A new set of Lean indicators to assess Greenhouse Gas emissions related to industrial losses

Marcello Braglia, Francesco Di Paco, Roberto Gabbrielli and Leonardo Marrazzini
Dipartimento di Ingegneria Civile e Industriale, University of Pisa, Pisa, Italy

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Abstract

Purpose – This paper presents a new and well-structured framework that aims to assess the current environmental impact from a Greenhouse Gas (GHG) emissions perspective. This tool includes a new set of Lean Key Performance Indicators (KPIs), which translates the well-known logic of Overall Equipment Effectiveness in the field of GHG emissions, that can progressively detect industrial losses that cause GHG emissions and support decision-making for implementing improvements.

Design/methodology/approach – The new metrics are presented with reference to two different perspectives: (1) to highlight the deviation of the current value of emissions from the target; (2) to adopt a diagnostic orientation not only to provide an assessment of current performance but also to search for the main causes of inefficiencies and to direct improvement implementations.

Findings – The proposed framework was applied to a major company operating in the plywood production sector. It identified emission-related losses at each stage of the production process, providing an overall performance evaluation of 53.1%. The industrial application shows how the indicators work in practice, and the framework as a whole, to assess GHG emissions related to industrial losses and to proper address improvement actions.

Originality/value – This paper scrutinizes a new set of Lean KPIs to assess the industrial losses causing GHG emissions and identifies some significant drawbacks. Then it proposes a new structure of losses and KPIs that not only quantify efficiency but also allow to identify viable countermeasures.

Keywords Greenhouse gas, Climate change, Sustainability, Lean manufacturing, Overall Equipment Effectiveness, Performance indicators

Paper type Research paper

1. Introduction

To cope with an increasingly competitive and dynamic market, businesses have extensively implemented Lean management. Manufacturing companies recognize it as one of the most significant ways to manage their business (Forrester *et al.*, 2010) and to discover opportunities to develop systems that make efficient use of resources (Netland *et al.*, 2015). Lean principles, by reducing resource usage for equivalent outcomes, align with addressing environmental challenges, curbing material, energy, and water consumption and minimizing environmental impact. In today's global market, economic success alone is insufficient;

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Data availability: The data used to support the findings of this study are supported within the manuscript.

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organizations must prioritize environmental considerations due to stakeholder pressure for enhanced sustainability (Jiang *et al.*, 2016).

Lean principles, when effectively implemented, offer substantial contributions to enhancing environmental performance (Cherrafi *et al.*, 2016). Alayón *et al.* (2017) highlight the common focus of both Lean and environmental practices on waste reduction. Lean targets process inefficiencies, while environmental management emphasizes greenhouse gas emissions and waste resulting from raw material processing (Molina-Azorín *et al.*, 2009). Successful integration of Lean and environmental practices has been demonstrated in various cases (Verrier *et al.*, 2014). Companies committed to environmental improvement enjoy benefits such as premium pricing for eco-friendly products, improved reputation, market access and enhanced competitiveness (Carvalho *et al.*, 2017). Consequently, environmental management has emerged as a new approach to properly manage the ecological impact of production systems and ensure economic and environmental development. In this way, financial targets can be achieved and the environment and people living in it can be preserved.

In recent years, research on the impact of Lean management on emissions reduction for industrial firms has surged. These studies show that Lean practices can enhance both productivity and environmental performance, offering numerous benefits. Various approaches, such as Sustainable-VSM (Brown *et al.*, 2014) and mathematical models (Carvalho *et al.*, 2017), have been developed to balance green and Lean practices. Additionally, load diagrams technique has been explored for assessing environmental and operational performance (Thanki and Thakkar, 2016), while the influence of environmental and information technologies on Lean procedures has been investigated (Sartal *et al.*, 2017). In addition, other tools, such as Overall Equipment Effectiveness (OEE), a key performance metric used within Total Productive Maintenance to assess the efficiency and effectiveness of equipment (Hansen, 2002), has been properly adapted to enhance environmental performance of industrial systems (more detail are given in Section 2).

The relationship between Lean and Green is readily apparent due to their shared principles of efficiency and waste reduction. Lean efforts focus on operational efficiency and waste reduction resulting in reduced resource and energy consumption and lower environmental impact (Wei Dong *et al.*, 2019). This alignment makes Lean a valuable tool for promoting environmental sustainability. Both Lean and Green initiatives align in their goal to optimize operations, making the connection between them evident and synergistic (Singh *et al.*, 2021).

Thanks to its logic and schematic framework, Lean management can offer companies tools and methods focusing on the identification of losses that cause GHG emissions. Although the topic has been widely studied and is currently part of an important research strand, the literature points to the need for operational methods and tools that can both assess emissions for industrial companies and support in the process of their mitigation (Hristov *et al.*, 2022; Muñoz-Villamizar *et al.*, 2019).

Based on this, this manuscript will focus on the first conventional operational phase of the analysis of a production process using a Lean project: "*Identify and deliver value to the customer value: eliminate anything that does not add value*". Providing structured indicators to assess whether a production system makes efficient use of its resources is the first necessary step to developing an effective loss reduction program. Key Performance Indicators (KPIs) represent a quantifiable measure of performance over time to monitor the progress toward a pre-set target in every area of business.

In literature very little attention has been given to developing holistic methodologies that permit, with adequate tools and metrics, to investigate the relationship between GHG emissions and industrial losses with the ultimate goal of eliminating the losses through appropriately targeted improvement actions (more details are given in Section 2).

To fill this gap, we introduced a new and well-structured framework for assessing environmental impact in the context of GHG emissions. This framework is designed to address the pressing need to evaluate and manage GHG emissions effectively. The key contribution of this paper is the development of a set of Lean KPIs that serve as a unique tool for systematically identifying and quantifying losses in industrial processes that contribute to GHG emissions.

The framework, due to its associated KPIs, provides a dual perspective on the environmental impact:

(1) It allows for a quantitative assessment of how current GHG emissions compare to predefined emission reduction targets. This aspect highlights whether an organization is on track to meet its environmental goals and identifies the extent of any deviation.

(2) It offers a diagnostic approach to identify the root causes of inefficiencies and losses that lead to GHG emissions. This diagnostic capability helps organizations pinpoint the specific areas in their operations that are responsible for emissions and supports informed decision-making for implementing improvements.

The remaining part of this work is organized as follows. Section 2 frames this work into the relevant literature and highlights research gaps. Section 3 presents a new set of KPIs and the associated classification of the losses. To show the operating principles and potential results of this novel tool, a real industrial implementation concerning an important company operating in the plywood manufacturing sector is presented in Section 4. Finally, Section 5 is devoted to conclusions and future remarks.

2. Theoretical background and relevant literature

This section provides a theoretical background on performance indicators and reviews significant literature on how structured metrics have been developed to assess the environmental impact of industries.

As pinpointed in the literature, see for instance Braglia *et al.* (2019) and Naslund and Norrman (2019), the need to measure performance to properly manage production systems is long established.

Performance indicators play a crucial role in helping companies assess their systems' adherence to standards and progress toward specific goals. When it comes to environmental performance, numerous indicators have been developed to evaluate aspects like greenhouse gas (GHG) emissions, water consumption, waste generation and resource depletion. However, a significant focus in these indicators is on energy performance, as evidenced in various reviews. The recent study by Contini and Peruzzini (2022) identified 63 key environmental indicators used in manufacturing companies, with 38 of them primarily centered on energy and its consumption. However, viewing energy consumption as the sole negative impact in sustainability assessments may be overly simplistic. Environmental analyses should consider additional factors such as raw material usage and waste disposal.

Current environmental indicators often lack structured approaches, primarily featuring simple ratios or absolute values, like the total GHG emissions or water use per unit of product (Hristov *et al.*, 2022). While these indicators provide valuable performance insights, they fall short in pinpointing areas or equipment that need attention for substantial improvements. Furthermore, these unstructured indicators do not facilitate the initiation of improvement projects. To address these limitations, a new type of indicator, inspired by Lean principles, can offer a more comprehensive tool for assessing overall system performance. This structured indicator features a breakdown structure, enabling the identification of the sources of losses and corresponding remedies. By considering a broader array of environmental aspects and providing actionable insights, this approach can enhance companies' environmental performance assessment and guide sustainable improvement initiatives.

OEE is a key Lean metric used to understand, measure and improve current performance and used to evaluate and enhance current performance in various production aspects. Originally developed for machine utilization assessment, its logical framework has been extended to measure effectiveness in labor (Braglia *et al.*, 2021), materials (Braglia *et al.*, 2018), energy (May *et al.*, 2015) and space utilization (Braglia *et al.*, 2023).

However, traditional OEE lacks the ability to measure environmental impact. To address this gap, Domingo and Aguado (2015) integrated a sustainability factor into OEE calculations, focusing on environmental aspects without providing practical improvement actions. May *et al.* (2015) modified OEE and introduced a 7-step methodology for custom energy-related KPIs that allow cause-effect analysis. Muñoz-Villamizar *et al.* (2018) applied OEE's breakdown structure to environmental sustainability, identifying green value-added activities. Lastly, Muñoz-Villamizar *et al.* (2019) introduced a metrics-based approach to Value Stream Mapping, encouraging companies to incorporate environmental efficiency and productivity. These adaptations enhance performance evaluation and drive sustainability efforts in various production domains.

Considering the above studies, several shortcomings are evident. First, structured performance metrics primarily focus on individual environmental factors, such as energy efficiency and material usage. While it is logical to consider the concurrent adoption of these metrics for GHG emission reduction, several challenges persist. To begin with, such an approach may hinder a holistic view, potentially overlooking drawbacks arising from combined improvements. For instance, the introduction of a new energy-intensive machine could decrease material consumption but increase energy usage and vice versa. Consequently, analysts might proceed without adequate control over the situation. Furthermore, there's a need for a more granular breakdown of losses to avoid missed mitigation opportunities. For example, shifting to a more sustainable packaging material while maintaining the same overall material consumption might be disregarded. Secondly, existing indicators, which encompass sustainability aspects, fall short when it comes to consistently pinpointing and categorizing industrial activities responsible for GHG. They also lack the ability to trigger the essential actions required for improvement.

As stressed above, in line with these considerations, this paper aims to develop a structured framework and novel KPIs that bridge the gap between GHG emissions and Lean principles, allowing organizations not only to assess their current environmental performance but also to uncover and address the underlying causes of inefficiencies and emissions. This approach provides a valuable tool for organizations seeking to reduce their environmental footprint and make informed decisions to drive improvements in sustainability and emissions management.

Specifically, the paper presents a new metric called Overall Emission Efficiency (OEmE) which translates the logic of OEE in the field of GHG emissions. This metric is presented with reference to two different perspectives: on the one hand, according to the logic of feedback control, it aims to highlight the deviation of the current value of emissions from the target. On the other hand, according to the feed-forward control perspective, it adopts a diagnostic orientation not only to provide an assessment of current performances but also to search for the main causes of inefficiencies and to focus on improvement implementations. By exploiting the layered structure of the OEmE, it is possible to identify areas where the implementation of improvements could be most effective.

3. Overall Emissions Effectiveness (OEmE)

This section describes a new set of Lean indicators to assess GHG emissions related to industrial losses. Before describing the indicators, a new classification of emissions is provided.

3.1 A new classification of emissions due to industrial losses

In this section, the authors present a novel method to classify and analyze industrial losses that cause GHG emissions (Figure 1). Thanks to this systematic approach, it is possible to assess the cause of losses and their related impact. Specifically, the classification of losses has been conceived enriching losses presented in the literature (Axelson *et al.*, 2021; Braglia *et al.*, 2020; May *et al.*, 2015; Zhou, 2020) with typical criticalities of companies collected by several interviews, recording testimonies of sustainability and environmental managers, process

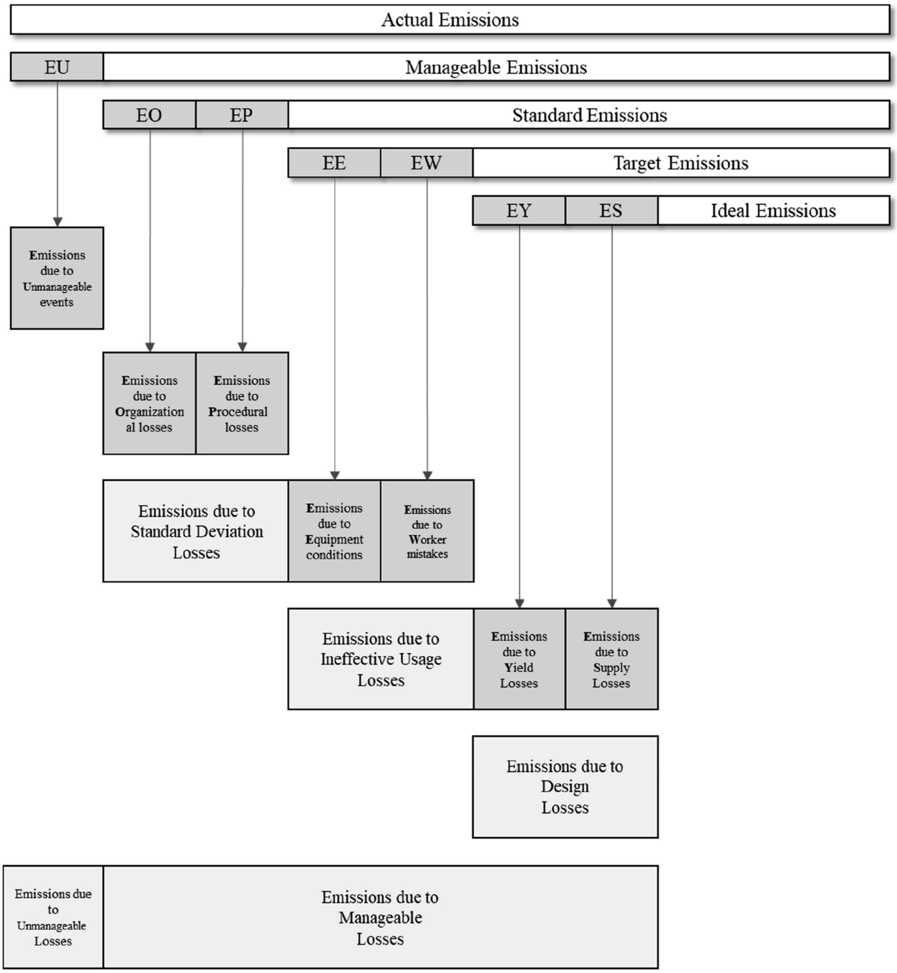

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Figure 1.
A new classification of emissions due to industrial losses

operators, operations managers and responsible employees from the design office. Table 1 depicts the proposed list of emissions categories.

Owing to these considerations, the authors propose to categorize emissions losses-related into two main categories: Unmanageable and Manageable Losses. We define Unmanageable Losses as losses due to uncontrollable events such as leakages of fluids on external supplying pipelines (fuel, water, methane, etc.), shipping problems, and non-compliant quality of supplies on which the company does not have any control and cannot be exactly quantifiable. Excluding this type of losses, which are outside of the influence of the company, the remainders, i.e. Manageable Losses, constitute the ones that are effectively mitigable since they are under the control and influence of the company. Manageable losses are further subdivided into categories that specify the nature of each considered loss: Standard Deviation Losses, Ineffective Usage Losses and Design Losses. These categories are defined as follows:

(1) *Standard Deviation Losses*. Standard Deviation Losses are related to deviations from a documented standard or due to the absence of the standard itself. This category of losses generates GHG emissions due to Organizational (EO) and Procedural (EP) losses. The formers encompass processes or activities that do not need to be performed, such as heating/cooling components that should not be heated/cooled. The latter include standard mistakes such as wrong process parameters and missing

Table 1.
Emissions categories and loss types

Emission category	Loss type	Scope 1	Scope 2	Scope 3
EU	Deliveries compliance			•
	Quality of supplies			•
	Shipping problems			•
	Leakages of fluids on external pipelines (fuel, water, methane, etc)			•
	Missing systems stop (i.e. shift change, absenteeism)	•	•	
EO	Not required start-up or shutdown		•	
	Not required heating/cooling	•		
	Not required use of lighting system		•	
EP	Missing procedure		•	
	Mistake in production planning	•	•	•
	Missing/mistake documentation		•	
	Erroneous process parameter	•		
EE	Leakages of fluid (fuel, vapor, oil, air, refrigerant, etc.)	•		
	Failure			•
	Scrap disposal			•
	Degradation of thermal insulation	•		
	Rework		•	
	Performance degradation of equipment		•	
EW	Inefficient use of equipment		•	
	Inefficient use of air conditioning		•	
	Inefficient material handling system	•	•	
EY	Thickness of insulations	•		
	Inefficient lighting/air conditioning system	•		
	Oversized lighting/air conditioning system		•	
	Low nominal equipment performance		•	•
ES	Purchasing of non-sustainable packaging			•
	Purchasing of non-sustainable raw material			•
	Purchasing of non-sustainable fluid (oil, refrigerant, etc.)			•

Source(s): Author's own creation

procedures or documentation, whose lackness implies emissions. For example, an excessive temperature parameter increases energy consumption and can alter the proper functioning of the process. By subtracting emissions due to Standard Deviations Losses from Manageable Emissions it is possible to evaluate the Standard Emissions. This type of GHG emissions comprises all the emissions associated with processes the standard of which are well-defined by specific procedures and documentation.

(2) *Ineffective Usage Losses.* Ineffective Usage Losses refer to losses that generate GHG emissions that are caused by pieces of equipment that are operated or used incorrectly. This category of losses generates GHG emissions due to Equipment conditions (EE) and Worker mistakes (EW). EE are related to equipment malfunction due to degradation and failure. For instance, the degradation of pipe insulation leads to increased energy consumption and thus GHG emissions. According to a life cycle approach, failures cause emissions due to energy and material consumption used to fix them or the purchase of spare parts, the production of which is associated with increased emissions. EW refer to worker errors caused by a lack of training or carelessness such as ineffective use of equipment and systems. For example, the inefficient use of a heating tool such as a torch during welding operations can significantly increase the energy consumption of the process, or the scraps which are originated by a mounting error in assembly lines. By subtracting GHG emissions due to Ineffective Usage Losses from Standard Emissions it is possible to assess the Target Emissions. These stand for the theoretical emissions that would be generated if all the equipment and the system were properly operated.

(3) *Design Losses.* Finally, GHG emissions due to Design Losses would occur even if the equipment involved in operations were used correctly, as they are related to the design choices made both for equipment and supplies. Design Losses generate GHG emissions due to Yield (EY) and Supply (ES) losses. The former includes losses due to nominal performance, such as insufficient pipe insulation thickness and low-rated performance gears. The latter are related to the choices made at the supply level. They involve the materials consumed in the production process such as non-sustainable plastic packaging, raw material and fluid. Following a life cycle approach, the purchasing of materials is associated with GHG emissions due to the primary material extraction, processing and transportation of materials. It is not always possible to assess this kind of emissions. Typically, data are obtained from environmental reports (European Union CRF, 2022), academic literature (see, for example, Kissinger *et al.*, 2013) or directly by the data provided by the supplier. The exchange of environmental data between suppliers and clients has seen a significant surge in recent years, driven by heightened corporate consciousness of environmental concerns. Nevertheless, there are instances where a company may be hesitant to disclose its data. In such scenarios, acquisition strategies may encompass leveraging economic incentives, such as maintaining an exclusive client relationship or establishing tailored contractual agreements. By subtracting GHG emissions due to Design Losses from Target Emissions it is possible to evaluate the Ideal Emissions. Ideal Emissions should be evaluated based on the state-of-art of the facility under consideration.

We define Ideal Emissions as GHG emissions associated with carrying out technologically and methodologically optimized activities, considering currently available technologies and methods. Therefore, nowadays, Ideal Emissions cannot be zero. With this in mind, the ultimate goal cannot be to eliminate all Ideal emissions, because a certain amount of GHG emissions remains, but they can be progressively reduced with the introduction of technological improvements in the future. For instance, innovative machines fueled by green hydrogen are capable of operating without emissions at the use stage. However, it is important to note that emissions from both the upstream production process and the downstream processes persist. While such a solution can significantly reduce Ideal emissions, achieving absolute zero Ideal emissions remains unattainable.

Each loss type in Table 1 is also associated with the scope of the GHG emissions that are produced. According to the leading GHG Protocol corporate standard (WBCSED/WRI, 2010), GHG emissions are classified into three scopes: Scope 1, 2 and 3. This is a way of categorizing the different kinds of carbon emissions a company bears in its own operations, and in its wider value chain. In practice, this classification is organized as follows:

(1) Scope 1 – Direct emissions. Scope 1 deals with direct emissions released into the atmosphere by a set of companies' activities. In other words, these GHG emissions come from company-owned and controlled resources. These GHG emissions are divided into four categories: (*1*) stationary combustion (all fuels, but biofuels, producing GHG emissions must be included); (*2*) mobile combustion, including all vehicles, owned or controlled by a firm, and burning fuel (e.g. cars, vans, trucks). Electric vehicles fall into Scope 2; (*3*) fugitive emissions, which are related to GHG emissions (e.g. refrigeration, cooling consumed from air conditioning units); (*4*) process GHG emissions, produced by industrial processes or general production processes, and on-site manufacturing (factory fumes, chemicals such as nitrous oxide, etc.).

(2) Scope 2 – Indirect emissions. Scope 2 is related to indirect emissions, released by the consumption of purchased electricity, steam, heat and cooling consumed. Most of the time acquired electricity is the unique source of Scope 2 emissions. If the energy is used during transmissions and distribution, it falls under Scope 3 emissions.

(3) Scope 3 – Indirect emissions. Scope 3 emissions include all other indirect emissions – not incorporated in Scope 2 – produced by the value chain. Both upstream and downstream emissions are included, which are linked to the company's operations.

The traditional classification by scope is well-established worldwide. In sustainability reports, companies check their progress by showing the reduction of emissions per scope. However, it is important to emphasize that this categorization does not provide information on how activities are performed, and therefore does not make it possible to assess the current situation, areas which require attention and how improvement projects can be addressed. For example, as already mentioned, Scope 2 emissions consider emissions associated with energy purchase, but no information is provided on emissions related to energy efficiency. Consequently, a more accurate classification is needed that can assess the current situation and extrapolate useful information for possible improvements, such as the one proposed by the Authors.

To assess the performance of a plant from an environmental perspective, it is necessary to define a well-defined spatial and temporal domain. The spatial domain determines the direct and indirect emissions associated with operations owned or controlled by the reporting company and eventually, the scope of accounting. For instance, setting the spatial domain to coincide with the physical boundaries of the plant means counting all 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 accounting for them as direct. Normally, a corporate environmental report covers a one-year time horizon. However, in this scenario, the time horizon can be assumed to be either the standard one-year period or any other duration that the analysis team deems significant. When it comes to re-evaluating the indicator, it can align with the designated time horizon. However, it is crucial to exercise caution when implementing significant changes in the plant, such as introducing a new production system. In such cases, an immediate re-evaluation is required.

3.2 The new lean indicators

Starting from the classification structure of the emissions previously reported, we propose a new indicator named Overall Emissions Effectiveness (OEmE), that enables the analyst to assess GHG emissions related to industrial losses:

$$\text{Overall Emissions Effectiveness} = \text{OEmE} = \frac{\text{Ideal emissions}}{\text{Manageable emissions}} \tag{1}$$

The term "*Overall*" means the ability to evaluate, in a structured manner, all the causes of emissions, except for those that are due to uncontrollable events. This is because only controllable losses can be tackled through improvement actions. The diction "*Emissions Effectiveness*" is related to the final purpose of this indicator, which is to reach maximum emissions efficiency by eliminating any controllable, i.e. mitigable, loss. Considering this, it is essential to emphasize that the parameters used to calculate emissions are influenced by inherent random variations and dynamics. In an initial effort to address these challenges, we opt for the average value obtained through time integration over the data collection period.

The gap between Ideal and Manageable Emissions can be explained as the occurrence of many losses, which progressively increase the emissions associated with carrying out activities. OEmE makes it possible to assess current conditions by establishing a baseline for future improvements. Obviously, more significant progress can be achieved with a more accurate view. Indeed, it is worth noting that the OEmE can also be obtained as the product of three separate indicators, namely: Standard Emission Effectiveness, Usage Emissions Effectiveness and Design Emissions Effectiveness. This is shown in the following Formula (2):

$$\begin{aligned}\text{OEmE} = &\text{Standard Emission Effectiveness} \times \text{Usage Emissions Effectiveness} \times \\ &\text{Design Emissions Effectiveness}\end{aligned} \tag{2}$$

where,

$$\text{Standard Emissions Effectiveness} = \frac{\text{Standard emissions}}{\text{Manageable emissions}} \tag{3}$$

$$\text{Usage Emissions Effectiveness} = \frac{\text{Target emissions}}{\text{Standard emissions}} \tag{4}$$

$$\text{Design Emissions Effectiveness} = \frac{\text{Ideal emissions}}{\text{Target emissions}} \tag{5}$$

Specifically, the three indicators are defined as follows:

(1) *Standard Emissions Effectiveness.* According to Figure 1, it can be observed that Standard Emissions Effectiveness (Formula 3) evaluates only the performance with respect to standard procedures. This indicator highlights how processes are managed in terms of organization, documentation and procedures. A value far below 1 implies the need for managing tools such as Lean tools that can standardize activities as the primary step of process optimization.

(2) *Usage Emissions Effectiveness.* Usage Emissions Effectiveness (Formula 4) considers all the emissions due to losses that are related to equipment degradation and mistakes in use. This indicator points out how activities are performed in terms of operative problems. A value far below 1 implies the need for interventions for improving the machines' reliability and workers' capability.

(3) *Design Emissions Effectiveness.* Design Emissions Effectiveness (Formula 5) assesses all the emissions that are caused by equipment and products used during the process even if all the operations are carried out properly. A low value of this indicator is the basis for design shortcomings in the choice of equipment, systems and external supplies. Therefore, the company must embark on a plant-wide redesign process that includes both suppliers and the technical department.

The representation that Formula (2) provides is significant for supporting the interpretation of the causes behind emissions inefficiency. While OEmE is a global assessment of current performance concerning sustainability, each of the three components of OEmE pinpoints specific aspects of the process that can be targeted for enhancement. OEmE is considered to be the final stage of improvement, which means to operate by emitting an amount of emissions equal to the Ideal emissions. The three components represent the intermediate stages to be passed through. The reading of the identification areas for improvement interventions is easy: the farther the KPI value is from the ideal value of 1, the greater the need for intervention within the area defined by the emissions cluster associated with the indicator. For instance, a low value of Usage Emissions Effectiveness with respect to other indicators prompts a need for enhancing actions within maintenance and/or workers' training. It is important to exercise caution when selecting the actions for improvement. Indeed, it is possible that a corrective measure implemented in a specific location could worsen the performance in another, resulting in an overall negative outcome. To prevent this issue, it is crucial to thoroughly assess the potential consequences of any interventions at the plant level by conducting a comprehensive analysis of how these measures interact with one another before their implementation. It should be noted that there may be cases where the optimal value of OEmE (i.e. 1) cannot be achieved due to negative interactions between improvement actions. However, the application of the KPI remains the same, with the analysis team that aims for reaching the maximum value, which means reducing emissions and improving environmental performance.

To allow the indicators to be calculated, according to the above logic, each loss type is associated with a tailored expression that enables the analyst to properly assess the loss' impact (Table 2). Additional information regarding the description of the formulas used for the calculation can be found in Appendix 1. It is significant to emphasize that EP are closely related to the specific case under investigation and therefore it is particularly difficult to propose a universally valid formula for their evaluation. More details about the calculation formulas can be found in Appendix 1.

4. Case study

This section presents the implementation of OEmE in a real case study concerning an important company operating in the plywood manufacturing sector. In addition to describing some operational issues, it allows us to demonstrate its applicability and effectiveness in the assessment of GHG emission performances in a production process. The company has a total production capacity of 82,598 m^3 per year, distributed over 140 items. Over the past 20 years, the company has oriented its development toward the pursuit of a twofold objective. On the one hand, it has focused on product quality, gaining important new customers in the luxury sector, such as superyachts and cruise ships. On the other, it has obtained certifications

Emission category	Loss type	Formula	Nomenclature
EO	Not Required start-up	$(P_{ru} \cdot T_{ru} + P_{stand} \cdot t) \cdot E_f$	$E_{H/C}$ – Energy consumption for heating/cooling E_f – Emission factor P_{ls} – Power consumption of lighting system P_{ru} – Power consumption at start-up P_{stand} – Power consumption in standby t – Reference Time T_{ru}- Start-up time
	Not Required use of lighting system	$P_{ls} \cdot t \cdot E_f$	
	Not Required heating/cooling	$E_{H/C} \cdot E_f$	
EE	Leakages of fluid (air or vapor)	$Q_v \cdot E_v \cdot E_f$	E_f – Emission factor E_m – Emissions due to new pieces purchase E_s – Emissions for unit of scrap disposal E_v – Energy consumption for unit of vapor/air quantity P_{main} – Power consumption during maintenance P_{proc} – Power consumption during processing Q_l – Leakage quantity Q_r – Rework quantity Q_s – Scrap quantity Q_v – Vapor/air quantity t – Reference Time T_{proc} – Processing time T_r – Repair time ΔP_m – Power consumption due to performance degradation ΔE – Energy consumption due to degradation GWP – Global Warming Potential
	Leakages of fluid (GHG)	$Q_l \cdot GWP$	
	Failure	$P_{main} \cdot T_r \cdot E_f + E_m$	
	Scrap disposal	$Q_s \cdot E_s$	
	Degradation of insulation	$\Delta E \cdot E_f$	
	Rework	$P_{proc} \cdot T_{proc} \cdot Q_r \cdot E_f$	
	Performance degradation of equipment	$\Delta P_m \cdot t \cdot E_f$	
EW	Inefficient use of equipment	$\Delta P_m \cdot t \cdot E_f$	E_d – Energy consumption for unit of distance covered E_f – Emission factor P_m – Average power consumption t – Reference Time ΔP_m – Power consumption due to inefficiency Δd – Inefficient distance covered
	Inefficient use of air conditioning	$P_m \cdot t \cdot E_f$	
	Inefficient material handling system	$\Delta d \cdot E_d \cdot E_f$	
EY	Thickness of insulation	$\Delta E \cdot E_f$	E_f – Emission factor P_m – Average power consumption t – Reference Time ΔP_m – Power consumption due to inefficiency/oversizing/low performance ΔE – Energy consumption due to insufficient thickness $\Delta \eta$ – Performance inefficiency
	Inefficient lighting/air conditioning system	$\Delta P_m \cdot t \cdot E_f$	
	Oversized lighting/air conditioning system	$\Delta P_m \cdot t \cdot E_f$	
	Low nominal equipment performance	$\Delta \eta \cdot P_m \cdot t \cdot E_f$	

(*continued*)

Table 2.
Loss types and calculation formula

Emission category	Loss type	Formula	Nomenclature
ES	Usage of not renewable energy	$AC \cdot E_f$	$E_{f,pre}$ – Preventive emission factor
	Not sustainable packaging	$Q_p \cdot E_p$	E_f – Emission factor E_p – Emissions due to packaging
	Fossil Fuel Consumption	$AC \cdot NCV \cdot E_{f,pre} \cdot (1 - BF) \cdot OF$	Q_p – Packaging quantity AC – Activity data BF – Biomass fraction NCV – Net calorific value OF – Oxidation factor

Table 2.

Source(s): Author's own creation

guaranteeing responsible forest management based on strict economic, social and environmental standards. In addition, the company, aware that ecological commitment is becoming increasingly important to the business, has decided to set up a carbon emissions program. Thanks to our long-term collaboration, the company believes that OEmE can offer significant advantages for the assessment of current conditions and subsequent project implementation.

4.1 Company production cycle

Figure 2 depicts the plywood production cycle, where yellow blocks represent the company's in-house production stages, green blocks relate to production and external procurement of raw materials, brown blocks to production waste, while blue, refer to electric energy, thermal energy and fuels. It involves several steps, which are described as follows:

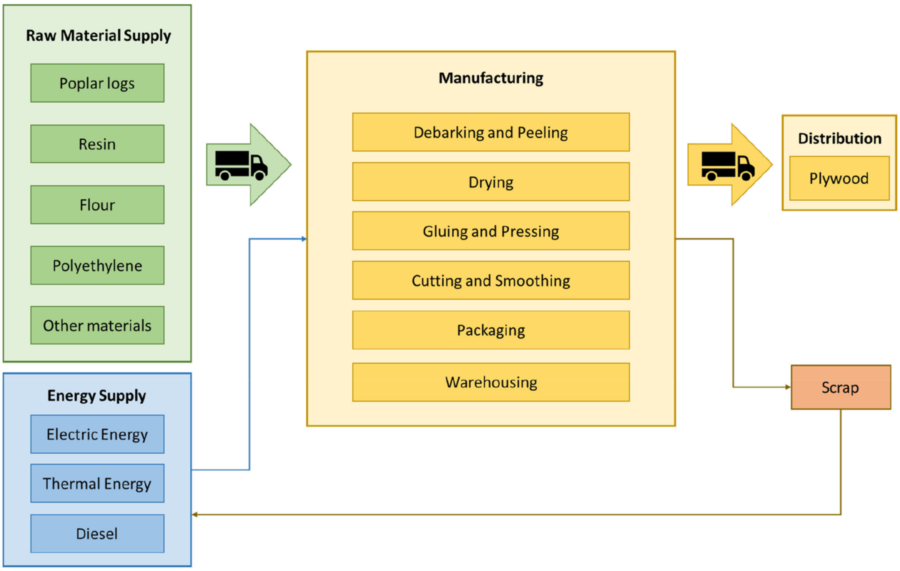


Figure 2. Company production cycle

Source(s): Author's own creation

(1) *Raw material delivers*. Poplar logs and wood veneers from the USA and Africa are transported to the plant by trucks.
(2) *Debarking and peeling*. The logs are placed on a conveyor belt that takes them to a debarker. They are then moved onto peeling lines. The veneers, between 1 and 3 mm thick, are cut, sorted and stored. From these operations, the bark and irregular waste are chipped and used as fuel for the biomass power plant, while the wood cores are sold to pallet manufacturers.
(3) *Drying*. Green veneers are dried, leading to the creation of whole or spliced sheets for further processing.
(4) *Gluing*. A dedicated machine applies adhesive mixtures to the veneer sheets, with resins and flour mixed in a separate room.
(5) *Composing*. A "composing" machine arranges layers of wood, alternating between glued and unglued sheets.
(6) *Pressing*. Automatic hot presses compress the layers using superheated water for heating.
(7) *Slide cutting*. A squaring machine trims the pressed sheets to obtain rectangular panels.
(8) *Smoothing*. Panels go through a calibrating-smoothing machine, enhancing the material's quality.
(9) *Packaging*. Plywood panels are sorted, labeled, strapped and packaged into packs, ready for storage and 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 plant. Emission losses have been collected and classified by the analysis team for about a year, following the scheme presented within the paper.

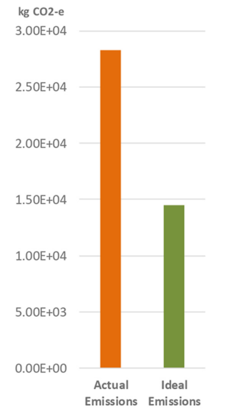
4.2 OEmE evaluation

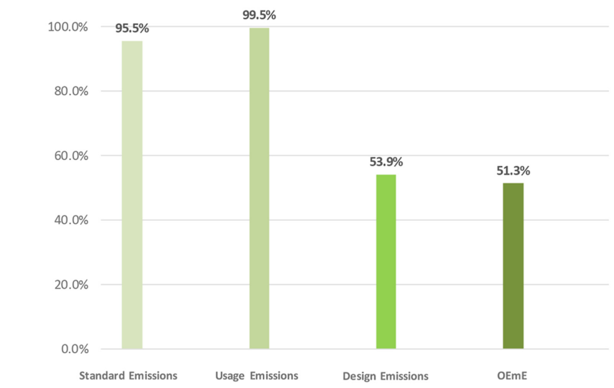
Figure 3 shows the datasheet that was used to analyze the emissions and calculate the OEmE indicator. The evaluation of emissions was carried out according to the structure proposed in Figure 1. For each loss, the Emission category it belongs to, a brief description and the associated GHG emissions are indicated. The assessment of GHG emissions was developed using the ECOINVENT 3.7 database through the OPENLCA software. The production process was parameterized, and the emissions were quantified by comparing the *as-is* condition with that in which the losses were eliminated. Appendix 2 presents the detailed emission evaluation of the losses as reported in Figure 3.

What emerges from the analysis is that Actual Emissions, which concern the GHG emissions associated with all activities carried out within the plant and were estimated equal to about 28,300 t $CO_{2\text{-e}}$ thanks to a product LCA. The only unmanageable event that occurred during the observation period was a severe water leak in the national pipeline supplying the company. Since this event could not be managed by the company, the related emissions were not involved in the subsequent calculation, and the value of Manageable Emissions was taken as the actual one. Regarding Emissions due to Standard Deviation Losses (EO and EP), they accounted for 9.29% of the total GHG emissions. Notably, they were all related to incorrect process parameters and no OE were detected during the observation period. Emissions due to Inefficient Usage Losses (EE and EW) accounted for 0.89% of total. In

Data sheet for analysing losses and calculation of OEmE

Loss type	Loss ID	Details	Scope	t CO_2-e	Percentage	Emission category	t CO_2-e	Percentage
Erroneous Process Parameter	EP1	Excessive temperature of the drying rollers	1	9.36E+01	0.68%	EP	1.28E+03	9.29%
Erroneous Process Parameter	EP2	Excessive temperature of the presses	1	1.12E+01	0.08%			
Erroneous Process Parameter	EP3	Excessive smoothing speed	2	1.11E+01	0.08%			
Erroneous Process Parameter	EP4	Non-optimal operative glue thickness	3	1.11E+03	8.03%			
Erroneous Process Parameter	EP5	Non-optimal size of the load unit	2	5.88E+01	0.43%			
Degradation of thermal insulation	EE1	Degradation of piping thermal insulation	1	1.39E+00	0.01%	EE	1.80E+01	0.13%
Failure	EE2	Multiple failures of electric engines	3	1.25E-01	0.00%			
Rework	EE3	Plastering of non correctly pressed veneers	3	1.65E+01	0.12%			
Inefficient use of equipment	EW1	Inefficient log dragging due to too low grapple positions	1	1.05E+02	0.76%	EW	1.05E+02	0.76%
Thickness of insulation	EY1	Adjacent piping without thermal insulation	1	1.04E+01	0.08%	EY	1.04E+01	0.08%
Fossil fuel consumption	ES1	Diesel consumption as fuel for log handling machines	1	5.23E+02	3.79%	ES	1.24E+04	89.74%
Purchase of not renewable energy	ES2	Consumption of electric energy from national grid	2	1.18E+04	85.6%			
Non-sustainable Packaging	ES3	Consumption of polyethylene as wrapping material	3	5.21E+01	0.38%			





OEmE Calculation		t CO_2-e
Actual Emissions		2.83E+04
	EU	0
Manageable Emissions		2.83E+04
	EO	0
	EP	1.28E+03
Standard Emissions		2.70E+04
	EE	1.80E+01
	EW	1.05E+02
Target Emissions		2.69E+04
	EY	1.04E+01
	ES	1.24E+04
Ideal Emissions		1.45E+04
Standard Emissions Effectiveness		95.5%
Usage Emissions Effectiveness		99.5%
Design Emissions Effectiveness		53.9%
Overall Emissions Effectiveness (OEmE)		51.3%

Source(s): Author’s own creation

Figure 3.
Data sheet for analyzing losses and calculation of OEmE

particular, equipment condition-related (EE) losses accounted for 0.13%, while those due to worker error (EW) accounted for 0.76%. The largest contribution to overall emissions came from Emissions due to Design Losses (EY and ES). Indeed, they accounted for over 89.8%. An interesting observation is that losses related to emissions not only concern Scope 1 and 2, but also Scope 3 which, overall, account for 8.53% of the total GHG emissions. Indeed, the glue for the adhesive mixture (EP4), the epoxy plaster for rework (EE3), the electric motor failures (EE2) and the polyethylene casing (ES3) constitute material consumption, and therefore the emissions associated with them are classified as Scope 3. Typically, these emissions would not be included in the traditional analysis, which only includes Scope 1 and 2 emissions.

Once emissions had been evaluated, it was possible to assess the Standard Emissions Effectiveness, the Usage Emissions Effectiveness, the Design Emissions Effectiveness and thus to estimate the OEmE:

$$\text{Standard Emissions Effectiveness} = \frac{\text{Standard emissions}}{\text{Manageable emissions}} = \frac{2.7E+04}{2.8E+04} = 95.5\% \tag{6}$$

$$\text{Usage Emissions Effectiveness} = \frac{\text{Target emissions}}{\text{Standard emissions}} = \frac{2.69E+04}{2.7E+04} = 99.5\% \tag{7}$$

$$\text{Design Emissions Effectiveness} = \frac{\text{Ideal emissions}}{\text{Target emissions}} = \frac{1.45E+04}{2.69E+04} = 53.9\% \tag{8}$$

Formula (6) depicts that Standard Emissions were 95.5% of Manageable Emissions, of which approximately 86% is represented by Scope 3 emissions. The latter was evaluated by subtracting the Emissions due to Standard Deviation Losses. In this case, a total of 1,280 t $CO_{2\text{-}e}$ was released into the atmosphere. Formula (7) shows that Target Emissions were 99.5% of Standard Emissions, of which approximately 75% is represented by Scope 3 emissions. Altogether, these emissions are equal to 123 t $CO_{2\text{-}e}$. Formula (8) highlights that Ideal Emissions were 53.9% of Target Emissions. Specifically, 12,400 t $CO_{2\text{-}e}$ were released due to Design Losses. Formula (9) provides the OEmE, as the product of the previously described indicators:

$$\begin{aligned}\text{OEmE} = &\text{Standard Emission Effectiveness} \times \text{Usage Emissions Effectiveness} \times \\ &\text{Design Emissions Effectiveness} \\ &= 95.5 \times 99.5 \times 53.9 = 51.3\,\%\end{aligned} \tag{9}$$

The OEmE value of 51.3% suggests that emissions performance was far from optimal, and therefore that there was much opportunity for improvement. By exploiting the layered structure of the tool, it was possible to identify areas where the implementation of improvements could be most effective. As can be seen, the Design Emissions Effectiveness played an important role in the overall performance, promoting a more environmentally aware choice of materials and energy at the design stage. ES2 (85.6%) is the main source of GHG emissions within the plant, so its resolution represents a great opportunity to improve environmental performance. This could be done in several ways such as switching to certified renewable purchased electricity or installing a photovoltaic system for own renewable power generation. Since the electrical power installed in the factory is equal to 4 MW, the latter would require a large system that cannot be easily installed in the plant. The former, on the other hand, represents a much simpler solution with the signing of a new contract with renewable energy suppliers. Also, among the Design Losses, ES1 (3.79%) was the third largest loss. There are several more environmentally conscious alternatives on the market, such as B20 biodiesel, which contains 20 parts biomasses per 100 parts fuel, or the even better

B100, which is pure biodiesel. EP4, accounting for 8.03% of GHG emissions, stands as the second-largest contributor. To mitigate this impact, reducing glue thickness and enhancing operator training can curtail emissions and material use without compromising product quality. Unlike traditional analyses focusing on Scope 1 and 2 emissions from energy, these material-related Scope 3 emissions often go overlooked. This revelation provides companies with more avenues to bolster sustainability in their operations and procurement decisions. Importantly, these improvements require no capital expenditure. If successful, Usage Emissions Effectiveness and Design Emissions Effectiveness would reach 99.3 and 99.7%, resulting in an OEmE of 98.5%.

5. Conclusions

In this paper, a new Lean indicator to assess the current GHG emissions performances of production systems is presented. This new indicator, which is named OEmE, adopts a well-framed structure based on a new emissions-losses related classification. Specifically, the new indicator is the product of three separate components, which are related to the corresponding GHG emissions category: Standard Emissions Effectiveness, Usage Emissions Effectiveness and Design Emissions Effectiveness. OEmE aims simultaneously to assess the current performances and identify areas where greater opportunities of improvement reside. Indeed, each of the three components of OEmE pinpoints specific aspects of the process that can be targeted for enhancement. It is worth noting that the tool approaches performance assessment with a holistic view. It can be product, process or service oriented, yet the tool remains operational and effective, providing a valuable resource for planning and managing sustainable development strategies.

The OEmE was applied to a plywood production company providing an accurate assessment of the current situation and addressing improvement actions. Specifically, the OEmE detected losses at each process production step resulting in a global value equal to 51.3%. The intermediate indicators were 95.5%, 99.5% and 53.9%, respectively. The design phase contained many opportunities for improving environmental performances, dealing with both suppliers and the technical department. The plant manager recognized that the most attractive feature of the tool was its functionality and effectiveness. He also appreciated the fact that the calculation routines for the various metrics could be easily performed using electronic spreadsheets.

By analyzing the results of the application, several implications for practitioners clearly emerges:

(1) At the same time, the tool assesses performance and identifies room for improvement; practitioners recognize this as a clear opportunity to enhance environmental performance within their facilities.

(2) Utilizing the layered structure of the tool can help identify areas where implementation of improvements will be most effective. Practitioners should consider a systematic approach to address specific aspects of emissions performance.

Recognize that traditional environmental analyses often focus on Scope 1 and 2 emissions. However, our findings indicate that addressing material consumption aspects can have a significant impact on reducing emissions in Scope 3. With OEmE, practitioners are able to broaden their environmental analysis and include these aspects.

We are aware that OEmE has some limitations. First, it does not directly consider possible interactions between improvement actions. This requires the analysis team to carefully consider how the implementation of one corrective action in one part of the plant affects the performance of the others. Moreover, OEmE gives a purely deterministic measure of effectiveness. It is then possible to exploit an approach able for managing variance and uncertainty of OEmE, considering fuzzy triangular numbers instead of burdensome stochastic quantities (Braglia *et al.*, 2019). Finally, while the selection of improvement actions is guided by a well-structured use of metrics, there is currently a lack of a cost-effective comparative analysis among various solutions. Consequently, the assessment of the optimal solution for minimizing losses in a specific location lacks an economic perspective. These limitations highlight the need for future advancements in this area.

From a theoretical perspective, to provide a comprehensive environmental analysis, the tool could be integrated with the LCA approach. In this way, many environmental aspects such as water consumption, air pollution, ozone depletion, eutrophication, etc. could be considered. From a practical perspective, the tool could be developed in two different ways. On one hand, it could be accompanied by a cost–benefit analysis to support decision-making in selecting the most effective improvements. More generally, it could be part of a broader set of KPIs also covering social and economic aspects, in line with the goals of the Agenda 2030. Conversely, there is an opportunity to conduct a thorough examination of the interactions among corrective actions, considering both positive and negative effects. This investigation can help identify and capitalize on improvement chain opportunities.

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(The Appendix follows overleaf)

Appendix 1

Appendix 1 explains the calculation formulas adopted to estimate emissions due to industrial losses, which are presented in Table 2.

Emissions due to organizational losses **(EO)**

(1) Not Required start-up: $\left(\frac{P_{ru}}{2} \cdot T_{ru} + P_{stand} \cdot t\right) \cdot E_f$

P_{ru} – Power consumption at start up $[kW]$

T_{ru} – Start-up time $[h]$

P_{stand}- Power consumption in stand by $[kW]$

t – Stand by time $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

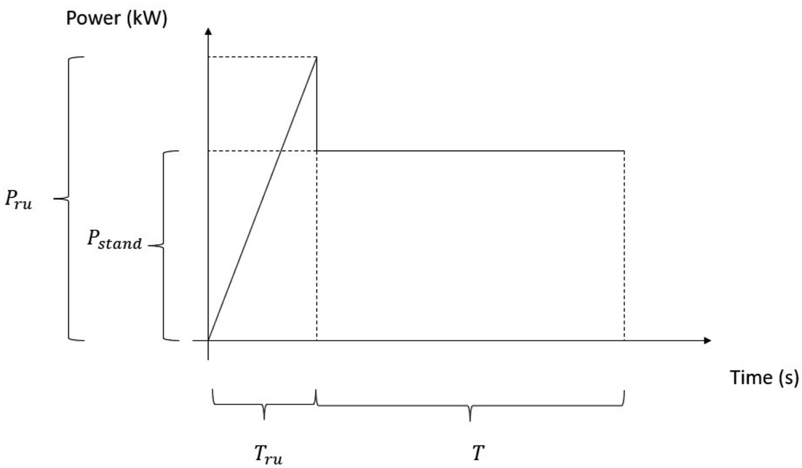

Figure A1. Start-up phase

Source(s): Author’s own creation

GHG emissions due to not required start-up are the product of the energy consumed during start-up multiplied by the specific emissions factor. The energy is the sum of two contributions: the energy consumed during ramp-up and the energy consumed during stand-by, when the equipment is on without operative functioning. Depending on the energy source, the emissions factor converts the energy consumed during the process into GHG emissions.

(2) Not Required Heating/Cooling: $E_{H/C} \cdot E_f$

$E_{H/C}$ – Energy consumption for heating/cooling $[kWh]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions due to Not Required Heating/Cooling are the product of the Energy consumed during the heating/cooling process multiplied by the specific Emissions factor.

(3) Not Required use of lighting system: $P_{ls} \cdot t \cdot E_f$

P_{ls} – Power consumed by the lighting system $[kW]$

t – Time lighting system use $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions due to Not Required use of lighting system are the product of the consumed Energy multiplied by the specific Emissions factor. The energy is the product of the power consumed by the lighting system multiplied by the time of lighting system use.

Emissions due to procedural losses **(EP)**

(1) It is significant to emphasize that EP are closely related to the specific case under investigation and therefore it is particularly difficult to propose a universally valid formula for their evaluation. For instance, a non-optimal operative glue thickness, or an excessive temperature of drying rollers.

Emissions due to equipment conditions **(EE)**

(1) Leakages of fluid (air or vapor): $Q_v \cdot E_v \cdot E_f$

Q_v – Air/Steam quantity [m^3 or kg]

E_v – Energy consumption for unity of air/steam quantity [$\frac{kWh}{m^3}$ or $\frac{kWh}{kg}$]

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions due to Leakages of fluids without GWP (such as, air or steam) are the product of the Energy consumed to produce the fluid multiplied by the specific Emission factor. The energy consumed is the product of the energy required per unit of steam/air multiplied by the quantity of steam/air produced.

(2) Leakages of GHG fluids with not negligible GWP: $Q_l \cdot GWP$

Q_l – Leakage quantity [kg]

GWP – Global Warming Potential $\left[\frac{t_{CO_2-e}}{kg}\right]$

Emissions due to leakages of fluid (GHG) are the product of the leakage quantity multiplied by the specific Global Warming Potential of the fluid.

(3) Failure: $P_{main} \cdot T_r \cdot E_f + E_m$

P_{main} – Power consumption in maintenance condition $[kW]$

T_r – Maintenance time $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

E_m – GHG emissions due to spare parts purchase [t_{CO_2-e}]

GHG emissions due to failures are the sum of two contributions: emissions generated during the maintenance process and emissions associated with the purchase of spare parts. GHG emissions generated during the process are the product of the power consumed under maintenance conditions multiplied by the maintenance time and the emission factor.

(4) Scrap disposal: $Q_s \cdot E_s$

Q_s – Scrap quantity [kg]

E_s – GHG emissions due to disposal of scrap unity $\left[\frac{t_{CO_2-e}}{kg}\right]$

GHG emissions due to Scrap Disposal are the product of the scrap quantity multiplied by the specific emissions for scrap unit associated with the disposal process.

(5) Degradation of insulation: $\Delta E \cdot E_f$

ΔE – Energy consumption due to degradation $[kWh]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions due to the degradation of insulation is the product of the lost thermal energy multiplied by the specific Emission factor.

(6) Rework: $P_{proc} \cdot T_{proc} \cdot Q_r \cdot E_f$

P_{proc} – Power consumption during processing $[kW]$

T_{proc} – Processing time $[h/kg]$

Q_r – Rework quantity $[kg]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions from rework are the product of the energy consumed in the rework process multiplied by the emission factor. The energy consumed is the product of the power required for processing multiplied by the processing time of the rework unit and the amount of work.

(7) Performance degradation of equipment: $\Delta P_m \cdot t \cdot E_f$

ΔP_m – Power consumption due to performance degradation $[kW]$

t – Usage time of the equipment $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions due to Performance degradation of equipment are the product of the power consumption due to degradation multiplied by the processing time and the emission factor.

Emissions due to worker mistakes (EW)

(1) Inefficient use of equipment: $\Delta P_m \cdot t \cdot E_f$

ΔP_m – Excessive power consumption due to inefficient use $[kW]$

t – Processing time $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

GHG emissions due to the inefficient use of equipment are the product of the power consumption due to the inefficiency multiplied by the processing time and the emission factor.

(2) Inefficient use of lighting/air conditioning system: $\Delta P_m \cdot t \cdot E_f$

ΔP_m – Excessive power consumption due to inefficient use $[kW]$

t – Processing time $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions due to the Inefficient use of lighting/air conditioning system are the product of the power consumption due to the inefficiency multiplied by the processing time and the specific emission factor.

(3) Inefficient material handling system: $\Delta d \cdot E_d \cdot E_f$

Δd – Inefficient distance covered [km]

E_d – Energy consumption for unit of covered distance $[\frac{kWh}{km}]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

Emissions due to the Inefficient material handling system are the product of the energy consumption for unit of covered distance multiplied by the inefficient covered distance and the emission factor.

***Emissions due to yield losses* (EY)**

(1) Thickness of insulation: $\Delta E \cdot E_f$

ΔE – Energy consumption due to insufficient insulation $[kWh]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

GHG emissions due to the insufficient thickness of insulation is the product of the thermal energy losses multiplied by the specific Emission factor.

(2) Inefficient lighting/air conditioning system: $\Delta P_m \cdot t \cdot E_f$

ΔP_m – Excessive power consumption due to inefficiency $[kW]$

t – Processing time $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

GHG emissions due to the Inefficient lighting/air conditioning system are the product of the power consumption due to the inefficiency multiplied by the processing time and the emission factor.

(3) Oversized lighting/air conditioning system: $\Delta P_m \cdot t \cdot E_f$

ΔP_m – Power consumption due to oversizing $[kW]$

t – Processing time $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

GHG emissions due to the Oversized lighting/air conditioning system are the product of the power consumption due to the oversizing multiplied by the processing time and the emission factor.

(4) Low nominal equipment performance: $\Delta P_m \cdot t \cdot E_f$

ΔP_m – Power consumption due to low nominal performance $[kW]$

t – Processing time $[h]$

E_f – Emission factor $\left[\frac{t_{CO_2-e}}{kWh}\right]$

GHG emissions due to the low nominal performances of equipment are the product of the power consumption due to the operating multiplied by the processing time and the emission factor.

***Emissions due to supply losses* (ES)**

(1) Purchasing of non-sustainable raw material: $Q_m \cdot E_m$

Q_m – Raw material quantity $[kg]$

E_m – Emissions due to raw material purchase $\left[\frac{t_{CO_2-e}}{kg}\right]$

GHG emissions due to purchasing of non-sustainable raw materials are associated with the extraction, production and transportation of raw materials. They are obtained as the product of the raw material mass purchased multiplied by the emissions per unit of the raw material.

(2) Purchasing of non-sustainable packaging: $Q_p \cdot E_p$

Q_p – Packaging quantity $[kg]$

E_p – Emissions due to packaging purchase $\left[\frac{t_{CO_2-e}}{kg}\right]$

GHG emissions due to Purchasing of non-sustainable packaging are associated with the production, transportation and disposal of packaging. They are obtained as the product of the packaging mass purchased multiplied by the emissions for the packaging unit.

(3) Purchasing of non-sustainable fluid: $Q_{fl} \cdot E_{lf}$

Q_{fl} – Fluid quantity $[m^3 \text{ or } kg]$

E_{lf} – Emissions due to fluid purchase $\left[\frac{t_{CO_2-e}}{m^3}\ or\ \frac{t_{CO_2-e}}{kg}\right]$

Emissions due to purchasing of non-sustainable fluid are associated with the production, transportation and disposal of fluid. They are obtained as the product of the fluid quantity purchased multiplied by the emissions per unit of fluid.

Appendix 2

Appendix 2 presents the detailed emission evaluation of the losses as reported in Figure 3. Emissions were estimated using the ECOINVENT 3.7 database through the OPENLCA software.

1. *Loss ID:* EP1

The surfaces of the dryer rollers are heated by superheated water at 190 °C. The surface temperature set point is gradually reduced to 180 °C, while still complying with the required humidity standard. This results in a saving of 10% of the total thermal energy required for drying (82% of the total thermal energy required by the whole production process), or 5,500 MWh.

Emissions were estimated equal to 93.6 t CO_2-e.

2. *Loss ID:* EP2

The surfaces of hot presses are heated by superheated water to 160 °C. The set point of the surface temperature is gradually reduced to 145 °C, while maintaining the necessary quality standards. This results in a saving of 20% of the total thermal energy required for pressing (6% of the total thermal energy required by the whole production process), or 712 MWh.

Emissions were estimated equal to 11.2 t CO_2-e.

3. *Loss ID:* EP3

During the plywood polishing process, the set sanding speed is 70 m/s. The surface quality standard was also met when operating at 63 m/s. As a result, it was possible to save 1% of the total electrical energy required for polishing (8.8% of the total electrical energy required for the entire production process), i.e. 15 MWh. In modeling, we assumed the Italian electricity mix reported in the AIB European Residual mix. For this calculation and the subsequent Scope 2 emission calculations, we implemented the low-voltage electricity production process model shown in the ECOINVENT 3.7 Database. Adopting the electricity mix described above, the emission factor is 0.694 kg CO_2-e/kWh.

$$\begin{aligned}\text{GHG emissions} &= 15,000\,\text{kWh} \times 0.694\,\text{kg}\,\text{CO}_2-\text{e}\,/\text{kWh} = 11,100\,\text{kg}\,\text{CO}_2-\text{e}\\ &= 11.1\,\text{t}\,\text{CO}_2-\text{e}\end{aligned}$$

4. *Loss ID:* EP4

The total annual mass of resin is approximately 5,693 t and the total mass of flour is approximately 1,087 t. The operators lack proper training, and specific procedures have to be implemented. By carrying out several tests, the required glue thickness could be reduced, and glue consumption was reduced by 10%.

Emissions were estimated equal to 1,107 t CO_2-e.

5. *Loss ID:* EP5

By simulating internal plant logistics with Anylogic® software, the loading unit and subsequent handling were redesigned. In particular, by stacking more layers of plywood, the distance travelled by forklifts could be reduced by 20%. The new loading unit stacks 2 or 3 more layers depending on layer thickness. The average electric energy required to charge a forklift truck in one shift is 76 kWh. Considering 250 working days, two shifts per day, and an average number of forklifts in circulation of 11, the annual energy savings can be estimated:

$$\text{Electric energy saving} = 152\,\text{kWh} \times 250\text{ days} \times 11 \times 0.2 = 85\,\text{MWh}$$

$$\text{Annual GHG emissions} = 85,000\,\text{kWh} \times 0.694\,\text{kg}\,CO_2 - \text{e}\,/\text{kWh} = 58,800\,\text{kg}\,CO_2 - \text{e} = 58.8\,\text{t}\,CO_2 - \text{e}$$

6. *Loss ID:* EE1

The temperature of the superheated water is 200 °C, while the thermal imaging camera has detected a surface temperature of the insulation equal to 150 °C. The insulated length is 25 m and the pipe's diameter is 200 mm. Assuming a heat exchange coefficient for the heat exchange with the environment equal to 8 W/m^2 K and an average ambient temperature of 15 °C, a dissipated thermal power of 20.36 kW was obtained. Considering that the equivalent operating load time is 4,000 h, the annual losses of thermal energy have been estimated as follows:

$$\text{Thermal energy loss} = 20.4\,\text{kW} \times 4,000\,\text{h} = 81.44\,\text{MWh}$$

Emissions were estimated equal to 1.385 t CO_2-e.

7. *Loss ID:* EE2

During the observation period, in the smoothing sectors, there were four electric motor failures. From the ECOINVENT 3.7 database, the life cycle emission factor for a 0.55 kW triphasic electric motor is 4.46 kg CO_2-e/kg. Considering the average engine mass is equal to 7 kg, it was possible to estimate the emissions associated with the engine substitution as follows:

$$\text{Engine failures emissions} = 7\,\text{kg} \times 4.46\,\text{kg}\,CO_2 - \text{e}\,/\text{kg} \times 4 = 125\,\text{kg}\,CO_2 - \text{e} = 0.125\,\text{t}\,CO_2 - \text{e}$$

8. *Loss ID:* EE3

The total amount of epoxy plaster mass used annually to repair surface damages on hot-pressed plywood is about 34.7 t. Through better control of the surface temperature of the press, it may be possible to reduce/eliminate this material consumption.

Emissions were estimated equal to 16.5 t CO_2-e.

9. *Loss ID:* EW1

Dragging the logs in the highest position decreases drag from the logs and yields the lowest possible fuel consumption. The lower the load, the greater the fuel consumption and the higher chance there is for the load to hit a stump or snag logging debris, which could further increase drag on the load. Considering the average skidder fuel consumption equal to 25 lt/h, rising the logs turns into a 20% fuel saving. The annual diesel consumption is 169 t. Considering a fuel density of 0.850 kg/lt, the annual volume of diesel is 198,800 litres. From ECOINVENT 3.7 database, the emission factor of diesel is equal to 2.63 kg CO_2-e/lt. The annual emissions associated with inefficient log dragging can be calculated as follows:

$$\text{Annual emissions} = 0.2 \times 198,800\,\text{lt} \times 2.63\,\text{kg}\,CO_2 - \text{e/lt} = 104,600\,\text{kg}\,CO_2 - \text{e} = 104.6\,\text{t}\,CO_2 - \text{e}$$

10. *Loss ID:* EY1

The temperature of the superheated water is 200 °C, while the thermal imaging camera has detected a surface temperature of the insulation equal to 150 °C. The insulated length is 30 m and the pipe's diameter is 120 mm. Assuming a heat exchange coefficient for the heat exchange with the environment equal to 8 W/m^2 K and an average ambient temperature of 15 °C, a dissipated thermal power of 16.7 kW was obtained. Considering that the equivalent operating load time is 4,000 h, the annual losses of thermal energy have been estimated as follows:

$$\text{Thermal energy loss} = 16.74\,\text{kW} \times 4,000\,\text{h} = 66.96\,\text{MWh}$$

Emissions were estimated equal to 10.4 t CO_2-e.

11. *Loss ID:* ES1

The annual diesel consumption is 169 t. Considering a fuel density of 0.850 kg/lt, the annual volume of consumed diesel is 198,800 litres. There are several greener alternatives on the market such as B20 biodiesel, which contains 20 parts biomass to 100 parts fuel, or the even better B100, which is pure biodiesel. The annual emissions associated with diesel consumption can be calculated as follows:

$$\begin{aligned}\text{Annual emissions} &= 198,800\,\text{lt} \times 2.63\,\text{kg}\,\text{CO}_2 - \text{e/lt} = 523,000\,\text{kg}\,\text{CO}_2 - \text{e} \\ &= 523\,\text{t}\,\text{CO}_2 - \text{e}\end{aligned}$$

12. *Loss ID:* ES2

The electricity required annually is equal to 16,998 MWh. The annual emissions due to electric energy consumption from the national grid can be estimated as follows:

$$\begin{aligned}\text{Annual emissions} &= 16,998,000\,\text{kWh} \times 0.694\,\text{kg}\,\text{CO}_2 - \text{e}\,/\text{kWh} = 11,800,000\,\text{kg}\,\text{CO}_2 - \text{e} \\ &= 11,800\,\text{t}\,\text{CO}_2 - \text{e}\end{aligned}$$

13. *Loss ID:* ES3

The required annual mass of polyethylene is 27 t. There are several more environmentally aware alternatives on the market. For example, cellophane is a widely used biodegradable material for packaging. However, a cellophane mass of 1.58 times that of polyethylene is required to perform the same wrapping. From the ECOINVENT 3.7 database, the life cycle emission factors for cellophane and polyethylene are 0.96 kg CO_2-e/kg and 3.45 kg CO_2-e/kg, respectively. The annual emissions related to the change of packaging material are estimated as follows:

$$\begin{aligned}\text{Packaging switch emissions} &= 27,000\,\text{kg} \times 3.45\,\text{kg}\,\text{CO}_2 - \text{e}\,/\text{kg} \\ &\quad - 1.58 \times 27,000\,\text{kg} \times 0.96\,\text{kg}\,\text{CO}_2 - \text{e}\,/\text{kg} \\ &= 52,100\,\text{kg}\,\text{CO}_2 - \text{e} = 52.1\,\text{t}\,\text{CO}_2 - \text{e}\end{aligned}$$

About the authors

Marcello Braglia graduated (with distinction) in 1988 in Electronic Engineering at Politecnico di Milano. Since 1995, he has been a Researcher in Mechanical Technology and Production Systems at the Università degli Studi di Brescia. Since 1998, he has been employed as a researcher and since 2002, as a Full Professor, in Industrial Plants at the Università di Pisa. His research activities mainly concern maintenance, reliability, production planning, lean production, logistics and statistical quality control. He is the author of about 180 technical papers published in national and international journals and conference proceedings. He is a member of ANIMP (National Association on Industrial Plants) and AIDI (National Association of Academicians on Industrial Plants).

Francesco Di Paco graduated in 2022 in Mechanical Engineering (110/110) at the University of Pisa. He is currently a PhD student in Industrial Mechanical Systems Engineering at the same university. His research activities mainly concern the development of Lean Manufacturing tools and methods for digital and environmental transition. In particular, the focus of his research includes energy efficiency,

improving resource consumption, mitigating greenhouse gas emissions and reducing pollution. Francesco Di Paco is the corresponding author and can be contacted at: francesco.dipaco@phd.unipi.it

Roberto Gabbrielli graduated with honors in Mechanical Engineering at the University of Pisa (Italy). He has a PhD in Energy Power Systems and is an Associate Professor in Industrial Systems Engineering at the Department of Civil and Industrial Engineering of the University of Pisa (Italy). His current research activity concerns the production planning and control, lean methods for material management, the development of decision support systems for industrial investments and the material logistics. To this purpose, novel management methods and mathematical models have been introduced for the performance improvement of the logistic systems. He is author of more than 40 papers published in scientific international journals with peer review.

Leonardo Marrazzini graduated in 2016 in Mechanical Engineering (110/110) at the University of Pisa. In 2020, he obtained a PhD degree in Industrial Engineering (cum Laude) at the University of Pisa. At present, he is a Universitary Researcher (RTDa) in Industrial Mechanical Systems Engineering in the same university. His research activities mainly concern the adaptation of the Lean Manufacturing principles to Engineer-to-Order production environments. In particular, the goal of the research is to develop techniques and models to support various company operations. He is the author of 30 technical papers published in international journals and conference proceedings. He is a member of AIDI (National Association of Academicians on Industrial Plants).