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Research Article

A Novel Model to Quickly Assess the Environmental Impact of Automotive Collision Repair Workshops

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The automotive industry has recently witnessed a growing emphasis on sustainability and environmental responsibility. Within this context, automotive collision repair workshops significantly contribute to the sector's environmental impact (EI), and it is crucial to evaluate EI efficiently, have better-informed decision-making, and promote sustainability within this domain. The conventional practices in these workshops often have a significant EI, from the disposal of hazardous materials to the energy-intensive processes of paint application and sheet metal repair. However, there is a significant gap in the literature regarding works undertaken to mitigate this problem. The primary objective is to create a computational program model that swiftly and accurately enables the evaluation of the EI of any automotive collision repair workshop for each service provided (e.g., washing and painting). The computational program, in turn, facilitates a process of continuous improvement concerning environmental sustainability (one of the Triple Bottom Line pillars). A detailed analysis of the reports on each service made it possible to scrutinize and highlight the factors contributing most negatively to the EI.

Keywords: automotive; collision repair; environmental footprint; paint shop

1. Introduction

The automotive industry has been one of the main pillars of the world economy in recent decades, but it has also been responsible for a substantial part of the aggressions caused by humanity on the environment. There has been a remarkable evolution in the way companies have managed their product development, trying to reduce the damage caused to the environment. This situation is challenging to manage, as vehicles have to meet a series of requirements demanded by the market in terms of performance, safety, and style, which has to be appropriately settled with increasingly restrictive legislation regarding environmental impact [1].

Academic researchers, who dedicate their efforts to the advancement of knowledge and the enhancement of various fields, have meticulously examined a multitude of strategies and methods aimed at significantly elevating the competitiveness of industries when viewed from an environmental standpoint, which inherently involves an array of resources, extensive data collection, and comprehensive research initiatives being conducted across different regions and countries around the globe [2]. A substantial portion of the vast and thorough research that has been undertaken in this domain is focused on the critical task of identifying the key drivers and influential factors that possess the potential to lead to notable success and positive outcomes in this increasingly important area of study and practice [3, 4]. The phenomenon of rapid industrialization that has occurred in the majority of countries around the world has unfortunately resulted in a marked increase in excessive consumption of vital resources such as water, energy, and raw materials, coupled with a concerning lack of regard for environmental

sustainability, thereby causing significant disruptions and detrimental impacts on the social development and overall well-being of the population [5, 6]. This situation necessitates a comprehensive approach that not only addresses the immediate challenges but also fosters long-term strategies aimed at promoting sustainable practices and responsible resource management, ensuring that future generations can thrive without compromising the planet's health.

There is an urgent need to change unsustainable production and social patterns of behavior to new sustainable paradigms, considering the following four segments: global, national, sectorial, and individual. Chen et al. [7] highlight the intense research on the so-called "green industries," mitigating emissions, reducing the consumption of raw materials, and, cumulatively, contributing to sustainable consumption and an economically viable future. Taisch et al. [8] noted that this environmentally sustainable change, as a competitive advantage, is not simple to implement. Some authors suggest strategies formulated as guidelines/models to be undertaken by companies [9] or governments [10]. These strategies often emphasize collaboration across sectors, innovation in technology, and the importance of consumer awareness to drive the transition towards sustainability.

Baumgartner and Rauter [3] posited that sustainable development encompasses economic, environmental, and social advancement that satisfies the requirements of the present generation without undermining the capacity of future generations to fulfill their own needs. In this framework, enterprises possess a pivotal responsibility. Consequently, sustainability assessment emerges as a preeminent business activity that illustrates the correlation between environmental strategy and the organization's dedication to a sustainable global economy [11]. These advancements have been gradual, underscoring the necessity for a more dynamic approach that enables organizations to engage strategically in this vital environmental domain.

The automotive sector has been increasing worldwide, inducing an increase in after-sales services and driving companies towards a sustainable development–oriented innovation, translating into a competitive market advantage [12]. The increase in the market impacts the aggression caused to the environment, such as CO_2 emissions, global warming, and scrap production, among others, due to the services provided to end consumers. In turn, awareness about the environment is increasingly present among potential consumers who support companies' activities [13].

Most consumers have researched to understand their direct impact (environmental footprint) on the act of consumption. In this sense, the consumer's profile has changed, leveraging the concern regarding environmental issues. This point leads to the need to adapt automotive after-sales services from a sustainable perspective against the backdrop of the circular economy and the measurement of CO_2 emissions using environmental performance indicators [14].

It has been a challenge to identify accurate key performance indicators for a sustainable environmental management system. Homrich et al. [15] highlight essential points, such as reducing energy/water consumption, recycling resources in general, and, in particular, materials and energy. According to de Jesus and Mendonça [16], as primary barriers to the implementation of sustainable metrics, the following stand out: investment costs, lack of environmental culture, and lack of means/ways to measure the factors of impact on environmental sustainability. Tura et al. [17] identify some drivers that tend to encourage sustainable practices, such as resource limitations to prevent adverse environmental impacts; the ability to act to reduce costs; search for new sources of income; raising awareness to improve sustainability; compliance with regulations/normative requirements; government policies of financial, fiscal, and subsidy support; ability to improve existing operations; the existence of new technologies (eco-innovation); and willingness to adopt them.

Babel et al. [18] compared water use, energy consumption, and CO_2 emissions across the five largest representative companies in the automotive industry (BMW, Daimler, FCA, Nissan, and Volkswagen). This study motivated the development of a model capable of managing environmental performance in the automotive collision repair sector based on environmental indicators duly explained in this study. As a main result, an environmental performance monitoring model was obtained, which makes it possible to monitor emissions (particles, CO_2 equivalent emission, etc.) resulting from the activity of car collision repair. A monitoring tool has also been developed to support the model. As the aim of the model developed is to be easy to apply and use, the tool developed takes into account the handling of the model for a general target audience in companies. In this sense, the model becomes a driver in the monitoring of environmental performance. Thus, it seems that there is a clear tendency towards the modernization of services taking into account environmental factors [19], but this effort has not yet been felt in services related to car repair.

Creating a model to measure environmental performance in the automotive collision repair industry is necessary. A sustainability indicator is a number or a group of numbers that gives specific information about certain variables. Helleno et al. [20] state that these indicators are meant to measure, review, and share complex information. Silvius [21] explains that it is possible to create such indicators using organized, precise, and dependable information, always rooted in the principles of the Triple Bottom Line concept. Büyüközkan and Karabulut [22] offered a way to simplify complicated processes, no matter how many indicators are used, which means a lower ability to convey all the information gathered in the field, leading to a varying degree of loss in information quality regarding the studied issue [23]. Table 1 illustrates the existing environmental performance models used in [22].

According to the research conducted by Čuček et al. [24], the following objectives have been comprehensively identified and are recognized as the primary goals of sustainability indicators: to notably enhance the level of awareness as well as deepen the understanding of sustainability issues among various stakeholders [25] and to succinctly report and present data that accurately reflects the current status and ongoing performance trends, which proves to be instrumental for making informed decisions in the future.

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TABLE 1: Main environmental performance indicators (strengths and weaknesses).

Models	Strengths	Weaknesses
ISO standards (14000, 26000)	- Widely known and used by companies - Global acceptance in all industries - Definition of primary and general principles - Update and continuous development	- Partial coverage (without evaluation integration pattern) - Lack of a tangible evaluation framework (criteria) - Limited disclosure - Lack of execution capacity
Carbon Disclosure Project	- Used by the world's largest business groups - Credible and standardized information on sustainability for investing companies - Factual assessment tool, ease of use (questionnaire)	- Targets the most prominent companies - Highly descriptive report
Global Reporting Initiative	- Global recognition and wide use in all countries and industries - Providing an evaluation and reporting model - Ease of use, accumulated experience and continuous development	- Flexible selection of criteria, generating over/underreporting - Open to subjective, biased, and oral assessments - Focus on reporting - Lack of audit
Stock exchange sustainability indices	- Public disclosure of sustainability performance as an additional investment parameter for individual and corporate investors - Incentive for companies to be listed to increase investor interest - Standard methodology applicable to all companies	- Very simplified sustainability assessment methodology - Limited information disclosure by companies - Limited focus (mainly environmental management and regulatory compliance) - Lack of standards

Additionally, it is essential to effectively measure the progress that has been made to the previously established objectives that have been set forth. Moreover, it is vital to foster an environment that promotes organizational learning and development and to provide a reliable instrument that can be used to assess and measure the degree of the organization's compliance with the sustainability objectives that have been established. Finally, it is of utmost importance to offer tools that actively encourage and facilitate stakeholder involvement in the decision-making processes that influence the direction and strategies of the organization to ensure that diverse perspectives are considered and integrated into the overall strategy. This collaborative approach not only enhances transparency but also builds trust among stakeholders, ultimately leading to more sustainable and effective outcomes.

According to the comprehensive research conducted by Stacchezzini et al. [26], it is imperative that sustainability indicators are meticulously identified and judiciously selected based on a multitude of essential factors that are delineated below: First and foremost, these indicators should be underpinned by reliable, valid, and readily available data, alongside accurate information that is easily accessible to all stakeholders involved in the sustainability assessment process. Furthermore, they must possess the qualities of being technically measurable, reproducible, and low-cost and should also be straightforward to apply and evaluate in diverse contexts [27]. In addition, the preparation, identification, and selection of these indicators should be executed through a transparent and inclusive open process that invites contributions from various interested parties. The resulting set of indicators must be not only simple and meaningful but also comprehensible, employing a dual approach that combines both top-down and bottom-up methodologies to ensure inclusivity and relevance [28]. Moreover, these indicators should encompass both qualitative and quantitative metrics, allowing for a holistic evaluation of sustainability performance. Lastly, they must be designed to facilitate usability in temporal comparisons, thereby enabling effective tracking over the designated calculation and control periods, as well as providing a clear and precise unit of measure to guide assessments.

Many important measures have been taken to lessen the environmental impact, but they are insufficient for achieving the needed balance. The number of articles created about the automotive sector to tackle this environmental issue is countless [29]. The research has mainly concentrated on the car's design and manufacturing, while very little attention has been given to the car repair industry by researchers. This service sector also plays a role in harming the environment. It requires thorough examination to grasp how and to what extent it can harm the environment initially and then to implement actions to reduce the environmental damages caused [30]. These efforts have been the primary drive behind this research, which addresses a gap found in the literature concerning models that can evaluate the environmental impact of car repair shops, specifically targeting car collision repair shops, which typically handle toxic materials like abrasives, powdered/liquid paints, and similar products, along with energy usage. In this scenario, creating a detailed model that assesses both the direct and indirect consequences of these activities is crucial for establishing best practices and regulatory frameworks that can guide the industry towards more sustainable practices.

2. Methods

When it comes to continuous improvement (*lato sensu*), it is crucial to identify/assess the problems to obtain efficient and effective results. Caridade et al. [31] understood the current

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scenario (*genchi genbutsu*) was very important (direct observation leads to the identification of problems and the search for adequate solutions to mitigate the negative aspects identified). Overall, continuous improvement results from cycles of observation, planning, implementation, analysis and monitoring, review, and reassessment for a new cycle phase. The proposed objectives are only achievable if a critical analysis of the problem guided by a method is developed—a well-structured procedure that defines how to approach each phase of the problem analysis and the implementation of the proposed solutions.

The methodology used in this work consists of action-research. This methodology can be described as a family of investigation processes that simultaneously include action (or change) and investigation (or understanding) [32], using a cyclical or spiral system that alternates between action and critical reflection, improving methods/data in later cycles based on the experience (knowledge) obtained in previous cycles. Lessons learned should constitute "transferable knowledge," that is, applicable in similar situations [33]. Thus, the methodological plan outlined for the present work can be seen in Figure 1.

Thus, the content of the different methodological stages can be defined as follows:

1. Initial diagnosis: (a) on-site observation (if possible and/or necessary)—modus operandi of the collision, (b) identification of environmental problems and their causes/consequences to minimize them, and (c) documentation and classification of evidence
2. Action plan for the sustainability model elaboration: (a) bibliographic research related to the topic under study; (b) defining countermeasure actions—sustainable actions; and (c) implementation planning, according to evidence priorities
3. Implementation of the sustainability model: Implement the measures defined concerning the sustainability model
4. Evaluation of the implemented model: (a) evaluation of the outputs of the implemented measures and (b) identification and correction of continuous improvement actions (kaizen) and evaluation methods and indicators
5. Model monitoring: (a) critical analysis; (b) list of lessons learned; and (c) definition of "transferable knowledge," with a view to application in similar situations in other automotive repair sectors

These five stages provide the corresponding insights to assess the environmental impact of workshops, in a first approach related to collision repair, but scalable to other types of workshops with adequate adjustments.

3. Situational Diagnosis

The first step is diagnosing the initial situation, so it is necessary to know how to get the required information. Defining a model based on environmental indicators based on Čuček et al.'s [24] and Stacchezzini et al.'s [26] assumptions is essential to quantify the environmental impact of car collision repair services. Such indicators must be accessible and easy to collect and work with effective outputs. To ensure that the collection of inputs is credible as intended, the following points must be considered:

- Categorization of collision repair levels and their relationship to environmental impact
- Optimal environmental flow of collision activity
- Internal and external inputs to the organization

3.1. Collision Repair Level Classification and How It Relates to Environmental Effect. Regarding the repair levels, the categorization can be established in three different levels. After that, a succinct explanation of each is provided, along with relevant examples. In Table 2, it is possible to see the required repair process according to the repair level.

The repair levels need to be defined. Thus, an accurate definition of each repair level can be found in the following topics:

- Repair Level 1: This type of repair, also called an intelligent repair, involves superficial repairs, for example, painting of localized damage, such as scratches on a door (Figure 2a). This type of repair is the least harmful to the environment
- Repair Level 2: This type of repair involves repair and/or replacement of components. As an example, the repair of the side of the vehicle is shown (Figure 2b)
- Repair Level 3: Given the damage suffered by the vehicle, this type of repair involves repairing the chassis (chassis traction—straightening bench and welding of the replaced elements) (Figure 2c). This repair type is the most harmful to the environment

Level 2 and 3 repairs are the most important to consider, as they have a greater impact on energy consumption and therefore on environmental impact.

3.2. Drawing the Flow Diagram Corresponding to the Environmental Analysis in Collision Activity. Subsequently, a systemic diagram is presented to explain the modus operandi for the inputs for the proposed model. By analyzing the collision activity from an environmental perspective, it seems that the two repair areas (sheet metal and painting) have different energy consumption. On the one hand, paint repair represents a considerable weight in energy consumption (constant use of painting ovens); on the other hand, sheet metal repair uses welding processes and a flattening bench, which generally has a lower expression in energy consumption. Thus, for a reliable and exhaustive analysis, it is necessary to measure the energy consumption of each area so that it can be translated into environmental impact per vehicle repaired. For simplification and better understanding, the optimal flow of environmental analysis is

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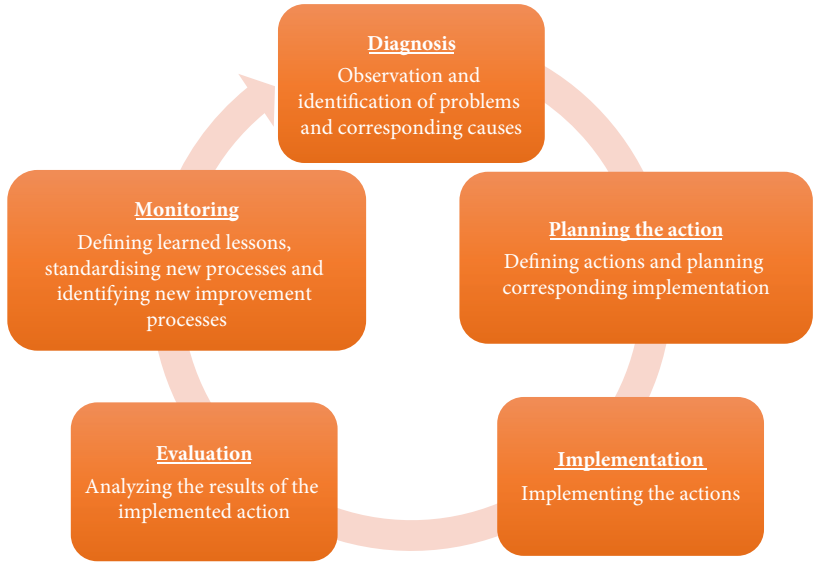


Figure 1: Action-research methodology cycle.

TABLE 2: Collision repair level categorization.

Repair level	Component restoration	Component substitution	Partial painting	Integral painting	Welding	Straightening bench
Level 1	X		X			
Level 2	X	X	X	X		
Level 3		X		X	X	X



(a)



(b)



(c)

Figure 2: Different repair levels considered in the workshop.

presented in Figure 3, which allows the construction of the respective proposed model. To measure the energy consumption of each sector, the procedure can be carried out in one of two ways presented below:

a. Survey the electrical tools used in each repair area, and based on these, measure the corresponding consumption in each sector. In other words, this option starts from the particular (each tool consumption) to the general (consumption of the associated sector—-sheet metal and/or painting).

b. Consider the energy consumption of each sector whenever there are separate measurement systems.

Given what was previously mentioned, to determine the environmental impact of the collision area, an initial analysis focused on global energy consumption, followed by an examination of its distribution by each sector.

3.3. Data Depending on the Organization to Feed the Model. The data needed to feed the environmental performance assessment model (Table 3) can be obtained directly from the evaluated organization used to validate the model. To this end, using factors such as electricity, water, natural gas and/or diesel measurement systems, and consumables inherent to the collision repair process is necessary.

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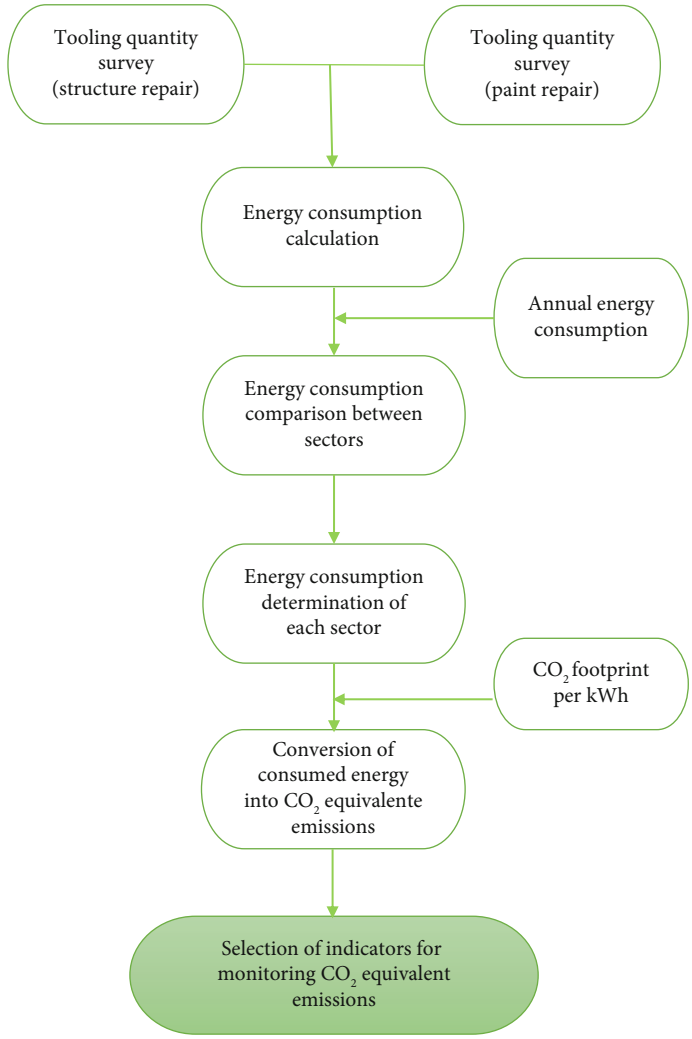


Figure 3: Flow diagram of collision environmental analysis.

TABLE 3: Internal data needed from the organization to feed the assessing model.

Internal data	Variable	Units
Number of repaired vehicles	NRV	[—]
Collision worked hours	CWH	[h]
Painting worked hours	PWH	[h]
Sheet metal worked hours	SWH	[h]
Collision sector consumed energy	CCE	[kWh]
Painting sector consumed energy	PCE	[kWh]
Sheet metal sector consumed energy	SCE	[kWh]
Water consumed in washing	WW	[L]
Recycled residues	RR	[kg]
Volatile organic compounds	VOC	[kg/h]
Paint booth fuel	PBF	[kWh]
Insulation paper	IP	[m^2]
Released particle in painting	RPP	[kg/h]

3.4. Data Depending on External Sources of Information to Feed the Model. The data to be collected externally to the organization to be evaluated (Table 4) refer to the values of equivalent CO_2 emission factor (electrical energy, paper, plastic, fuel, etc.). This is a common factor found as a reliable variable able to translate the different consumptions and deal with the diversity of variables necessary to deal within the model. It is essential to highlight the importance of these values depending on the transforming entities/industries (oil, electricity producers/plants, etc.). These values convert energy, water, plastic, and paper consumption values into equivalent CO_2 emissions.

3.5. Conversion of the Consumption Values Into Equivalent CO_2 Emission. Considering the information pointed out in Table 2, it is possible to quantify and convert the consumption values (energy, water, paper, and particles) into equivalent CO_2 emission based on the equivalent emission factors explained in Table 3. The model converts all the factors

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TABLE 4: Data needed from external entities to feed the assessing model.

External data	Variable	Unit
Equivalent CO_2 emission factor of the energy produced	FEE	[g CO_2/kWh]
Equivalent CO_2 emission factor of natural gas produced	FEG	[g CO_2/kWh]
Equivalent CO_2 emission factor of the paper produced	FEP	[kg CO_2/kg of paper]

contributing to the environmental impact into equivalent CO_2 emissions, the standard measurement variable for all factors. Thus, the mathematical expressions that allow the calculation of the equivalent CO_2 emitted were indicated, being grouped into a final value afterwards, which translated the environmental impact of any service performed in a car collision repair workshop. Thus, the leading mathematical expressions presented in the following sections convert all the adverse environmental effects into a single variable—-equivalent CO_2 emission.

3.5.1. Calculating the Equivalent CO_2 Emission in the Electric Energy Consumption. Electricity consumption is one of the main factors to account for the environmental impact of this repair service. For this, it can be converted into CO_2 equivalent through Equation (1):

$$\text{Equivalent carbon emission} = \frac{\text{amount consumed [kWh]} \times \text{equivalent emission factor}}{1000^*} \quad (1)$$

The asterisk in the above equation denotes that since emission factors express the amount of CO_2 emitted in grams [g] for each kWh of energy produced, to obtain in kilograms [kg], there is a need to divide it by 1000.

As an example, it can be considered that a particular service consumes an amount of electrical energy of 100 kWh. Given that the equivalent emission factor corresponding to electrical energy is 190 g CO_2/kWh, and applying Equation (1), the calculation provides the following result:

$$\text{Equivalent carbon emission} = \frac{100 \times 190}{1000} = 19\ [\text{kg}\,CO_2]$$

3.5.2. Calculating the Equivalent CO_2 Emission From the Natural Gas/Diesel Consumption for the Painting Oven. As the painting services later require an oven to provide the heat for the cure/solidification of the paint film, which is fed by gas or diesel, it is also necessary to convert the value of fuel consumption into equivalent CO_2 emission through Equation (2):

$$\text{Equivalent carbon emission} = \frac{\text{amount consumed [kWh]} \times \text{equivalent emission factor}}{1000^*} \quad (2)$$

3.5.3. Calculating the Equivalent CO_2 Emission Regarding the Paper Consumption. Collision repair activity also consumes paper because there is the need to isolate the areas out of the planned intervention, even before painting, avoiding the ink projection over unintended surfaces. To convert paper consumed into CO_2 equivalent emitted, Equation (3) should be used:

$$\text{Equivalent carbon emission} = \frac{\text{area consumed } [m^2] \times \text{equivalent emission factor}}{1000^*} \quad (3)$$

3.6. Determining Sustainability Indicators. To determine the sustainability indicators, in the initial phase, the indicators were divided into three groups (Table 5):

1. Group A (general indicators of the collision sector (including sheet metal and paint))
2. Group A1 (indicators specific to the painting sector)
3. Group A2 (specific indicators for the sheet metal sector)

Table 6 presents the proposed indicators able to support the proposed model.

Various emission factors (CO_2, VOCs, and particles) were calculated to quantify automobile repair's best possible environmental impact.

4. Results

A Portuguese company devoted to collision repair was selected to validate the proposed model. The company started its automotive operations in 1968, and its business portfolio includes 25 collision centers (within the scope of this study). The workshop selected for applying and validating the proposed environmental performance model is located in Oliveira do Douro (Portugal).

When analyzing the automotive collision repair activity, the following emission factors are identified as (A) energy consumed in sheet metal repair (welding processes) and painting (paint booth), (B) water consumption in washing (after vehicle repairs), (C) generated waste (scrap) resulting from repairs (recyclable/nonrecyclable components removed from the vehicle + complimentary materials used during the repair process), (D) energy consumed in the paint booth (fuel—natural gas), and (E) VOCs and suspended particles resulting from polyester putty sanding processes.

A. Energy consumed in sheet metal repair (welding processes) and painting (paint booth)

Regarding the collected company's data, Table 7 presents the overall annual energy consumption for the sheet metal and painting sector.

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TABLE 5: Indicators' categorization.

Maximum emitted CO_2	A. General indicators for the collision sector: Comprehensive indicators, which aim at a macro control of the collision repair operation, from an environmental perspective. For these indicators, it is important to obtain global data on energy, water, and waste management (recycled/nonrecycled)
	A1. Sheet metal–specific indicators: Specific indicators for the sheet metal sector. These indicators make it possible to measure the sheet metal operations in the workshop in detail. Energy is the main factor
	A2. Paint-specific indicators: Specific indicators of the painting sector. These indicators make it possible to measure the impact of the painting sector in detail. To this end, they rely on factors such as energy, water, plastics/paper used in nonpainting products, and released VOCs

TABLE 6: Proposed environmental performance indicators.

Name of the proposed indicator	Definition	Sector	Inputs needed	Calculations
Energy consumed in the collision (ECC)	Total energy consumed in the sector (plate and painting)	A	- Collision sector consumed energy (kWh) (CCE) - Emission factor (g CO_2/kWh) (EF) - Number of repaired vehicles (NRV)	$\frac{CCE \times EF}{NRV}$
Water consumed in washing (WCW)	The total water consumed in the washing of vehicles repaired in the collision	A	- Water consumed in washing (m^3) (WW) - Number of repaired vehicles (NRV)	$\frac{WW}{NRV}$
Quantity of recycled wastes (QRW)	Quantity of recycled waste per repaired vehicle	A	- Recycled residues (kg) (RR) - Number of repaired vehicles (NRV)	$\frac{RR}{NRV}$
Sheet metal sector consumed energy (SMCE)	Energy consumption in the sheet metal sector (lighting, heating, bench, welding machine)	A1	- Sheet metal sector consumed energy (kWh) (SCE) - Emission factor (g CO_2/kWh) (EF) - Sheet metal worked hours (h) (SWH)	$\frac{SCE \times EF}{SWH}$
Energy consumption in the painting sector (ECP)	Energy consumption in the painting sector (lighting, heating, equipment, paint booth)	A2	- Painting sector consumed energy (kWh) (PCE) - Emission factor (g CO_2/kWh) (EF) - Painting worked hours (h) (PWH)	$\frac{PCE \times EF}{PWH}$
Fuel consumption in the paint studio (FCPS)	Fuel combustion for the operation of the paint booth (diesel, natural gas, electricity, etc.)	A2	- Paint booth fuel (kWh) (PBF) - Emission factor (g CO_2/kWh) (EF) - Painting worked hours (h) (PWH)	$\frac{PBF \times EF}{PWH}$
Volatile organic compounds released in painting (VOCP)	Volatile organic compounds from paint bases, primers, and varnishes	A2	- Volume of consumed (base, varnish, primer) (L) - Volumetric mass density of each product (kg/L) - VOC's quantity per kg - Painting worked hours (h) (PWH)	$\frac{VOC}{PWH}$
Released particles in painting (RPP)	Particles released through the chimney	A2	- Amount of particles released per painting worked hour (h) (PWH)	$\frac{RPP}{PWH}$

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TABLE 7: Annual total electrical energy consumption.

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total energy consumption [kWh]	1028	943	1629	1038	754	833	1006	844	539	894	882	992

Table 8 highlights the distribution of energy by the repair sector. This distribution is significant in enabling the measurement of the environmental impact of each sector.

B. Water consumption in washing (after vehicle repairs)

Considering that the modus operandi of current painting repair processes does not require direct water use (previously used in sanding processes), the quantity of water considered in Table 9 refers only to washings after repair.

C. Generated waste (scrap) resulting from repairs (recyclable/nonrecyclable)

In the analysis of collision activity, the waste generated in the repair process was listed.

1. Paint and varnish sludges containing organic solvents and/or other hazardous substances
2. Trimmings and filings of ferrous metals
3. Engine, transmission, and lubrication oils
4. Mixtures of waste from oil/water separators
5. Other solvents (degreasing products)
6. Plastic packaging
7. Contaminated packaging
8. Cleaning cloths, absorbents, and protective clothing
9. Antifreeze fluids
10. Ferrous metals (parts removed from the vehicle)
11. Glass
12. Used tires

According to Directive 2008/98/EC, D codes refer to disposal operations and R codes refer to recovery/recycling operations (Annexes I and II of Directive 2008/98/EC). Table 10 presents the waste generated quantity, treated quantity, and their respective treatment destinations. It is worth noting that these data were obtained from the company responsible for collecting/treating the generated waste and may vary from facility to facility. The presented data were extracted from the company's report, where the model validation was conducted. The waste numbering corresponds to the waste list provided above.

Based on the presented values, it is essential to summarize the quantity of recycled waste generated (Table 11).

D. Energy consumed in the paint booth (fuel—natural gas)

TABLE 8: Distribution of energy consumption by repair sector (sheet metal and painting).

Sector	Distribution %	Energy consumption [kWh]
Sheet metal	35	3983
Painting	65	7398

TABLE 9: Used water for washing collision vehicles.

Parameters	Value
Water quantity consumed [L]	90,000

TABLE 10: Quantification and qualification of generated waste.

Waste	Quantity generated [kg]	Quantity treated [kg]	% treated	Treatment code (destination)
1	170.00	170.00	100.00	D15—Disposal/storage
2	8160.00	8160.00	100.00	R12—Recycling
3	11,890.00	11,890.00	100.00	R12—Recycling
4	17,480.00	17,480.00	100.00	R12—Recycling
5	695.00	113.00	16.25	R12—Recycling
6	153.00	149.00	97.25	R12—Recycling
7	1451.00	1451.00	100.00	R12—Recycling
8	4707.00	4707.00	100.00	R12—Recycling
9	144.00	144.00	100.00	R12—Recycling
10	1912.00	1912.00	100.00	R12—Recycling
12	2680.00	2680.00	100.00	R12—Recycling
Total	49,442.00			

TABLE 11: Quantification of recycled waste per repaired vehicle.

Parameters	Quantities
Generated waste [kg]	49,442.00
Recycled waste [kg]	48,686.00
Nonrecycled waste [kg]	756.00
Recycled waste [%]	98.40

Since the painting booth is adapted for natural gas, its quantification is presented in Table 12.

E. VOCs and suspended particles resulting from polyester putty sanding processes

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TABLE 12: Quantification of natural gas consumed in the painting booth.

Natural gas consumed [m^3]	27,160.43
Reference higher heating value of natural gas [kWh/m^3]	11.67
Energy contained in consumed natural gas [kWh]	316.70

TABLE 13: Gaseous effluents from the painting area and reference to the respective legislation.

Source	Pollutant	Current regulation
Joint preparation area with paint finishing Dual preparation area (paint booths)	Particles and VOCs	Decree No. 675/2009

TABLE 14: Gas emissions.

Source	Pollutants	Mass flow [kg/h]	Concentration [mg/m^3 (N)]
Joint paint preparation and finishing area	VOC	0.094 ± 0.031	7.400 ± 1.900
	Particles	0.260 ± 0.041	20.300 ± 2.000
Dual preparation area (paint booths)	VOC	1.658 ± 0.275	70.900 ± 2.100
	Particles	0.126 ± 0.020	5.400 ± 1.800

Note: mg/m^3(N) represents a mass concentration at normal pressure and temperature (NPT).

According to the characterization of gaseous effluents to verify legal requirements, Tables 13 and 14 present the data obtained from the last report by the Associate Laboratory for Energy, Transports and Aerospace (LAETA-INEGI).

According to the data presented in Tables 15 and 16, general sector indicators and specific indicators for each activity (sheet metal and painting) were calculated. The denominators for calculating the general and specific indicators are presented in Table 15.

As different collision types imply different time dedicated to it, two new variables, SHWC and PHWC, were created to provide better knowledge of the mean cost of SWH and PWH per hour. Using Equations (1) and (2) to convert energy values into maximum CO_2 emissions and applying the calculation rules mentioned in Table 5, the indicators of the maximum CO_2 emission model were calculated (Table 16).

Figures 4 and 5 show the image of the tool created to monitor these denominators.

Next, the demarcated zones with characters in Figure 4 are presented:

- Zone D: an area dedicated entirely to inputs (input of model data)
- Zone E: area dedicated entirely to outputs (KPIs)
- Zone F: cells for inputting input values
- Zone G: values of the obtained indicators, with the respective units associated with the indicator under analysis
- Zone R: commands for inputting inputs and extracting PDF reports

TABLE 15: Denominators for calculating the general (A) and specific (A1/A2) indicators.

Sector	Denominator	Values
Collision	Number of repaired vehicles [NRV]	1.388 un.
Sheet metal	Sheet metal hourly worked cost [SHWC]	5.406 €/h
Painting	Painting hourly worked cost [PHWC]	11.270 €/h

Figure 5 is a pop-up menu to introduce the input data that appears whenever buttons of input/output data are activated.

5. Discussion

The results obtained with the proposed action-research methodology offered a systematic approach, including observation, planning, implementation, evaluation, and monitoring, ensuring a structured problem-solving process. The emphasis on assessing and mitigating the environmental impact of collision repair services demonstrates a commitment to sustainability and corporate social responsibility. van Bruggen et al.'s [34] study offers an approach to sustainability assessments with a solution-focused lens tailored for the shift towards a circular economy, specifically examining the use of plastics within the automotive industry. On the other hand, Schöggl et al. [35] examined the impediments to sustainable and circular product design within the European automotive industry, employing theoretical analysis and empirical prioritization. Unclear profitability and insufficient top management support emerge as key individual barriers. Nevertheless, Wolff et al. [36] delved into the transformation of automotive firms into exemplars

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TABLE 16: Maximum CO_2 emission indicators.

Sector	Consumables	Values	Units
Collision: General	Energy	1.62	[kg of CO_2/repaired vehicle]
	Water	64.84	[L/repaired vehicle]
	Recycled residues	35.04	[kg of waste/repaired vehicle]
Sheet metal	Sheet metal sector energy	0.14	[kg of CO_2/sheet metal worked hours]
Painting	Painting sector energy	0.13	[kg of CO_2/painting worked hours]
	Paint booth fuel	5.10	[kg of CO_2/painting worked hours]
	Suspended particles in painting	0.39	[kg/painting worked hours]
	VOC	1.76	[kg/painting worked hours]

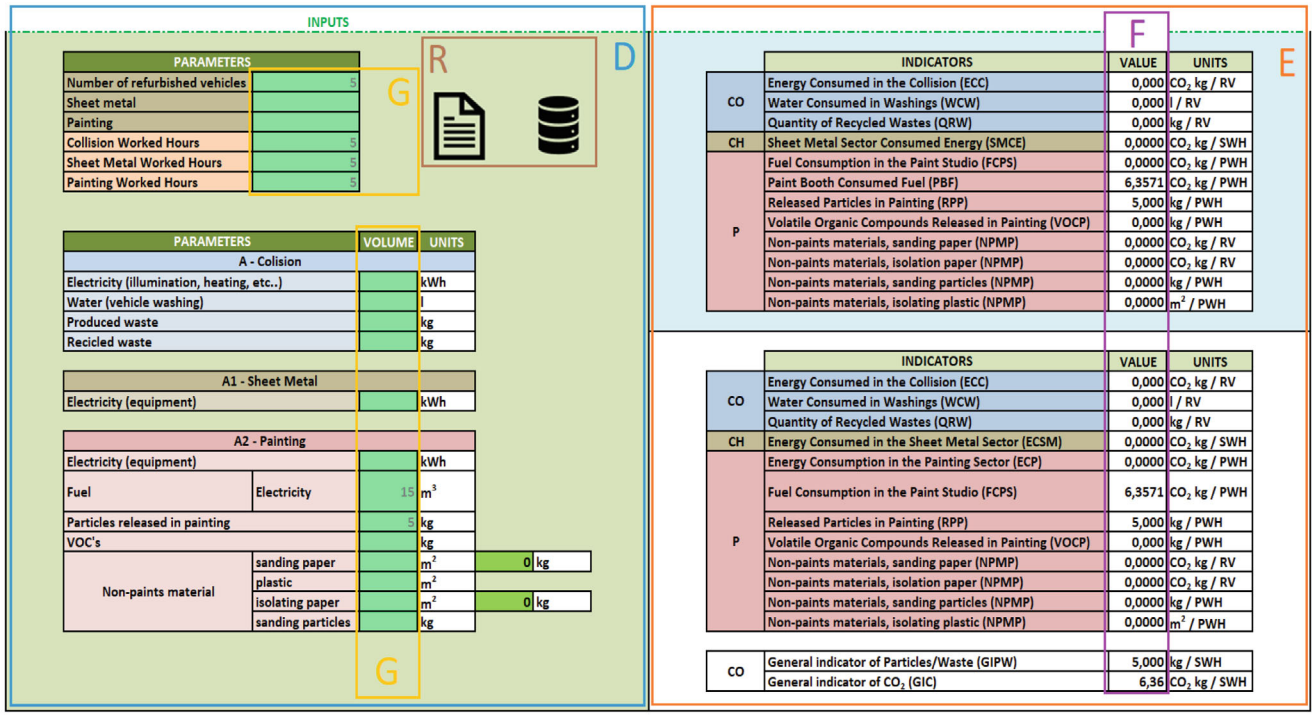


FIGURE 4: Tool to support the maximum CO_2 emission model.

of sustainability, presenting a framework for navigating prevailing obstacles.

These studies have dived into the automotive industry sustainability theme but are always considering implementing sustainability KPIs, whether in the automotive fabrication process itself or when considering a circular economy (second life of the car). Limited literature explicitly addresses the environmental impact of automotive collision repair workshop assessment. The model incorporates internal and external data sources to capture various aspects of energy consumption, waste generation, and environmental emissions, providing a holistic view of the operation. This paper outlines clear steps and indicators that can be applied to automotive repair workshops, facilitating practical implementation and evaluation. Jasiński et al. [37] proceeded to a meticulous selection of automotive sustainability criteria. The iterative process culminated in developing a comprehensive framework for assessing automotive sustainability. However, the efficacy of this framework needed to be validated through empirical testing, utilizing input data sourced from car manufacturers.

Implementing and promoting environmentally sustainable practices have enhanced the reputation and market positioning of this automotive repair workshop, which may attract, on a long-term basis, environmentally conscious customers and business partners. Nevertheless, resistance from internal stakeholders, including employees, management, or shareholders, may hinder the adoption of new methodologies or practices, particularly if perceived as disruptive or costly to existing operations. Wolff et al. [36] stated that embedding sustainability within automotive enterprises remains a persistent challenge, marked by a notable disparity between sustainability reporting and actual implementation efforts. The continuous improvement encouragement and

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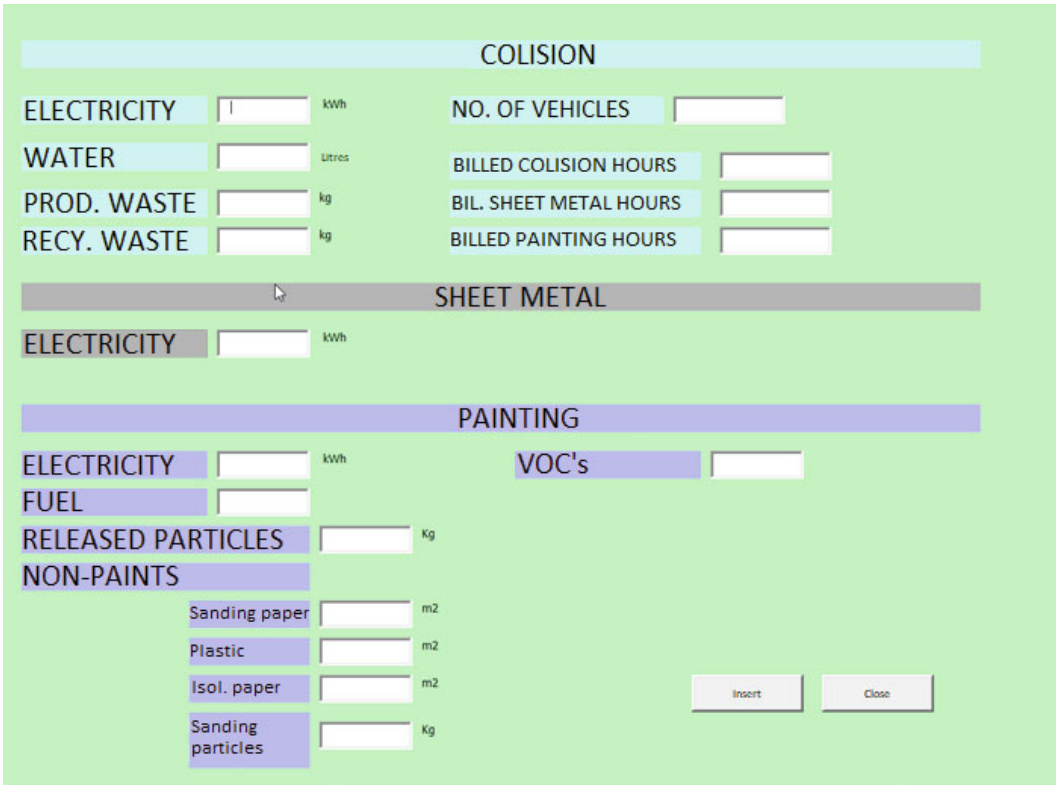


Figure 5: Pop-up menu to introduce the input data.

knowledge transfer provide opportunities for innovation in processes, technologies, and materials further to reduce the environmental impact of automotive repair workshops and enhance operational efficiency. Sánchez-García et al. [38] emphasize the current juncture poised at the brink of a technological revolution, underscoring the critical need to address this transformative potential with an innovative perspective. The authors also advocate a concerted effort to ensure that technological advancements are harmonized with ethical, social, and environmental considerations. Therefore, this work contributed to the joint effort to make services a more sustainable sector that is better integrated into the circular economy.

6. Concluding Remarks

This research was aimed at enhancing environmental sustainability in car collision repair by assessing and quantifying resource usage. Collision repair shops contribute significantly to emissions of compounds, particles, and pollutants in the automotive industry. Accurate measurement of CO_2 equivalents and other relevant metrics is essential for validating models and interpreting results. Furthermore, recognizing the paramount importance of human capital within organizations is essential and goes beyond establishing SMART indicators. Enhanced awareness of human capital is imperative for effectively implementing the model, including tasks such as data collection, processing, monitoring, and devising improvement strategies.

The newly developed model and its associated tool are designed to be user-friendly and accessible to a broad audience, including researchers, industry professionals, and practitioners. This inclusive design is aimed at minimizing usage barriers and boosting efficiency and adoption. Built on Microsoft Excel, the tool facilitates environmental monitoring over 5 years and enables detailed analysis of individual workshops and cross-organizational comparisons. This boosts operational efficiency and drives sustainable practices, encouraging the industry to adopt greener methods.

The model's primary constraints arise from the diverse technologies, materials, and processes used in different collision repair shops, which complicates the calculation of environmental impacts. For example, variations in painting or metalworking techniques can lead to different consumption profiles, which affects the accuracy of environmental impact assessments. This diversity poses a challenge to the model's applicability because it relies on standardized data that may not accurately reflect a specific workshop's conditions.

Additionally, the model relies on external data, such as emission factors from electricity and fuel production. These factors can fluctuate based on geographical and temporal variables, which introduces uncertainty into the impact calculations. Therefore, the precision of the model depends on the accuracy and relevance of these external inputs.

This study has profound practical significance for industry professionals, offering a systematic tool to evaluate and enhance the environmental performance of collision repair operations. Using this model, practitioners can identify critical areas of resource use and associated emissions, enabling

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them to make more strategic decisions towards sustainability. The model supports the ongoing monitoring and comparison of environmental impacts and advocates for the integration of eco-friendly technologies and processes.

Future research could refine the model by including various technological approaches and more detailed lifecycle assessments. Integrating real-time data and precise, process-specific impact factors could significantly improve the tool's accuracy and utility. Empirical validation from a diverse array of workshops would further bolster the model's reliability and adaptability, resulting in more accurate environmental performance metrics and customized sustainability initiatives.

In summary, this approach introduces a novel, organized framework for mitigating the environmental footprint of collision repair services. It serves as a vital instrument for the automotive sector to refine its sustainability strategies. However, the model's effectiveness depends on careful planning, responsible resource use, and continued commitment to sustainability.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Disclosure

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Ricardo Pinto, André F. V. Pedroso, and Rita C. M. Sales-Contini: conceptualization, methodology, formal analysis, and investigation. Ricardo Pinto, Francisco J. G. Silva, Arnaldo M. G. Pinto, and Isabel M. Pinto: funding acquisition, project administration, resources, and data curation. Ricardo Pinto, André F. V. Pedroso, and Rita C. M. Sales-Contini: writing—original draft preparation and review and editing. Ricardo Pinto, Francisco J. G. Silva, Arnaldo G. Pinto, and Isabel M. Pinto: visualization and supervision. Rita C. M. Sales-Contini, André F. V. Pedroso, and Francisco J. G. Silva: writing—review and editing.

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