Measurement 240 (2025) 115493

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Sustainability-aware measurement design: How to select the right measuring system

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ARTICLE INFO

Keywords:
Measurement sustainability
Measuring systems
Carbon footprint
Greenhouse gases
GUM
Environmental sustainability
Industry 5.0
Life-cycle assessment
Measurement uncertainty
Sustainability

ABSTRACT

Environmental sustainability assessment has been establishing itself as a requirement when selecting any good or service. This approach also applies to the Information and Communication Technology (ICT) infrastructure, and to *Measurements*, which represent integral components of ICT. This means that, in the *measurement design*, the traditional parameters of target uncertainty and costs should be accompanied by environmental sustainability ones.

To address this aspect, among the steps of the measurement design process, this paper focuses on the selection, for a given measurand, of the most suitable measuring system from a sustainability perspective. Specifically, to guarantee also consistency of the approach, the proposed methodology is developed within a framework that takes into account the pillars of measurement uncertainty (i.e. the *Guide to the Expression of Uncertainty in Measurement, GUM)* and those of sustainability assessment (i.e. the *ISO14000* family of standards).

As a case study, three resistance measuring systems are compared under different simulated and experimental scenarios. The obtained results demonstrate how, through the incorporation of sustainability considerations alongside metrological performance criteria, this methodology facilitates a holistic approach to the selection of measuring systems, promoting environmentally conscious practices within the field of Metrology.

1. Introduction

The concept of *Sustainability*, which entails the conscious and careful management of available resources [1], has emerged as a necessity to ensure that future generations can meet their needs as people do today [2]. This concept encompasses a wide range of areas, as every human activity has an impact on social, economic, or environmental aspects [3].

With regards to the latter, the wasteful consumption of resources during the past century has resulted in a significant increase in greenhouse gas (GHG) emissions. In this scenario, environmental sustainability plays a crucial role in curbing climate change by promoting a more responsible and rational utilization of finite resources [4]. Consequently, this aspect is being considered in various domains to explore alternative and more sustainable solutions to those implemented thus far [5].

Among these different domains, Information and Communication Technologies (ICTs) are often employed to serve as a functional framework for developing solutions that effectively reduce GHG emissions [6, 7]. Examples include the optimization of energy use in buildings [8], transportation systems [9], and industrial processes [10]. However, like any product or service, also ICTs have their own environmental impact, which should be considered in terms of equivalent GHG emissions. For the sake of example, in the manufacturing of electronic devices numerous materials are utilized, a significant portion of which are toxic and pose environmental and human health risks [11]. This dual aspect of ICTs is often referred to in the literature as *Green by ICTs* and *Green of ICTs* [12]. The former is related to how the introduction of ICTs can contribute to overall sustainability, while the latter focuses on the sustainability of ICTs themselves. As such, similar to other domains, the need to reduce emissions and prioritize environmental sustainability has become imperative within the realm of ICTs as well.

Given this increasing sensitivity to sustainability, it becomes crucial to reassess Measurements, which constitute an integral component of ICT infrastructure, from a sustainability-driven perspective: this means to consider their environmental impact and to explore potential means for reducing emissions while preserving metrological performance.

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https://doi.org/10.1016/j.measurement.2024.115493
Received 20 February 2024; Received in revised form 2 August 2024; Accepted 9 August 2024

Based on these considerations, this work aims to provide an innovative methodology for a sustainability-aware design of Measurements. In particular, among the different steps of the measurement design process, this work delves into the selection of the most appropriate measuring system to be employed for a given measurand. In [2,13], an approach was proposed, which involved a preliminary analysis to compile a checklist of each component of the considered measuring system, followed by individual impact calculations through the Life-Cycle Assessment (LCA). The approach presented in [2,13] represented an important starting point for gaining insight into the emissions generated by a measuring system and for facilitating a better understanding of how and where interventions can be made to enhance its overall sustainability.

Starting from the results reported in [2,13], in this work, an important step forward is made to provide a more comprehensive evaluation that considers the environmental impact as one of the performance parameters of a measuring system. On such basis, the goal of this work is to outline a broader methodology in which, in addition to metrological metrics or instrumentation cost, also the environmental impact could become a driver in the selection of measuring systems.

For the sake of feasibility and robustness, the proposed methodology is developed only within the framework that takes into account the pillars of both measurement uncertainty (i.e. the *Guide to the Expression of Uncertainty in Measurement (GUM)* [14]) and sustainability assessment (i.e. the *ISO 14000* family of standards).

The paper is organized as follows. Section 2 provides a more detailed statement of the problem. Then, Section 3 describes the background of sustainability assessment, focusing on the estimation of GHG emissions of measuring systems. Next, in Section 4, the proposed methodology to include sustainability as an evaluation parameter for the choice of measuring systems is presented. Section 5 describes the considered case study, which involves the comparative analysis of three resistance measurement methods (namely the Wheatstone Bridge, the Voltamperometric Method, and the Two-wire Method, under simulated and experimental scenarios). Results obtained by applying the proposed methodology to the case study are presented in Sections 6 and 7, for the simulated scenarios; while in Section 8, an experimental scenario is presented. Finally, conclusions are drawn and future work is outlined.

2. Rationale of the work

As outlined in Section 1, this work addresses the identification of a methodology to enable sustainability-aware design of measurements. Considering the measurement model outlined by the *Guide to the Expression of Uncertainty in Measurement (GUM)* [14], which includes (i) the identification and definition of the measurand, (ii) the selection of measurement method and procedure, and (iii) the expression of the measurement result, this work focuses on the choice of the measurement procedure and, more specifically, of the most suitable measuring system to be employed for the measurand identified.

Currently, this selection process relies on evaluating the performance provided by the system, mainly in terms of measurement uncertainty, alongside its associated costs. However, given the increasing emphasis on environmental sustainability, the proposed methodology integrates this additional aspect as an evaluation parameter in selecting the measuring system.

Hence, for each measuring system considered for selection, the methodology introduced by this work is based on separate evaluations of the uncertainty provided and the environmental impact. These evaluations consider only variables pertaining to the measuring system operating within a known environment, assuming that (i) all known and significant systematic effects of the measurement have been adequately compensated for, and (ii) all the interactions between the measurand and the measuring system are neglected.

3. Background on sustainability assessment

The current cultural, political, and economic trends indicate a growing recognition of sustainability assessment as a necessity in the design, implementation, or selection of any good or service. Hence, many companies are setting sustainability goals, which relate to the reduction or cancellation of their emissions, also known as *net-zero emissions* [15]. To meet these goals, companies abide by a series of regulations published by the *International Organization for Standardization (ISO)*. The *ISO 14000* family contains all the standards on *environmental management* and defines how to adequately manage the requirements of sustainability. In particular, the *ISO 14040-44* (*Life Cycle Assessment, LCA*) [16] and *ISO 14064-67* (*Carbon Footprint*) [17] describe the methodology to employ for the evaluation of impacts and the monitoring and reporting of emissions, respectively.

Basically, measuring the environmental sustainability of a good or service involves assessing its impact on the environment, which is quantified by the amount of greenhouse gases (GHG) generated throughout its life cycle. These gases, including carbon dioxide (CO_2), methane, and ozone, occur naturally in the atmosphere and play a vital role in regulating Earth's temperature [18]. An increase in GHG emissions contributes to a significant rise in temperatures, driving the alarming phenomenon of climate change and its adverse effects on the planet. Since CO_2 is the primary component of greenhouse gases, GHG emissions are often referred to as *Carbon Footprint*, and measured in kilograms of carbon dioxide equivalent (kg $CO_{2,eq}$) [19] which, according to the (ISO), is defined as *the measurement unit for comparing the radiative forcing of a GHG to that of carbon dioxide* [17].

3.1. Life-Cycle assessment for ICTs

As aforementioned, ISO regulations are general and relate to all contexts without distinction. Hence, the *International Telecommunication Union (ITU)* adapted them specifically to the ICT field (*L.1410-12/2014*) [20]. These ITU recommendations provide guidance on the implementation of LCA based on ISO standards for assessing the environmental impact of ICT goods, networks, and services. It is a widely used approach for evaluating the environmental impacts of a product, service, or project throughout its entire life cycle. As described in [2], LCA consists of three main steps:

1. The first step is to establish boundaries that clearly define what is included and excluded from the assessment, as well as the rationale behind these choices. The determination of boundaries is case-specific and requires making appropriate assumptions. In the context of measuring systems, a checklist with six categories can be utilized to guide this process: (i) hardware; (ii) software; (iii) consumables and supportive products; (iv) site infrastructure; (v) movements of goods; (vi) movements of people.
   Unlike the ITU recommendations, when considering measuring systems, the storage of goods and the working environment are typically included within the category of *site infrastructure* rather than being treated as separate entities. This approach is based on the understanding that, in many instances, storage and working environments are integral components of the overall site infrastructure
2. Therefore, in order to conduct a thorough assessment, it is necessary to assign each element to its respective category from the six categories provided. This process ensures that all relevant components of the measuring system are appropriately accounted for and considered within the defined boundaries.
3. The final step entails acquiring the impacts for each element and aggregating them to derive the overall impact. These impacts can be classified into two categories: *embodied* impacts, which arise from production and waste, and *operational* impacts, which directly correspond to the specific measurement being conducted.

As embodied impacts occur solely at the beginning and end of the life cycle, it is advisable to distribute them uniformly across the entire lifespan of the measured item.

To implement this approach, it is essential to compile a comprehensive list of all the components comprising the measuring system. This includes generators, meters, sensors, resistors, capacitors, as well as cables, computing units, and equipment for ambient monitoring and control. The checklist should encompass not only the measuring system itself but also all the necessary elements for ensuring controlled measurement conditions. While hardware and software components are relatively straightforward to identify, there may be other supplementary items that are more challenging to address. These items are associated with the measurement process but do not constitute the core components of the measuring system. Examples of such elements are site infrastructure components like air conditioning, lighting, network infrastructure, and storage facilities.

For each item, it is crucial to assess both the embodied and operational impacts, although gathering impact data may pose certain challenges. Indeed, in [2], the information was acquired and refined by referring to existing literature and available technical reports online. This approach proved valuable in introducing the concept of sustainability into measuring systems, but it requires further refinement to achieve more accurate estimations. Therefore, this current study not only relies on literature review but also leverages the opportunity to model measuring systems using appropriate software tools wherever possible.

4. Proposal

This section describes the proposed methodology for a sustainability-oriented design of measurements, focusing on the selection of the more adequate measuring system under the assumptions stated in Section 2.

The evaluation of the measurement uncertainty provided by the considered measuring systems is carried out using Supplement One to the *GUM* [21], which describes the adoption of the Monte Carlo Method (MCM) within the metrology framework.

On the other hand, the assessment of the environmental impact associated with the given measuring systems, expressed in terms of carbon footprint, is performed by leveraging the framework provided by *ITU* recommendations and *ISO* standards, as already conducted in [2]. However, in order to contribute to the advancement of knowledge in terms of sustainability measurements, the procedure has been further refined in this study.

4.1. Measurement uncertainty

In Fig. 1-a, the chosen strategy for evaluating the measurement uncertainty of measuring systems is presented.

1. *Measurand Model*: first, the identification and definition of the measurand Y are established, considering its relationship with the input quantities $X_1, X_2, \dots, X_N$.
2. *PDFs assignment*: subsequently, probability density functions (pdf) are assigned to the input quantities. These pdfs can be determined based on information obtained from on-field measurements, a priori knowledge from previous experimental campaigns, or datasheets provided by the manufacturer.
3. *PDFs propagation*: once a pdf is assigned to each input quantity, they are propagated by considering a finite number of extractions (e.g., 10^6) for each input quantity. This process results in a probability density function for the measurand Y.
4. *Coverage Interval*: finally, the coverage interval, associated with a specific confidence level, is obtained from the pdf of the measurand. This coverage interval is determined as the shortest interval that encompasses the desired percentage of the area under the pdf.

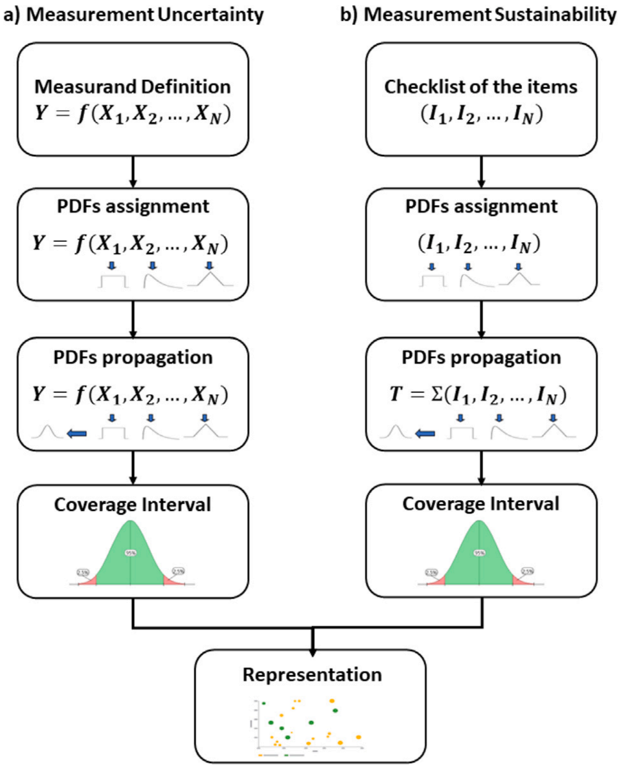

Fig. 1. Graphical representation of the proposed methodology: (a) block architecture of the employed method for evaluating measurement uncertainty; (b) block architecture of the proposed method for measuring the carbon footprint of measuring systems.

4.2. Measurement sustainability

On the other hand, Fig. 1-b illustrates the approach proposed for evaluating the carbon footprint of measuring systems. As aforementioned, an improved strategy to utilize the recommendations provided by the *ITU* and the standards set by the *ISO* is employed.

1. *Checklist of the items*: to evaluate the carbon footprint, a checklist is created, comprising the various components that constitute the measuring system.
2. *PDFs assignment*: then, following the previously described Monte Carlo method, a pdf is assigned to each of these components. These pdfs can be established based on information obtained from the literature, as conducted in [2], or by employing suitable tools for assessing in a more accurate way the carbon footprint of products and systems.
3. *PDFs propagation*: the assigned pdfs are then propagated by conducting a finite number of extractions (e.g., 10^6) for each input quantity. These extractions are summed, resulting in an output pdf representing the distribution of the carbon footprint of the measuring system.
4. *Coverage Interval*: Similar to the previous approach, the coverage interval, associated with a specific confidence level, is obtained from the output pdf by identifying the shortest interval that encompasses the desired percentage of the area under the pdf. This coverage interval serves as a measure of the carbon footprint of the considered measuring system.

It is worth mentioning that, in general, carbon footprint measurement can be also conducted through the Law of Propagation of Uncertainty [14]. However, due to the peculiarities of this work, assuming a normal pdf for the output may be unreliable as the assumption of the central limit theorem cannot be met. Therefore, adopting the

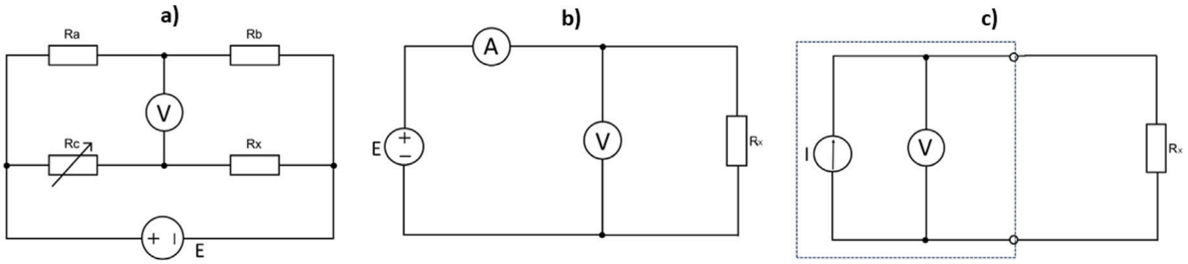

Fig. 2. Circuit representation of the measuring systems considered: (a) Wheatstone Bridge; (b) Voltamperometric method; (c) Two-wire method.

framework of Supplement 1 [21] is more accurate for expressing the measurement result.

4.3. Representation

Once the previously mentioned coverage intervals have been obtained, a two-dimensional representation can be provided, delineating the axes of measurement uncertainty and measurement sustainability. In this manner, when comparing different measuring systems, it becomes straightforward to evaluate which among them yields optimal performance and, if distinct, which facilitates the least harmful environmental impact.

5. Case study and relevant scenarios

In this work, a case study centered on Resistance Measurement is presented. The choice of this case study, with well-known measuring systems and familiar to practitioners, allows to focus on the proposed methodology and to highlight all the steps. In spite of the specific case study, however, its implications extend beyond the immediate context and offer valuable insights into the broader problem of sustainability-oriented selection of measuring systems.

After the description of the considered measuring systems, the different case scenarios (both simulated and experimental) are introduced.

5.1. Description of the case study

This study considers three measuring systems employed for measuring a resistor with a nominal value of 100 Ω. Each measuring system (sketched in Fig. 2) undergoes an assessment of both the measurement uncertainty and the carbon footprint, following the methodology outlined in Section 4.

The following list provides a brief description of each system:

- *Wheatstone Bridge:* The Wheatstone Bridge is a widely used electrical circuit configuration employed for resistance measurements [22]. The bridge configuration consists of four resistors, a voltage generator denoted as E, a multimeter represented by V, and connecting cables. The resistors in question encompass the measurand resistor, denoted as R_x, as well as two fixed resistors denoted as R_a and R_b, and an adjustable resistor denoted as R_c. To measure the resistance of R_x, the resistor R_c is adjusted iteratively. The objective is to attain a state of balance within the bridge circuit. Once the multimeter V registers a voltage reading of 0 V, indicative of a balanced bridge condition, the measured value of R_x can be determined by utilizing the following expression:

$$R_x = \frac{R_b}{R_a} R_c \tag{1}$$

  In practical scenarios, due to the finite resolution of the adjustable resistor R_c, it is possible that the voltage on the diagonal of the bridge circuit may not precisely reach zero. Consequently, the negative voltage V_n and the positive voltage V_p, which are the closest to zero, are considered. These voltages correspond to the resistance values of R_{cn} and R_{cp}, respectively.
  Considering these real-world conditions, the measured value of the target resistor R_x can be expressed as follows:

$$R_x = \frac{R_b}{R_a} \left[R_{cn} + \frac{R_{cp} - R_{cn}}{V_p - V_n} (-V_n) \right] \tag{2}$$

- *Voltamperometric Method:* The Voltamperometric method is another widely used technique for resistance measurement [23]. To measure the resistance of the measurand resistor R_x, an amperometer A is connected in series with a voltage generator E. The amperometer is further connected to both the resistor R_x and a voltmeter V, resulting in a parallel configuration between the voltmeter and the resistor. Under the assumption that the resistance of R_x is negligible compared to the input impedance of the voltmeter, it can be inferred that the entire current supplied by the voltage generator and measured by the amperometer flows through the target resistor. Consequently, the measured value of R_x can be determined by utilizing the following expression:

$$R_x = \frac{V_m}{A_m} \tag{3}$$

  where V_m is the voltage measured by the voltmeter, and A_m is the current measured by the amperometer.
- *Two-wire Method:* The Two-wire method, also known as the simple or direct method, is a basic technique for measuring resistance [24]. In this method, the resistance to be measured R_x is connected directly to the measurement instrument using two wires. The instrument applies a known current to the resistance and measures the resulting voltage across it. However, the Two-wire method can introduce measurement errors due to the resistance of the connecting wires, which are in series with the resistance being measured. These wire resistances can affect the accuracy of the measurement, particularly when dealing with low resistance values.

5.2. Relevant scenarios

To employ the proposed methodology for assessing measuring systems, three different scenarios were considered: two simulated and one experimental.

First, let us assume the necessity of performing a resistance measurement with a nominal value of 100 Ω. For this task, three distinct laboratories were taken into consideration. Each of these laboratories undertakes the resistance measurement employing a distinct method. Specifically, Laboratory #1 employs the Wheatstone Bridge, Laboratory #2 employs the Voltamperometric Method, and Laboratory #3 employs the Two-wire Method. The three considered scenarios are the following:

- Simulated Scenario #1: each of the three laboratories employs different measurement instrumentation, encompassing signal generators, multimeters, and laptops for instrumentation control. For the sake of simplicity, it was assumed that the site infrastructure and supplementary items (i.e., software, internet modem, pen-drive, etc.) were held equal.

- Simulated Scenario #2: each of the three laboratories adopts the same measurement instrumentation. Thus, in this scenario, only the measurement methods and the amount of subsequent equipment vary. Also in this case, for the sake of simplicity, the site infrastructure and supplementary items were deemed equal.
- Experimental Scenario: each of the three laboratories employs commercially available measurement instrumentation and was supposed to work in similar site infrastructure.

6. Results for simulated scenario #1

In this simulated scenario, let us assume that Laboratory #1, utilizing the Wheatstone Bridge as a resistance measuring system, opts for the following measurement equipment:

- Two resistors with a nominal value of 100 Ω and a tolerance of 1%;
- A variable resistor spanning 1 Ω with 1% tolerance;
- A benchtop multimeter weighing ≈1.5 kg with an accuracy of 30 part per million (ppm) of reading +7 ppm range for voltage readings;
- A benchtop signal generator weighing ≈1.5 kg;
- And a standard laptop weighing ≈1.5 kg.

Then, let us assume that Laboratory #2, which employs the Voltamperometric Method selects:

- Two high-performance benchtop multimeters weighing ≈2.5 kg with an accuracy of 15 ppm of reading +4 ppm range for voltage readings, and 100 ppm of reading +300 ppm range for current readings;
- A high-performance benchtop signal generator weighing ≈2.5 kg;
- And a high-performance laptop weighing ≈2 kg.

Finally, consider that Laboratory #3, operating with the Two-wire Method, chooses:

- A portable multimeter weighing ≈0.5 kg with an accuracy of 0.2% of reading +1 Ω for resistance readings;
- And a small laptop weighing ≈1 kg.

Under these assumptions, it is possible to proceed with the evaluation of the measurement uncertainty and measurement sustainability.

6.1. Measurement uncertainty

The evaluation of the measurement uncertainty for the three measuring systems was conducted following the methodology described in Section 4. To evaluate the pdf of each input quantity in the measuring system, the technical specification previously described were considered. Then, the resulting 100% coverage interval for each input quantity of the considered measuring systems is provided in Table 1. A uniform distribution is assumed for each input quantity. As can be seen, the Two-wire method do not require any input quantity as it involves a direct measurement of the measurand R_x. For reproducibility purposes, the measured quantity value was considered equal to 100.00 Ω for each of the measuring systems. Therefore, Monte Carlo simulations were conducted by considering a number of extractions equal to 10^6 for each input quantity. The resulting 99% coverage interval of the measurand R_x for each of the considered measuring systems is shown in Table 2. The Measurement Uncertainty at 99% confidence level is represented by the semi-amplitude of the obtained coverage intervals.

Table 1
100% coverage intervals for the input quantities in the resistance measurement of the specified measuring systems, namely the Wheatstone Bridge (WB), the Voltamperometric Method (VA), and the Two-wire Method (2W), for the simulated scenario #1. A uniform distribution is assumed. No input quantities were included for the Two-wire method as it consists of a direct measurement of the measurand R_x.

WB	
Quantity	Coverage interval
R_a	[99.00 ÷ 101.00] Ω
R_b	[99.00 ÷ 101.00] Ω
R_{cn}	[99.99 ÷ 102.01] Ω
R_{cp}	[98.01 ÷ 99.99] Ω
V_n	[−0.012406 ÷ −0.012393] V
V_p	[0.012593 ÷ 0.012607] V
VA	
Quantity	Coverage interval
V_m	[4.999885 ÷ 5.000115] V
A_m	[0.049965 ÷ 0.050035] A
2W	
Quantity	Coverage interval
–	–

Table 2
99% coverage interval for the measurand R_x of the considered measuring systems for the simulated scenario #1.

Method	Coverage interval (Ω)
WB	[99.02 ÷ 101.00]
VA	[99.93 ÷ 100.07]
2W	[98.81 ÷ 101.19]

6.2. Measurement sustainability

According to the methodology outlined in Section 4, each measuring system required specific considerations regarding the items involved and measurement conditions. Table 3 presents a comprehensive checklist that encompasses various aspects, including hardware, software, site infrastructure, and working environment. The hardware category includes the core elements of the measuring systems, as well as laptops for instrument control, and internet equipment. The software category takes into account the necessary software components for implementing the instrument control application, such as an automatic test station developed in *LabVIEW*. In terms of consumable items, only a 32-GB pen drive was considered. This checklist also incorporates considerations for site infrastructure and working environment (i.e., dimension of the laboratory, lights, air conditioning). Additionally, the travel of a single operator was taken into account, while no transport of goods was considered in this case study, assuming that the measurement laboratory already possesses all the necessary items. Despite the simplicity of this case study, it encompasses various aspects found in many measuring systems and includes common components.

Once the checklist of the items was established, the assignment of pdf was performed, with corresponding $C0_{2,eq}$ values expressed in kg assigned to each item. In order to obtain more accurate estimates with respect to [2], the assessment of the carbon footprint for each element of the measuring systems was conducted in two ways.

- Modeling the items using *Open LCA*: Open LCA is a software largely employed for life cycle assessment, which evaluates the environmental impacts of products and processes throughout their entire life cycle, from extraction through disposal [25]. The carbon footprint for Resistors and Lights was directly available in Open LCA. Instead, the models of other items (such as the Laptop Multimeter, or Signal Generator) were created from scratch, considering the weight of the devices and components, packaging, transport, and end-of-life.

Table 3
Checklist for carbon footprint evaluation of the three considered measuring systems: Wheatstone Bridge (WB); Voltamperometric Method (VA); Two-wire Method (2W).

Item	WB	VA	2W
Hardware			
Signal generator	×1	×1	–
Multimeter	×1	×2	×1
Laptop	×1	×1	×1
Internet equipment	×1	×1	×1
Resistor	×4	×1	×1
Cables	≈1.5 kg	≈1.5 kg	≈0.5 kg
Software			
Instrumentation control	×1	×1	×1
Consumables and supportive products			
32 GB pen-drive	×1	×1	×1
Site infrastructure			
Lights		(20 ÷ 40) m^2 room[a]	
Air conditioning			
Movements of goods			
Goods transport		–	
Movements of people			
Car		(40 ± 10) km/day[b]	

[a] Indicates uniform distribution.

[b] Indicates normal distribution.

Table 4
99% coverage interval for the carbon footprint measured for the considered measuring systems, and site infrastructure and people movement, for the simulated scenario #1.

Method	Coverage interval ($kg\ CO_{2,eq}$/year)
WB	[352.7 ÷ 447.0]
VA	[574.7 ÷ 747.8]
2W	[180.3 ÷ 229.2]
Site infrastructure and people movement	[4492.0 ÷ 24 259.4]

- Information retrieval from the literature: this approach was employed when there were insufficient data available in Open LCA to model the items, such as the power consumption of the electrical components, or the embodied contribution of software. Therefore, relevant information were obtained from literature sources, as previously conducted in [2].

Embodied footprints were evaluated on an annual basis, considering eight-hour workdays, five-day work weeks, and four-week months, resulting in a total of 1920 working hours. Operational footprints were mostly evaluated on an hourly basis due to their relation to energy consumption: as indicated in [2], each kilowatt-hour of energy corresponds to a carbon footprint of 0.6 kg $CO_{2,eq}$. This conversion factor was chosen based on the International Energy Agency's estimation of $CO_{2,eq}$ emissions from global electricity generation [26]. For each item, the corresponding values in terms of mean, standard deviation, and probability distribution are presented in Table A.1, along with a symbol to clarify if the item was modeled by means of Open LCA or by means of information retrieved from the literature. Overall, normal and uniform distributions were typically considered, except for

- The embodied contribution of the air conditioning, which was evaluated using MCM simulations by combining the room dimension, assumed to follow a uniform distribution between 20 and 40 square meters, and the air conditioning contribution retrieved from the literature, which ranges from 4 to 12 kg $CO_{2,eq}/m^2$/year, and follows a uniform distribution.
- The operational contribution of the car, which was evaluated using MCM simulations by combining the assumed daily movement, following a normal distribution and expressed as 40 ± 10 km/day, with the carbon footprint of fuel consumption, following a uniform distribution and ranging from 0.12 to 0.27 kg/km.

The choice of normal or uniform distribution was based on various factors, including the market scenario for the embodied contribution, and the typical energy consumption for the operational contribution [2,13]. Some entries in the table were left blank because resistor consumption was already accounted for in the generator consumption, while the consumption of the instrument control software and pen drive was included in the laptop consumption.

Finally, for each measuring system, all the environmental footprints (listed in Table A.1 of the Appendix) were summed together according to the checklist reported in Table 3. Clearly, the operating footprints, expressed in kg/h, were converted to kg/year before being added to the embedded footprints, considering the defined working time interval of 1920 h/year. MCM simulations were performed considering 10^6 extractions for each item. The resulting 99% coverage interval is shown in Table 4. As visible, a separate evaluation was conducted by considering on one hand, the contributions of hardware, software, and consumables for each of the measuring systems, and on the other hand, the contributions of the common site infrastructure and people movement. This helps to better understand the difference in terms of carbon footprint between the three measuring systems considered. As evident, the contribution of site infrastructure and people movement is significantly greater than that of the measuring system itself. For this reason, it is this contribution that offers the most potential for making measurement processes more sustainable.

Overall, while the operational impact cannot be entirely eliminated due to the energy required for item utilization, the embodied impact can be mitigated. One approach, in line with the principles of a circular economy, is to reuse instruments already available in the laboratory. Another strategy may involve selecting items from more sustainable suppliers who prioritize minimizing transportation costs. However, as aforementioned, there is a scarcity of data on sustainable practices in this regard.

6.3. *Representation*

Table 5 shows the obtained results in terms of environmental sustainability and performance for the three considered measuring systems within the simulated scenario #1. In particular, it reports the carbon footprint, as well as the corresponding relative uncertainty achieved. The *Carbon Footprint* column displays the amount $CO_{2,eq}$ emitted per year for each measuring system. In this scenario, the Two-wire Method is characterized by the lowest carbon footprint (about 204 kg $CO_{2,eq}$ /year). Instead, the *Relative Uncertainty (%)* column indicates the relative uncertainty associated with the carbon footprint estimation, expressed as a percentage. It represents the uncertainty provided in the measurement of the measurand R_x. In this scenario, the lowest value is obtained by the Voltamperometric Method (about 0.1%).

Fig. 3 shows a scatter plot that directly illustrates the three considered measuring systems with respect both to the sustainability and performance dimensions. By comparing the carbon footprints and relative uncertainties among the measurement methods, one can assess their environmental impact and performance achieved: lower relative uncertainties indicate more precise and reliable measurements; lower carbon footprints indicate fewer $CO_{2,eq}$ emissions.

It is evident from the figure that there exists a trade-off between performance and environmental sustainability: on one hand, the system with the lowest uncertainty, namely the Voltamperometric Method, exhibits the highest environmental impact. On the other hand, the system with the lowest environmental impact, i.e., the Two-wire Method, is also the one with the poorest performance in terms of uncertainty. As can be seen, the measures of environmental sustainability among the three measuring systems at 99% confidence are not compatible with each other. This implies that it is possible to assert that the measured

Table 5
Mean carbon footprint (index of the environmental contribution) and relative uncertainty (index of the performance) provided by the considered measuring systems for the simulated scenario #1.

Method	Mean $CO_{2,eq}$ (kg $CO_{2,eq}$/year)	Rel. Unc. (%)
WB	399.8	1.0%
VA	661.2	0.1%
2W	204.7	1.2%

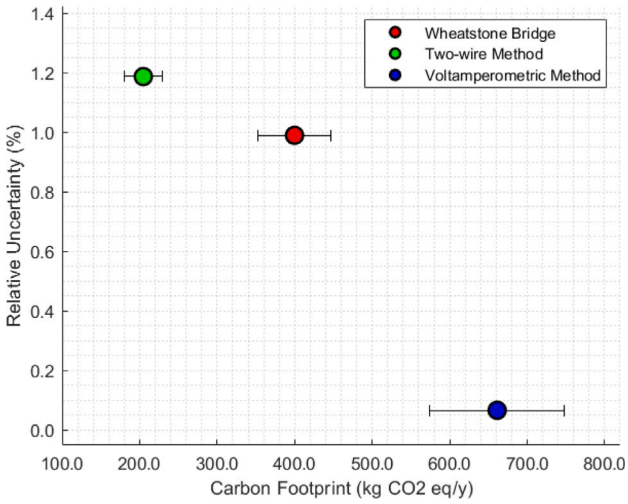

Fig. 3. Scatter plot of the carbon footprint (measured at 99% confidence level) and the Relative Uncertainty for each of the considered measuring systems for the simulated scenario #1.

environmental contribution of each system significantly differs from the others.

The result obtained from this simulated scenario allows us to understand how, currently, it could not always be possible to achieve a perfect balance between performance and sustainability. This consideration can lead to the necessity to include environmental sustainability as an evaluation parameter.

7. Results for simulated scenario #2

In this second simulated scenario, it is assumed that the three Laboratories employ the same measurement equipment. To delve into specifics, let us consider that Laboratory #1, employing the Wheatstone Bridge, selects:

- Two resistors with a nominal value of 100 Ω and a tolerance of 1%;
- A variable resistor spanning 1 Ω with 1% tolerance;
- A benchtop multimeter weighing ≈1.5 kg with an accuracy of 30 ppm for reading +7 ppm range for voltage readings, an accuracy of 100 ppm for reading +300 ppm range for current readings, and an accuracy of 0.2% + 1 Ω for resistance readings;
- A benchtop signal generator weighing ≈1.5 kg; and
- A high-performance laptop weighing ≈2 .

While Laboratory #2, which employs the Voltamperometric Method, adopts the same benchtop multimeters, signal generator, and laptop as Laboratory #1. Finally, Laboratory #3, operating with the Two-wire Method, chooses the same benchtop multimeter and high-performance laptop as Laboratory #1 and #2. Under these assumptions, the evaluation of the measurement uncertainty and measurement sustainability is conducted as done in Section 6.

Table 6
100% coverage intervals for the input quantities in the resistance measurement of the specified measuring systems, namely the Wheatstone Bridge (WB), the Voltamperometric Method (VA), and the Two-wire Method (2W), for the simulated scenario #2. A uniform distribution is assumed. No input quantities were included for the Two-wire method as it consists of a direct measurement of the measurand R_x.

WB	
Quantity	Coverage interval
R_a	[99.00 ÷ 101.00] Ω
R_b	[99.00 ÷ 101.00] Ω
R_{cn}	[99.99 ÷ 102.01] Ω
R_{cp}	[98.01 ÷ 99.99] Ω
V_n	[−0.012406 ÷ −0.012393] V
V_p	[0.012593 ÷ 0.012607] V
VA	
Quantity	Coverage interval
V_m	[4.999780 ÷ 5.000220] V
A_m	[0.049965 ÷ 0.050035] A
2W	
Quantity	Coverage interval
–	–

Table 7
99% coverage interval for the measurand R_x of the considered measuring systems for the simulated scenario #2.

Method	Coverage interval (Ω)
WB	[99.02 ÷ 101.00]
VA	[99.93 ÷ 100.07]
2W	[98.81 ÷ 101.19]

7.1. Measurement uncertainty

With regards to the evaluation of the measurement uncertainty of the three measuring systems, the technical specifications previously introduced were used to evaluate the pdf of each input quantity in the measuring system. For the sake of brevity, the procedure applied was the same described in Section 6.1. The 100% coverage interval for each input quantity is shown in Table 6, while the resulting 99% coverage interval of the measurand after Monte Carlo simulations is shown in Table 7 for the three measuring systems. Again, the Measurement Uncertainty at 99% coverage is represented by the semi-amplitude of the obtained intervals.

7.2. Measurement sustainability

Also the evaluation of the environmental sustainability of the three considered measuring systems is conducted following the same strategy described in Section 6.2. The checklist of the items and the relative considerations are the same as reported in Table 3 and previously discussed. Table A.2 (in the Appendix) provides, for each item, the corresponding values in terms of mean, standard deviation, and probability distribution, along with a symbol to clarify if the item was modeled by means of Open LCA or by information retrieval from the literature. MCM simulations were performed considering 10^6 extractions for each item and summing all the relative environmental footprint according to the checklist reported in Table 3.

The resulting 99% coverage interval is shown in Table 8. Once more, a separate evaluation was conducted by considering, on one hand, the contributions of hardware, software, and consumables for each measuring system, and on the other hand, the contributions of the common site infrastructure and people movement. Also in this case, this latter contribution is significantly greater than that of the measuring system itself.

Table 8
99% coverage interval for the carbon footprint measured for the considered measuring systems, and site infrastructure and people movement, for the simulated scenario #2.

Method	Coverage interval ($kg\ CO_{2,eq}$/year)
WB	[421.3 ÷ 530.4]
VA	[479.4 ÷ 616.9]
2W	[345.9 ÷ 437.7]
Site infrastructure and people movement	[4492.0 ÷ 24 259.4]

Table 9
Mean carbon footprint (index of the environmental contribution) and relative uncertainty (index of the performance) provided by the considered measuring systems for the simulated scenario #2.

Method	Mean $CO_{2,eq}$ ($kg\ CO_{2,eq}$/year)	Rel. Unc. (%)
WB	475.8	1.0%
VA	548.2	0.1%
2W	391.8	1.2%

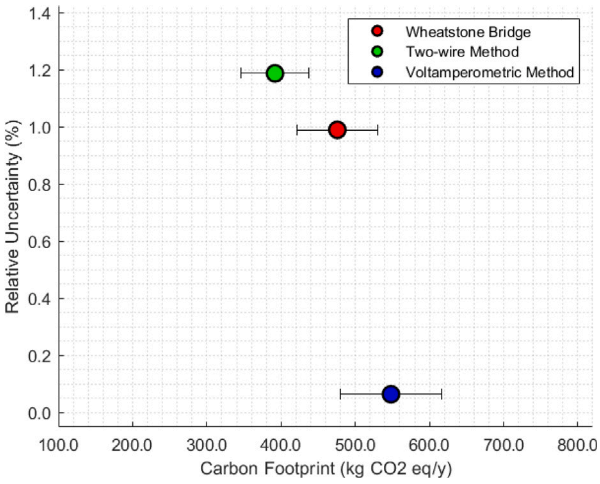

Fig. 4. Scatter plot of the carbon footprint (measured at 99% confidence level) and the Relative Uncertainty for each of the considered measuring systems for the simulated scenario #2.

7.3. Representation

Following the procedure already shown in Section 6.3, Table 9 provides the obtained results in terms of environmental sustainability and performance for the three considered measuring systems within the simulated scenario #2. Also in this scenario, the Two-wire Method is characterized by the lowest carbon footprint (about 204 $kg\ CO_{2,eq}$/year), while the lowest uncertainty value is obtained by the Voltamperometric Method (about 0.1%). However, by observing Fig. 4, which shows a scatter plot that directly illustrates the three considered measuring systems with respect both to the sustainability and performance dimensions, it results evident that the three measured environmental contributions are compatible. This result is indicative of the fact that, at the present state, there are not enough details available to adequately model the environmental contribution of different measuring systems that utilize similar instrumentation. This stands as a gap to be filled in order to establish, with greater confidence, the validity of a measuring system both in terms of its sustainability aspect and its performance aspect.

8. Results for the experimental scenario

After introducing the two simulated scenarios, this Section shows the experimental results obtained for the measurement uncertainty and the carbon footprint of the considered measuring systems in a real-world application. A comprehensive comparison between the results is also conducted to provide a thorough analysis of the proposed methodology.

Table 10
Mean carbon footprint (index of the environmental contribution) and relative uncertainty (index of the performance) provided by the considered measuring systems for the real-world scenario.

Method	Mean $CO_{2,eq}$ ($kg\ CO_{2,eq}$/year)	Rel. Unc. (%)
WB	511.1	1.0%
VA	617.9	0.1%
2W	383.0	1.0%

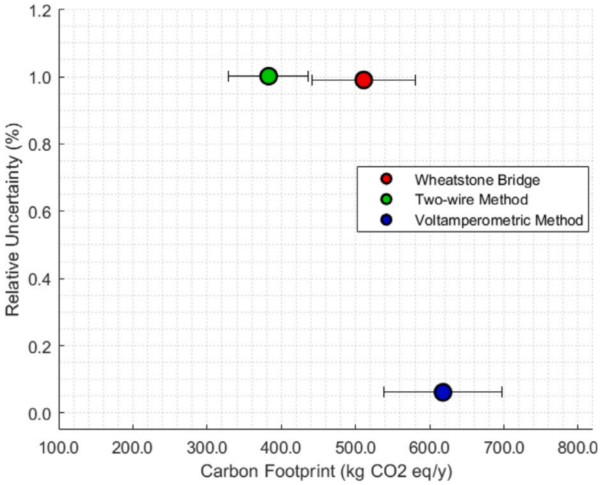

Fig. 5. Scatter plot of the carbon footprint (measured at 99% confidence level) and the Relative Uncertainty for each of the considered measuring systems for the real-world scenario.

In this specific scenario, the instrumentation considered for the measurements consisted of:

- A multimeter, specifically the *Keithley 2000* [27], which was employed as a voltmeter, ammeter, and for the Two-wire direct resistance measurements. The technical specifications were considered at an operating temperature of (23 ± 5) °C over a period of 90 days.
- A signal generator, specifically the *Agilent 33220A* [28];
- Two carbon film resistors, each with a nominal value of 100 Ω and a tolerance of 1%;
- A variable resistor with a resolution of 1 Ω and a tolerance of 1%; and
- An off-the-shelf laptop weighing ≈1.5 kg.

The site infrastructure (room, air conditioning, lights) and the other supplementary items (internet equipment, USB pen-drive) were the same as defined in Sections 6 and 7, and modeled in Tables A.1 and A.2. After applying the methodology described in Fig. 1 and in Section 6 and Section 7, Table 10 and Fig. 5 represent the obtained results both in terms of carbon footprint and relative uncertainty at 99% confidence.

Fig. 5 highlights the two issues that arose during the formulation of the two simulated scenarios. On one hand, there is a performance-sustainability trade-off between the Two-wire Method and the Voltamperometric one, which demonstrates the risk that arises in not being able to determine the existence of an *optimal* measuring system from both uncertainty and environmental impact perspectives. On the other hand, the lack of detailed information prevents achieving the necessary granularity in the data to allow for non compatible measurements. In fact, both the Wheatstone Bridge Method and the Voltamperometric Method prove to be compatible.

Despite its simplicity, this real case study does not compromise generality and demonstrates the potential outcome when different measuring systems exist for a given measurand, and the most suitable one must be chosen, considering not only performance but also environmental impact.

9. Conclusion

This paper proposed a methodology that integrates performance and sustainability considerations in the measurement design, with particular reference to the selection of the most appropriate measuring system to use for a given measurand.

Along with traditional evaluations of measurement uncertainty, this methodology leverages *ITU* recommendations and *ISO* standards to assess the carbon footprint of individual components within a measuring system, while employing the guidelines outlined in the *Supplement One* to the *GUM* to obtain a measure of the system's carbon footprint.

Through a case study involving three resistance measuring systems, the Authors evaluated the measurement uncertainty and the carbon footprint for each system both in simulated and real-world scenarios. Despite the simplicity of the case study, the obtained results enable informed decision-making to select the more adequate measuring system to meet both sustainability and performance criteria. Hence, the proposed paper offers an opportunity to optimize performance while simultaneously reducing emissions and resource consumption. It highlights the significance of sustainable practices and showcases the potential for innovation and progress in the field of Metrology, by encouraging a holistic approach that goes beyond traditional metrics and emphasizing environmental responsibility.

In this way, the proposed approach complements the *Industry 4.0* paradigm by putting research and innovation at the service of the transition to a sustainable, human-centric and resilient European industry, paving the way for the transition towards *Industry 5.0*.

Future efforts will be dedicated to the refinement of the estimation of carbon footprints for the components of measuring systems, as well as for site infrastructure and the working environment, in order to obtain more accurate and precise results. Additionally, while the present work focuses on the measuring system, future work will address the sustainability of the other functional elements of the measurement design.

CRediT authorship contribution statement

Leopoldo Angrisani: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Mauro D'Arco:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Egidio De Benedetto:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Luigi Duraccio:** Writing – original draft, Validation, Software, Investigation, Formal analysis, Data curation. **Monica Imbò:** Writing – original draft, Validation, Software, Investigation, Data curation. **Annarita Tedesco:** Writing – review & editing, Supervision, Methodology, Formal analysis.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

This study was financially supported by the Italian Ministry of University and Research (MUR) through the project: "Made in Italy Circolare e Sostenibile", PNRR PE11 (CUP E63C22002130007).

Appendix

See Tables A.1 and A.2.

Table A.1

Embodied and operational footprint for each item of the three considered measuring systems for the simulated scenario #1.

Item	#Lab	Embodied $CO_{2,eq}$ (kg/year)			Operational $CO_{2,eq}$ (kg/h)		
		Mean	Std	Pdf	Mean	Std	Pdf
Hardware							
Signal generator	1	43.5	2.5	Uniform[a]	0.0200	0.0012	Uniform[b]
	2	68.4	3.9	Uniform[a]	0.0300	0.0017	Uniform[b]
Multimeter	1	43.5	5.0	Uniform[a]	0.0150	0.0017	Uniform[b]
	2	68.4	7.9	Uniform[a]	0.0200	0.0023	Uniform[b]
	3	18.6	2.1	Uniform[a]	0.0100	0.0012	Uniform[b]
Laptop	1	79.9	4.7	Uniform[a]	0.0500	0.0029	Uniform[b]
	2	98.3	5.7	Uniform[a]	0.0800	0.0046	Uniform[b]
	3	61.0	1.6	Uniform[a]	0.0200	0.0012	Uniform[b]
Internet equipment	All	14.2	1.5	Normal[a]	0.06	0.02	Uniform[b]
Resistor	All	0.005	≈0	Uniform[a]	–	–	–
Cables	All	0.023	0.002	Normal[a]	0.0015	0.0030	Uniform[b]
Software							
Instrumentation control	All	50.5	3.2	Uniform[b]	–	–	–
Consumables and supportive products							
32-GB pen-drive	All	1.8	0.2	Normal[a]	–	–	–
Site infrastructure							
Lights	All	0.0013	0.0004	Normal[a]	0.015	0.003	Uniform[b]
Air conditioning	All	253	116	MCM[b]	3.9	1.9	Uniform[b]
Movements of people							
Car	All	402	129	Uniform[b]	1.0	0.5	MCM[b]

[a] Indicates the items modeled by means of Open LCA; instead.

[b] Indicates the items modeled by means of the information retrieved from the literature.

Table A.2

Embodied and operational footprint for each item of the three considered measuring systems for the simulated scenario #2.

Item	Embodied $CO_{2,eq}$ (kg/year)			Operational $CO_{2,eq}$ (kg/h)		
	Mean	Std	Pdf	Mean	Std	Pdf
Hardware						
Signal generator	43.5	2.5	Uniform[a]	0.0200	0.0012	Uniform[b]
Multimeter	43.5	5.0	Uniform[a]	0.0150	0.0017	Uniform[b]
Laptop	98.3	5.7	Uniform[a]	0.0800	0.0046	Uniform[b]
Internet equipment	14.2	1.5	Normal[a]	0.06	0.02	Uniform[b]
Resistor	0.005	≈0	Uniform[a]	–	–	–
Cables	0.023	0.002	Normal[a]	0.0015	0.0030	Uniform[b]
Software						
Instrumentation control	50.5	3.2	Uniform[b]	–	–	–
Consumables and supportive products						
32-GB pen-drive	1.8	0.2	Normal[a]	–	–	–
Site infrastructure						
Lights	0.0013	0.0004	Normal[a]	0.015	0.003	Uniform[b]
Air conditioning	253	116	MCM[b]	3.9	1.9	Uniform[b]
Movements of people						
Car	402	129	Uniform[b]	1.0	0.5	MCM[b]

[a] Indicates the items modeled by means of Open LCA; instead.

[b] Indicates the items modeled by means of the information retrieved from the literature.

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