables such as Table 2, which, however, can be tailored appropriately to the case under investigation. We suggest these values for the coefficient as they ensure a delicate equilibrium between the two factors constituting the operational cash flow: the cash flow linked to the improvement technique and that stemming from emissions reduction. An optimal balance is achieved through these values, as higher ones would exaggerate the environmental impact on the end customer, whereas lower values would lessen its influence.

In order to identify enhancement strategies that maximize advantages, guarantee a positive cash flow overall, control the total project expenses, and account for potential marketing influence within a predefined budget (referred to as B), we employed a methodology akin to

		Location	Improvement technique	GPN	Appeal coefficient	NPV	NPV/F(0)
Causal losses	Loss c_1	Functional Area 1	$Tech_{c_1,1,1}$	$GPN_{c_1,1,1}$	$\alpha_{c_1,1,1}$	$NPV_{c_1,1,1}$	$NPV_{c_1,1,1}/F(0)_{c_1,1,1}$
			…				
			$Tech_{c_1,1,d}$	$GPN_{c_1,1,d}$	$\alpha_{c_1,1,d}$	$NPV_{c_1,1,d}$	$NPV_{c_1,1,d}/F(0)_{c_1,1,d}$
			…				
		…					
		Functional Area s	$Tech_{c_1,s,1}$	$GPN_{c_1,s,1}$	$\alpha_{c_1,s,1}$	$NPV_{c_1,s,1}$	$NPV_{c_1,s,1}/F(0)_{c_1,s,1}$
			$Tech_{c_1,s,d}$	$GPN_{c_1,s,d}$	$\alpha_{c_1,s,d}$	$NPV_{c_1,s,d}$	$NPV_{c_1,s,d}/F(0)_{c_1,s,d}$
		…					
		Functional Area S	$Tech_{c_1,S,1}$	$GPN_{c_1,S,d}$	$\alpha_{c_1,S,1}$	$NPV_{c_1,S,1}$	$NPV_{c_1,S,1}/F(0)_{c_1,S,1}$
			…				
			$Tech_{c_1,S,d}$	$GPN_{c_1,S,d}$	$\alpha_{c_1,S,d}$	$NPV_{c_1,S,d}$	$NPV_{c_1,S,d}/F(0)_{c_1,S,d}$
			…				
	…						
	Loss c_h	Functional Area 1	$Tech_{c_h,1,1}$	$GPN_{c_h,1,1}$	$\alpha_{c_h,1,1}$	$NPV_{c_h,1,1}$	$NPV_{c_h,1,1}/F(0)_{c_h,1,1}$
			…				
			$Tech_{c_h,1,d}$	$GPN_{c_h,1,d}$	$\alpha_{c_h,1,d}$	$NPV_{c_h,1,d}$	$NPV_{c_h,1,d}/F(0)_{c_h,1,d}$
			…				
		…					
		Functional Area s	$Tech_{c_h,s,1}$	$GPN_{c_h,s,1}$	$\alpha_{c_h,s,1}$	$NPV_{c_h,s,1}$	$NPV_{c_h,s,1}/F(0)_{c_h,s,1}$
			$Tech_{c_h,s,d}$	$GPN_{c_h,s,d}$	$\alpha_{c_h,s,d}$	$NPV_{c_h,s,d}$	$NPV_{c_h,s,d}/F(0)_{c_h,s,d}$
		…					
		Functional Area S	$Tech_{c_h,S,1}$	$GPN_{c_h,S,1}$	$\alpha_{c_h,S,1}$	$NPV_{c_h,S,1}$	$NPV_{c_h,S,1}/F(0)_{c_h,S,1}$
			…				
			$Tech_{c_h,S,d}$	$GPN_{c_h,S,d}$	$\alpha_{c_h,S,d}$	$NPV_{c_h,S,d}$	$NPV_{c_h,S,d}/F(0)_{c_h,S,d}$
			…				
	…						

Fig. 6. The *E*-Matrix.

Table 2
Appeal coefficient evaluation table.

Appeal coefficient impact	Linguistic evaluation	Value
No impact	The customer does not recognize the value of the improvement	1.00
Low impact	The customer is somewhat aware of the value of the improvement	1.05
Medium impact	The customer recognizes the value of the improvement	1.10
High impact	The customer fully appreciates the value of the improvement	1.15

the one outlined in Braglia et al. (2020a) which can be easily implemented through spreadsheets.

The algorithm operates by assessing improvement projects in order of decreasing efficiency, which is measured as $NPV_{c_h,s,d}/F_{c_h,s,d}(0)$ for each causal loss c_h, functional area s, and the dth improvement technique. As a result, the algorithm provides a list of improvement projects that maximize benefits while adhering to the constraint of the maximum available budget. In other words, it prioritizes projects that offer the best return on investment, ensuring that they fit within the allocated budget.

3.3. Case Study

To demonstrate its functionality and effectiveness, we applied the GED method to a company dedicated to producing plywood. Over the last 20 years, the company has developed its competitiveness by focusing precisely on the production and product quality and ecological awareness, obtaining certifications that guarantee that forests are both managed correctly and responsibly in accordance with strict environmental, social, and economic standards, and that the emissions of its products are increasingly controlled and reduced. Aware that legislation on GHG emissions is becoming increasingly stringent and that great benefits can be derived from improved energy, material, and waste management, the company decided to increase its environmental commitment by implementing an emissions reduction program. The company has been collecting and classifying emission losses within the production plant for approximately one year, following the scheme presented in this paper.

3.3.1. Productive Cycle

Fig. 7 highlights the company's production cycle, where green blocks represent the company's in-house production stages, grey blocks refer to production and external procurement of raw materials, and brown

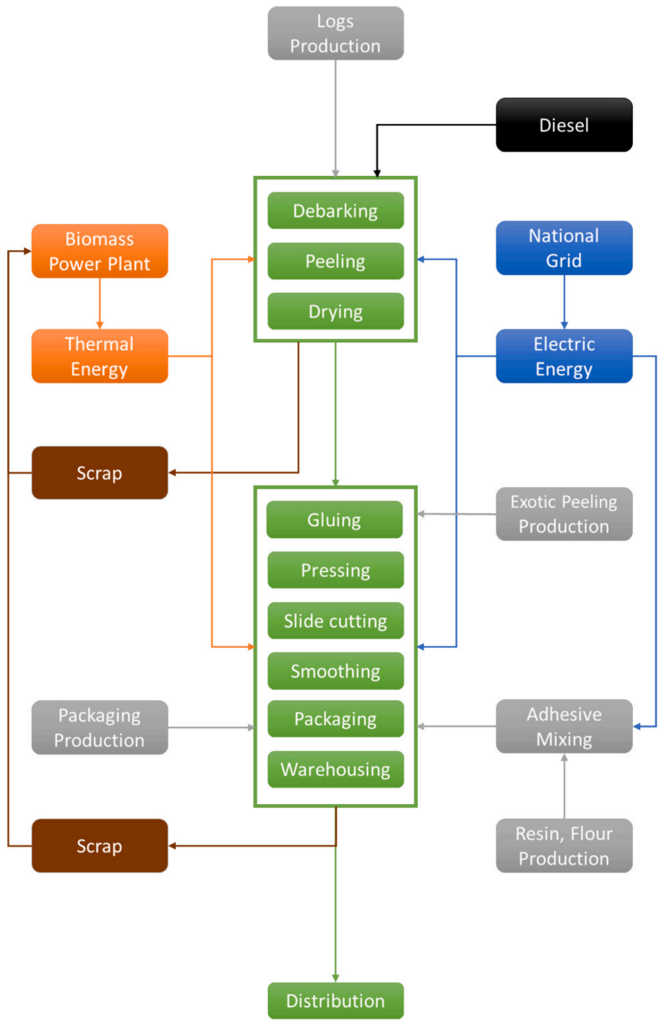

Fig. 7. Company production cycle.

blocks to production waste. On the other hand, blue, orange, and black refer to electric energy, thermal energy and fuels, respectively. The production of plywood uses poplar logs and exotic wood peel as raw materials, which are delivered to the factory by truck. Logs from cyclic plantations (poplar) and veneers of exotic or other hardwoods from non-European countries such as Africa and the USA are used in the processing. The logs are moved on a conveyor belt and taken to the debarker. The debarked logs are then sent to the peeling lines. The veneers, with thicknesses ranging from 1 to 3 mm, are cut, selected, and stored. Some waste products result from these primary operations: bark, wood cores, with a diameter of 9 cm, and irregular veneer scraps. The wood cores are sold to pallet makers, while the bark and rough cuts are chipped and consumed as fuel for a biomass-fired power plant. The veneers are dried by dry reels according to the veneer thickness and moisture content. Using a specific machine, the veneers are then glued together with an adhesive mixture based on urea or melamine resin and different types of flour with the subsequent addition of ammonium chloride.

A composing machine completes the panel by alternating several layers of wood, while a hot press compresses the layers. The presses are heated using a hot carrier (superheated water) circulating in a closed system. Once pressed, the plywood is checked manually, and any surface imperfections are removed using plaster. The plywood is then transferred to a sliding saw that cuts the irregular edges to obtain rectangular sheets with precise dimensions. In addition, the plywood sheets are automatically taken to a sanding machine that polishes them with specific appropriately gritted sandpaper. At the end of the process, only plywood that meets specific quality standards is selected. The last step involves the polyethylene packaging of the plywood, which is sorted by quality and specific features. The finished products are stored in the goods warehouse until they are picked up for shipment. In 2015, a biomass-fired power plant was installed that provides energy for the dryers, hot presses, log de-icing, and heating of the entire factory. The power plant is fed by bark, rough cuts, chips, and other processing waste.

4. Results and Discussion

The matrices resulting from the application of GED are presented and described below. The team identified and classified the losses that led to GHG emissions according to three different levels of criticalities. The A-Matrix shows very important losses within the red cells, important losses in the yellow cells, and minimal losses in the green cells (Fig. 8). The analysis team detected losses at each production stage. The purchase of electricity from the national grid was not traced to a specific functional area, as electricity consumption concerns all areas. To facilitate the understanding of the A-Matrix, a column with a more detailed description of the losses has been added.

Since the total number of losses detected was moderate, the team, together with the company manager, decided to take all the losses to the next stages of analysis. This was because the budget available was sufficient to manage all the losses identified. The B-Matrix highlights the causal-resultant relationship between the emissions losses (Fig. 9). The Supplementary Information (SI) provides a detailed description of the causal losses sequenced in the B-Matrix and their interrelationship with the resultant losses, the emission assessment reported in the C-Matrix, the improvement actions presented in the D-Matrix, and the calculation costs used in the cost-benefit analysis of the *E*-Matrix.

For the case study analysed here, only two emissions losses were considered as resultant. The first involved multiple failures of the smoother's electric motors due to the excessive plywood smoothing speed. The second was attributable to excessive hot press temperatures that damaged the outer veneers, which then had to be reworked with epoxy plaster. Together with the operators, the team verified that, by correcting these process parameters, the product quality would continue to meet the high standards required, while both motor failures and rework would decrease dramatically. It is worth noting that losses included emissions due to material consumption, classified as Scope 3 emissions, which are the most difficult to detect and assess.

The C-Matrix quantifies the GHG emissions and converts them into costs. GHG emissions were evaluated using the ECOINVENT 3.7 database through the OPENLCA software. The production process was parameterized, and emissions were quantified by comparing the as-is condition with that in which losses had been completely eliminated.

The conversion of emissions into costs required specific attention. Since the price of CP is increasing and is expected to continue doing so, three different scenarios were studied. The first one assumed the average CP price as of January 2023 and this value was adopted in the C-Matrix for the cost evaluation (Fig. 10). More numerical information regarding the compilation of the matrices can be found in SI, which provides a detailed description of the causal losses sequenced in the B-Matrix, their interrelationship with resultant losses and the emission assessment reported in the C-Matrix. The second scenario considered an increasing CP price forecast, with twice the value of the first. Finally, the last scenario adopted a CP price that was three times higher than the first, as the trend in recent years is clearly upward. Considering that environmental regulations are increasingly restrictive and that the amount of CP is increasing every year, it seems logical to include this forecast. The results of these two scenarios and how they influence the final decisions are shown at the end of this section.

After quantifying the emissions and associated costs, specific corrective actions had to be identified to mitigate and possibly eliminate

Loss Category	Scope	Loss type	Details	Debarking	Peeling	Drying	Gluing	Pressing	Smoothing	Packaging	Warehousing
				Production stages of plywood							
Standard Deviation Losses	1	Erroneous Process Parameter	Excessive temperature of the drying rollers								
	1	Erroneous Process Parameter	Excessive temperature of the presses								
	2	Erroneous Process Parameter	Excessive smoothing speed								
	3	Erroneous Process Parameter	Non-optimal operative glue thickness								
Ineffective Usage Losses	1	Degradation of thermal insulation	Degradation of piping thermal insulation								
	2	Inefficient Material Handling	Non-optimal sizing of the load unit								
	3	Failure	Multiple failures of electric engines								
	3	Rework	Puttying of non correctly pressed veneers								
Design Losses	1	Thickness of insulation	Adjacent piping without thermal insulation								
	1	Fossil fuel consumption	Diesel consumption as fuel for log handling machines								
	2	Usage of non-renewable energy	Consumption of electric energy from national grid								
	3	Non-sustainable packaging	Consumption of polyethylene packaging material								

Fig. 8. A-Matrix of the case study.

		Details	Where	Resultant losses	
				Failure	Rework
				Multiple failures of electric engines	Puttying of non correctly pressed veneers
				Smoothing	Smoothing
Causal Losses	Erroneous Process Parameter	Excessive temperature of the drying rollers	Drying		
	Erroneous Process Parameter	Excessive temperature of the presses	Pressing		x
	Erroneous Process Parameter	Excessive smoothing speed	Smoothing	x	
	Erroneous Process Parameter	Non-optimal operative glue thickness	Gluing		
	Degradation of thermal insulation	Degradation of piping thermal insulation	Drying		
	Inefficient Material Handling	Non-optimal sizing of the load unit	Warehousing		
	Thickness of insulation	Adjacent piping without thermal insulation	Pressing		
	Fossil fuel consumption	Diesel consumption as fuel for log handling machines	Debarking		
	Usage of non-renewable energy	Consumption of electric energy from national grid	Whole Plant		
	Non-sustainable packaging	Consumption of polyethylene packaging material	Packaging		

Fig. 9. B-Matrix of the case study.

the causal losses. The analysis team defined a series of improvement techniques, AS shown in the D-Matrix (Fig. 11). During this phase, the improvement techniques were introduced without going into technical specifics or conducting any particular benefit calculations. The experts evaluated the quality of these improvement techniques based on their knowledge and experience, using three ranking criteria. When multiple solutions were available for addressing a particular loss, the one with the highest GPN value was chosen. The objective was to conduct an initial screening to prevent the least effective corrective actions from being used, thereby minimizing the overall workload involved in the task.

The last matrix constructed was the *E*-Matrix (Fig. 12) with the purpose of determining which improvements should be implemented

				Resultant Losses		Indirect Emissions	Direct Emissions	Total Emissions	Total Emissions Cost
				Failure	Rework				
		Details		Multiple failures of electric engines	Putting of non correctly pressed veneers				
			Where	Smoothing	Smoothing				
				[kg CO2-e]	[kg CO2-e]	[kg CO2-e]	[kg CO2-e]	[kg CO2-e]	[€]
Causal Losses	Erroneous Process Parameter	Excessive temperature of the drying ro	Drying				$9.33 \cdot 10^4$	$9.33 \cdot 10^4$	93,560
	Erroneous Process Parameter	Excessive temperature of the presses	Pressing		$2.23 \cdot 10^3$	$2.23 \cdot 10^3$	$1.21 \cdot 10^4$	$1.42 \cdot 10^4$	1,423
	Erroneous Process Parameter	Excessive smoothing speed	Smoothing	$1.25 \cdot 10^2$		$1.25 \cdot 10^2$	$1.10 \cdot 10^4$	$1.10 \cdot 10^4$	1,100
	Erroneous Process Parameter	Non-optimal operative glue thickness	Gluing				$1.07 \cdot 10^6$	$1.07 \cdot 10^6$	106,650
	Degradation of thermal insulation	Degradation of piping thermal insulation	Drying				$1.29 \cdot 10^3$	$1.29 \cdot 10^3$	129
	Inefficient Material Handling	Non-optimal sizing of the load unit	Warehousing				$5.85 \cdot 10^4$	$5.85 \cdot 10^4$	5,850
	Thickness of insulation	Adjacent piping without thermal insulation	Pressing				$1.05 \cdot 10^3$	$1.05 \cdot 10^3$	105
	Fossil fuel consumption	Diesel consumption as fuel for log handling machines	Debarking				$4.95 \cdot 10^5$	$4.95 \cdot 10^5$	49,495
	Usage of non-renewable energy	Consumption of electric energy from national grid	Whole Plant				$1.19 \cdot 10^7$	$1.19 \cdot 10^7$	1,186,739
	Non-sustainable packaging	Consumption of polyethylene packaging material	Packaging				$5.24 \cdot 10^4$	$5.24 \cdot 10^4$	5,236

Fig. 10. C-Matrix of the case study.

first. Together with the plant manager, we decided on a 6 % interest rate and an improvement lifetime of 10 years, which are typical values for this industrial environment. The costs included both materials and installation of the improvement techniques, while the cash flow due to emission mitigation was obtained by multiplying the total emissions of the loss chain by the coefficient of appeal. Each coefficient was evaluated by questioning different actors in the plant, such as the operators, engineers and employees from other departments. Since many of the corrective actions did not require capital expenditure or at least required minimal initial expenditure, the team decided to use only the NPV as the deciding factor to prioritize. The analysis revealed that most corrective actions showed positive NPVs, indicating profitability over the chosen lifetime and at the specified interest rate. However, a few actions showed negative NPVs, indicating that they were not economically viable in the current scenario. In these cases, the projected operational cash flows were insufficient to offset the initial investment costs. For instance, installing new insulation or replacing existing insulation does not generate enough positive cash flow to justify the upfront investment required.

In the end, top management decided to disregard those improvement action with negative NPV values and to implement the improvements based on the ranking obtained in the conservative scenario reported in the *E*-Matrix with a CP of 100 €/t CO_2-e. This could result in the mitigation of more than 13,600 t CO_2-e, or approximately 48.5 % of the company's total GHG emissions. Of these, 41 % are attributed to the purchase of certified renewable electricity (Scope 2), while the remaining 7.5 % is split between 6.5 % due to the reduced consumption of materials (Scope 3) such as glue, epoxy plaster and electric motors, and 1 % due to in-house energy production (Scope 1). This analysis emphasizes that losses generating Scope 3 emissions have a significant impact, contributing 6.5 % of the total emissions mitigated, which is far from negligible. To further clarify the impact of each improvement action, we have included the emission scope in brackets within the "Loss Type" column in Fig. 12. This scope pertains to the root cause of the emissions (i.e. causal loss), and not necessarily the entire emission chain (i.e. resultant losses). For a comprehensive understanding of the scope associated with each loss and its cascading effects, please refer to the A-Matrix and B-Matrix presented earlier in this section.

Table 3 summarizes the impact of CP on the improvement actions selected. Each row details a specific improvement action, while columns display the NPV and ranking for each scenario with varying CP values. In the first scenario (CP = €100/permit), reduction in glue thickness is the best improvement action, followed by the purchase of certified renewable energy. As the CP increases (€200/permit) in the second scenario, the ranking shifts and the purchase of certified renewable energy improves the most. At the same time, changing the temperature of the drying rollers rises in position as does switching to certified green diesel, which becomes the third best corrective action. At the lower end of the ranking, the NPV of the switch to cellophane not only becomes positive, but also rises by two positions. The final scenario (CP = €300/permit) shows minimal changes from the second one, with all considered improvements becoming cost-effective. Given the trend towards stricter environmental regulations and rising CP costs, this scenario reflects a likely future reality.

The application of GED offers several advantages for decision-makers. Its stepwise approach, often using matrices, facilitates straightforward and immediate implementation. This allows for a systematic selection of priority improvements to address environmental impacts. Furthermore, GED surpasses traditional methods by encompassing all three emission scopes (Scope 1, 2, and 3) in its analysis, enabling the identification of losses across the entire production chain. This crucial feature provides companies with more ways to enhance sustainability in their operations and procurement decisions.

However, implementing GED also presents challenges. The method was applied to a single case study, however the selected company represents a significant example of how a typical production company carries out its operations, which enabled us to identify and measure different types of losses. Moreover, the extensive data collection required from all production units is a significant hurdle. This can be particularly difficult for small and medium-sized enterprises (SMEs), which may lack the financial resources for sensorisation or the technical expertise for data management. Additionally, conducting a thorough root-cause analysis to pinpoint the sources of losses and associated chains can be time-consuming and labour-intensive.

Ultimately, the effectiveness of GED hinges on three key factors: the chosen level of detail to quantify losses, the skillset of the analysis team, and the effectiveness of the implemented improvements. While navigating these challenges requires effort, GED has emerged as a powerful and practical tool. It can empower project managers and analysis teams to make informed decisions regarding environmental improvements without resorting to intricate models.

It is worth noting that the method approaches performance

				Improvement techniques														
				Engeneering techniques									Management techniques					
				Restoration of optimal operating condition			Design modification of the equipment			Switch to more sustainable material			TPM			Modification of productive plant management		
	Loss type	Details	Where	Efficacy	Ease	Cost	Efficacy	Ease	Cost	Efficacy	Ease	Cost	Efficacy	Ease	Cost	Efficacy	Ease	Cost
Causal losses	Erroneous Process Parameter	Excessive temperature of the drying rollers	Drying	4	5	5												
				100														
				Modification of the setting point of the control system in accordance with the optimal operating point														
	Erroneous Process Parameter	Excessive temperature of the presses	Pressing	5	5	5												
				125														
				Modification of the setting point of the control system in accordance with the optimal operating point														
	Erroneous Process Parameter	Excessive smoothing speed	Smoothing	4	5	5												
				100														
				Reduction of smoothing speed														
	Erroneous Process Parameter	Non-optimal operative glue thickness	Gluing	5	3	5												
				75														
				Reduction of glue thickness														
	Degradation of thermal insulation	Degradation of piping thermal insulation	Drying										4	4	4			
													64					
													Autonomous maintenance: substitution of degraded insulation and periodic check of equipment condition					
	Inefficient Material Handling	Non-optimal sizing of the load unit	Warehousing													3	3	4
																36		
																Redesign of the load unit by aggregating more plywood layers		
	Thickness of insulation	Adjacent piping without thermal insulation	Pressing				5	5	4									
							100											
							Installation of thermal insulation											
	Fossil fuel consumption	Diesel consumption as fuel for log handling machines	Debarking				5	3	1	5	3	3						
							15			45								
							Substitution of current handling machines with new electric ones			Switch to certified green diesel								
	Usage of non-renewable energy	Consumption of electric energy from national grid	Whole Plant				5	3	1	5	4	3						
							15			60								
							Installation of photovoltaic system			Purchase of certified renewable energy								
	Non-sustainable packaging	Consumption of polyethylene packaging material	Packaging							4	3	2						
										24								
										Switch to cellophane wrapping								

Fig. 11. D-Matrix of the case study.

assessment with a holistic view. It can be product, process or service oriented, however the method remains operational and effective, providing a valuable resource for planning and managing sustainable development strategies. Finally, its step-by-step features based on linked matrices make it easy to integrate into company management software. This integration would provide a digital tool used to monitor industrial emissions and improve the environmental commitment of companies.

	Loss type	Details	Where	Improvement technique	Appealing coefficient α	NPV [€]	Capex [€]
Causal Losses	Erroneous Process Parameter (*Scope 1*)	Excessive temperature of the drying rollers	Drying	Modification of the setting point of the control system in accordance with the optimal operating point	1	68,682	0
	Erroneous Process Parameter (*Scope 1*)	Excessive temperature of the presses	Pressing	Modification of the setting point of the control system in accordance with the optimal operating point	1	508,014	0
	Erroneous Process Parameter (*Scope 2*)	Excessive smoothing speed	Smoothing	Reduction of smoothing speed	1	29,292	0
	Erroneous Process Parameter (*Scope 3*)	Non-optimal glue thickness	Gluing	Reduction of glue thickness	1.05	5,608,256	0
	Degradation of thermal insulation (*Scope 1*)	Degradation of piping thermal insulation	Drying	Substitution of degraded insulation and periodic check of equipment condition	1	-1,873	2,821
	Inefficient Material Handling (*Scope 2*)	Non-optimal sizing of the load unit	Warehousing	Redesign of the load unit by aggregating more plywood layers	1	136,013	0
	Thickness of insulation (*Scope 1*)	Adjacent piping without thermal insulation	Pressing	Installation of thermal insulation	1	-923	1,693
	Fossil fuel consumption (*Scope 1*)	Diesel consumption as fuel for log handling machines	Peeling	Switch to certified green diesel	1.15	258,630	0
	Usage of non-renewable energy (*Scope 2*)	Consumption of electric energy from national grid	Whole Plant	Purchase of certified renewable energy	1.15	1,412,313	0
	Non-sustainable packaging (*Scope 3*)	Consumption of polyethylene packaging material	Packaging	Switch to cellophane wrapping	1.1	-34,734	0

Fig. 12. E-Matrix of the case study.

Table 3
NPV rankings of different scenarios.

	CP = 100		CP = 200		CP = 300	
Improvement	**NPV [€]**	**Ranking**	**NPV [€]**	**Ranking**	**NPV [€]**	**Ranking**
Modification of the setting point of the control system in accordance with the optimal operating point	68,682	6	137,364	6	206,045	6
Modification of the setting point of the control system in accordance with the optimal operating point	508,014	3	518,485	4	528,957	4
Reduction of smoothing speed	29,292	7	37,461	7	45,629	8
Reduction of glue thickness	5,608,256	1	6,432,456	2	7,256,656	2
Substitution of degraded insulation and periodic check of equipment condition	-1,873	9	-926	10	22	10
Redesign of the load unit by aggregating more plywood layers	136,013	5	179,068	5	222,123	5
Installation of thermal insulation	-923	8	-153	9	617	9
Switch to certified green diesel	258,630	4	677,562	3	1,096,494	3
Purchase of certified renewable energy	1,412,313	2	11,456,992	1	21,501,671	1
Switch to cellophane wrapping	-34,734	10	7,658	8	50,050	7

5. Conclusions

This paper presents a new lean method to address the environmental challenges faced by the industrial sector due to climate change. The GED has a similar structure to MCD, but differs in its scope and ultimate purpose. Through the construction and compilation of five matrices, GED aims to identify industrial losses that cause emissions. First, the method identifies losses and clarifies the cause-effect relationships between them. In addition, it quantifies emissions and converts them into costs. Finally, it supports decision-making by classifying improvements tailored to address the causal losses and performs a cost-benefit analysis to select the improvements to be implemented first.

Compared to the traditional Cap-and-Trade system, GED aims, when possible, to economically evaluate all emissions attributable directly and indirectly to the plant, and thus Scope 3 emissions are also considered. By assessing Scope 3 emissions, companies are able to identify significant opportunities for GHG reductions and, as a result, to become more environmentally conscious of their operations and the products they manufacture or purchase.

GED was applied to a plywood manufacturing company and its effectiveness has been proven. Following a step-by-step procedure, the company was able to identify the factors causing the greatest loss of energy and materials and were able to achieve cost savings of up to one million euros per year from their elimination. According to the plant manager, the most important feature of the method is its operability. In fact, its well-framed use of matrices enables a simple and immediate implementation. In terms of its practical application, the only improvement suggested by the team is the eventual extension of other possible environmental criteria that could be included within the method. Future research could thus include the integration of other environmental aspects such as, water use and consumption and pollutant production with an integrated approach considering impacts on soil, air and water from a whole-life perspective. GED could thus be integrated with LCA to provide a comprehensive environmental analysis. In fact, environmental sustainability includes various aspects such as ocean acidification, freshwater use, ozone depletion, and the industrial sector needs management tools to develop a more sustainable production system. In addition, the method could be extended to the entire supply chain by developing a method that can coordinate all upstream and downstream suppliers from an environmental perspective.

CRediT authorship contribution statement

Marcello Braglia: Conceptualization, Validation, Methodology. **Francesco Di Paco:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Roberto Gabbrielli:** Conceptualization, Data curation, Formal analysis, Validation, Visualization, Methodology. **Carlo Grassi:** Data curation. **Leonardo Marrazzini:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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