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A framework for defining, quantifying and implementing a noise footprint approach

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ABSTRACT

The noise footprint is emerging as a framework for assessing and communicating the impacts of noise. Although footprint terminology has been used across diverse areas of environmental acoustics research, its meaning, definition and application vary across fields. This research aims to provide a consensus-based noise footprint definition, identify the conceptual and methodological requirements that should guide future quantitative implementation and establish its basic operational characteristics. An adjusted Delphi process was conducted with a panel of 8 experts spanning two domains, namely acoustics and Life Cycle Assessment & environmental footprinting. The process combined semi-structured interviews and two rounds of questionnaires to establish consensus on the conceptual definition and quantitative characteristics of the noise footprint and thematic analysis of the collected material. The outcomes were subsequently synthesized through a SWOT analysis to identify strengths, weaknesses, opportunities, and threats associated with the proposed framework. In contrast to most existing noise footprint applications, the proposed framework suggests a life cycle perspective and supply chain attribution. The noise footprint is proposed, on the basis of expert consensus, as a measure for assessing and comparing noise, applicable to products and adaptable to individual and societal activities. It is best understood as a structured indicator with two levels of resolution: an emission-based level inventorying the sound energy of interconnected sources, and an impact-based level that incorporates exposure of affected receptors. The framework supports the tracing of acoustic pressures across systems, enabling the identification of impacts and shared responsibilities in noise management.

1. Introduction

Noise is an immaterial pollutant (Cucurachi et al., 2017) characterized by relatively rapid decay over time and distance (Hothersall and Chandler-Wilde, 1987), localized effects and strong dependence on landscape and built form (Forssén et al., 2022). Unlike material pollutants such as carbon dioxide, noise does not accumulate but fades away (Cucurachi et al., 2012; Müller-Wenk, 2004), persisting in cases of

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continuous sources (e.g., traffic noise) and enclosed environments (Echevarria Sanchez et al., 2016). The deleterious consequences of noise for human well-being (Babisch, 2005) and ecosystem health (Brumm, 2006) are interrelated. The World Health Organization identified a set of damage categories including cardiovascular disease, cognitive impairment in children, sleep disturbance and annoyance, typically linked to transportation noise (road, aircraft, rail) (Münzel et al., 2020). However, despite indications from epidemiological studies (Andersson et al., 2020; Sørensen et al., 2015) that strengthen evidence of the effects of noise on health, difficulties still remain in incorporating noise into standardized environmental policies and decision-making tools that extend beyond local contexts (Aletta, 2025). Introducing an environmental footprint perspective could thus help quantify noise as a broader environmental burden and clarify responsibility across complex production and consumption systems. This requires a shift from reactive control to preventive, systemic strategies, which a noise footprint framework could support. To establish such framework, it is important to clarify what a footprint is, what it measures, and how the Life Cycle Assessment (LCA) method has evolved to incorporate footprint-based approaches and noise.

1.1. Footprints and their position in sustainability assessment

Footprints can be described as sustainability metrics (Čuček et al., 2012), that act as diagnostic tools by enabling the detection and quantification of impacts and aiding comparisons among products, services and individual actions. They can be labeled as: (a) environmental footprints measuring human appropriation of natural resources (Hoekstra, 2019; Rees, 1992); (b) social footprints, quantifying the social sustainability performance of an organization; and (c) economic footprints, measuring the direct and indirect economic impacts of processes, products, or activities, as well as of a region or an entire country (Čuček et al., 2012). A universal definition of “footprint” is not available, as it would be impractical to incorporate the wide variety of footprint concepts under a single, restrictive definition. To address this, Fang et al. classified footprints by domains (environmental and socio-economic), groups and categories (Fang et al., 2016). Within the environmental domain, they distinguish “resource footprints”, describing inputs extracted from the environment, and “emission footprints”, measuring outputs released to the environment. These are further allocated into inventory-oriented footprints, which quantify resources or emissions in absolute terms, and impact-oriented footprints, which characterize resources or emissions according to their contribution to specific environmental problems (Fang et al., 2016). Before positioning noise within the “footprint family”, the carbon footprint (CF) offers a useful reference point. CF belongs to the emission footprint group because it accounts for substances released into the environment. It can be classified in two ways: as an inventory-based emission footprint, which represents the absolute mass of emitted carbon compounds, and as an impact-based emission footprint, which reflects the contribution of greenhouse gas (GHG) emissions to climate change. CF emerged as a simplified indicator during the 1990s–2000s, focusing on aggregated CO_2 or CO_2-equivalent emissions and was subsequently formalized through international standards (Wright et al., 2011). Their primary focus was on inventorying energy and resource use, emissions, and solid waste generation across each industrial process within a product's life cycle. As inventories became more complex, this emphasis gradually evolved into translating inventory results into environmental impact potentials such as climate change, eutrophication and resource scarcity (Bjørn et al., 2018). The term carbon footprint has since become widely recognized, used to describe the relationship between a certain amount of GHG emissions and a specific activity, product, or population. The carbon footprint is now applied across multiple scales, from products to organizations and national inventories (Asdrubali et al., 2025; Fantilli et al., 2019). Additionally, the concepts of carbon trade-offs and offsetting, referring to the balancing acts and compromises between reducing emissions and other environmental, economic, or social goals are distinct but interconnected in climate action (Lovell and Liverman, 2010). Specifically for carbon which is uniquely suited to offsetting, the approaches regard: (a) sequestration, which increases carbon uptake and storage through nature-based solutions (e.g., tree planting); (b) forestalling, which avoids emissions by supporting low-carbon alternatives such as wind or solar power; and (c) offsets linked to wider environmental co-benefits, where the primary value lies in outcomes such as biodiversity protection or ecosystem restoration rather than direct changes in the carbon balance (Lovell and Liverman, 2010).

The noise footprint is an emerging yet underdeveloped concept, applied across sectors such as aviation, maritime environments, transportation, and industry. Despite its growing use, the absence of a unified framework limits its comparability, policy relevance and integration into broader sustainability assessments. Similar to carbon, noise footprint can be classified as an inventory-based emission footprint when studies simply report noise emissions and as an impact-based emission footprint when the focus shifts to how noise affects human health or ecosystems (Tsaligopoulos et al., 2026). Notably, a noise footprint approach was developed as a consumption-based measure that quantifies the total noise impacts triggered by the private mobility demand of citizens in the study by (Cucurachi et al., 2019). The authors followed a life cycle approach that included inventory modelling using linear sound energy units (Joules). Furthermore, the study utilized the CNOSSOS-EU noise modelling framework (Kephalopoulos et al., 2012) to calculate sound power levels based on vehicle type and speed. The parallels often drawn between “footprinting” approaches and LCA are not coincidental. An example of this association is the Organization Environmental Footprint (OEF) (Martinez et al., 2019) and Product Environmental Footprint (PEF) methods, developed by the European Commission, are LCA-based methods used to measure and communicate the environmental performance of organizations and products, forming the EU Environmental Footprint framework (Damiani et al., 2022).

1.2. Noise as an impact category in life cycle impact assessment

Including noise in LCA is not an easy task as specific methodological challenges are raised (Heijungs and Cucurachi, 2017). Standard footprint and LCA terminology must be adapted while maintaining the same underlying logic and intent. Drawing parallels between standard LCA practice and noise-integrated LCA can support understanding of the noise footprint of products. From the early stages of the LCA method (goal and scope definition), the functional unit which is a quantified description of the service delivered by the system (Guinée et al., 2011) is defined. Along with the system boundaries (e.g. cradle to gate, cradle to grave) the impact category is selected. A common impact category is Global Warming Potential (GWP) (Smurthwaite et al., 2024), reported in carbon dioxide equivalents (CO_2-eq) (Jian et al., 2025; Ouattara et al., 2024) and expressed per functional unit (Bonamente et al., 2016). Similar to carbon, noise is an impact linked to the delivery of a product or service (Müller-Wenk, 2004).

A central methodological step is the definition of characterization factors that convert inventory flows into impact scores. A characterization factor acts as a “multiplier” that converts different substances or emissions into a common unit of impact. In the context of noise, the characterization factor quantifies the impact of sound energy on human health. Within Life Cycle Impact Assessment (LCIA), midpoint indicators occupy an intermediate position between emissions and final damage (Bjørn et al., 2018). For noise, they can be expressed using two practical approaches. A first approach defines the midpoint close to the exposure stage, using aggregated exposure metrics that combine sound level, time and population (e.g., person·Pa·s) (Cucurachi et al., 2012). A second approach defines the midpoint closer to human disturbance, using indicators such as the percentage of highly annoyed (%HA) by noise (Meyer et al., 2019). The final step involves the calculation of the endpoint indicators which stand as a quantified expression of damage to areas of protection, such as human health using the Disability Adjusted Life Years (DALY) indicator (Cucurachi et al., 2019). These developments provide the methodological foundation for noise footprints, whereas broader, non-LCA noise footprints remain largely undefined and still require conceptual development.

1.3. Research aim

Footprint-related terminology has appeared in environmental acoustics literature since the 1970s, across fields such as aviation, underwater acoustics and transportation. In most cases, it has functioned as a broad label, used to describe the geographic area affected by noise (Tsaligopoulos et al., 2026). Nevertheless, its meaning and application remain fragmented and inconsistent, which has hindered its integration into wider sustainability assessments. Consensus is lacking in both the definition of the noise footprint and the conceptual basis for its quantification.

The present study advances the field by proposing a consensus-based approach aligned with established environmental footprint frameworks similar to the carbon footprint, with particular attention to life-cycle-based product assessment, aiming to integrate noise into broader sustainability analysis. The study establishes the conceptual and methodological logic that should underpin the quantification of the noise footprint, providing the foundation for its detailed operationalization in future work which will require a substantial multidisciplinary effort. To achieve this, a synthesis of expert knowledge is required in the domains of environmental acoustics, footprint analysis and Life Cycle Assessment (LCA) within quantitative sustainability analysis. The study employs a modified Delphi methodology combined with thematic analysis of expert interviews and written comments collected throughout an iterative process, in order to reach expert consensus on the following research questions. The research questions (RQs) are listed below:

- *RQ1*: What is an expert-agreed definition of a noise footprint?
- *RQ2*: What are the conceptual and methodological requirements that should underpin the quantitative assessment of a noise footprint?
- *RQ3:* How can a noise footprint be operationalized as a decision-support tool, including compensation and trade-off mechanisms?

The article is organized as follows. Chapter 2 presents the methodology used in this research, outlining the steps undertaken. These include the identification of an expert panel and a core group acting as the coordination team. Chapter 3 presents the results, organized according to RQs 1, 2 and 3. Chapter 4 presents the discussion, structured around a SWOT analysis conducted by all authors. The SWOT analysis was selected as it provides a structured means of evaluating an emerging framework, systematically identifying the internal strengths and weaknesses (S and W) and external opportunities and threats (O and T) that will shape its further development and adoption.

2. Methodology

This study adopted a multi-method qualitative research design to address the conceptual, quantitative and operational dimensions of the noise footprint, as shown in Fig. 1. A structured approach was implemented, consisting of two main steps. Step 1 involved a Delphi process, including semi-structured interviews, two rounds of online questionnaires and embedded thematic analysis of all qualitative inputs. Step 2 consisted of a forward-looking implementation guidance, supported by a SWOT analysis.

2.1. Step 1 – Delphi and thematic analysis study design

The Delphi method is a well-established, systematic, iterative technique designed to gather and refine expert opinions in order to reach consensus on complex scientific topics (Dalkey and Helmer, 1963). The method has been applied to a wide range of topics (García-Melón et al., 2012; Mohorjy and Aburizaiza, 1997; Mullender et al., 2020), including noise-related issues (Andersen et al., 2025).

2.1.1. Expert panel assembly

In accordance with established Delphi reporting practices on Conducting and REporting DElphi Studies (CREDES) (Jünger et al., 2017)

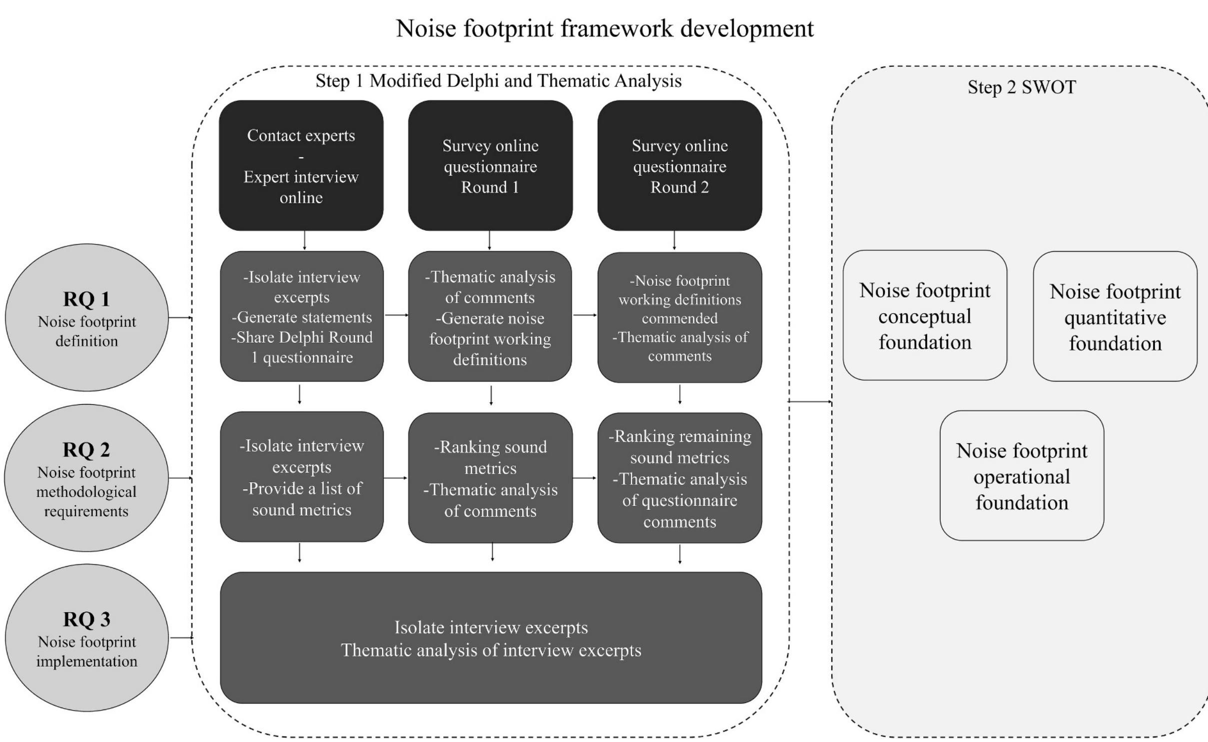

Fig. 1. Flow chart of the research process towards consensus for the noise footprint framework development.

Table 1
Expert panel across two branches, the Acoustics branch and the LCA & environmental footprints branch. Industry is also represented in the acoustics branch. Four out of eight experts (E) present dual expertise in both branches.

Expert panel		E1	E2	E3	E4	E5	E6	E7	E8
LCA & Environmental footprints branch	*Environmental footprints*	●	●	●		●	●		
	LCA	●		●		●			
	Quantitative sustainability	●				●	●		●
	Industrial ecology					●			
Acoustics branch	*Environmental acoustics*		●	●	●		●	●	●
	Soundscape		●	●				●	●
	Noise policy and regulation		●	●	●		●	●	●
	Psychoacoustics		●		●		●		

and the RAND methodological guidance for Delphi panels (Khodyakov et al., 2023), a panel was assembled based on expertise criteria. The Delphi panel consisted of 8 experts while a separate 4-member coordination team facilitated the process, all being co-authors of this research (Fitch et al., 2001; Khodyakov et al., 2023). The selection of experts was guided by demonstrated experience in the Acoustics and LCA & Environmental footprint domains. These two domains were previously identified in a scoping review of the noise footprint literature as the key disciplines informing the development of the noise footprint concept, which inherently sits at their intersection (Tsaligopoulos et al., 2026). The distribution of expertise across the panel is shown in Table 1.

A coordination group organized the Delphi rounds, synthesized responses and conducted thematic analysis, while the expert group provided input via interviews and questionnaires. The coordination team did not participate in voting at any stage, and the consensus threshold was applied exclusively to the ratings of the eight independent expert panelists. Participant anonymity was maintained throughout all Delphi rounds, including interviews and written feedback. Although panelists were co-authors, they were unaware of one another's identities as participants during the Delphi process; all communication was conducted individually through the corresponding author, and responses were collected, anonymized and presented back to the panel. This preserved the anonymity that distinguishes a Delphi process from open group discussion and guarded against conformity to a dominant view (Khodyakov et al., 2023). Consistent with the exploratory nature of the study, the panel was not intended to comprehensively represent all viewpoints in the scientific community, but to provide initial expert input for establishing a preliminary consensus framework in a largely undefined field. Iterative synthesis and controlled feedback were used to refine concepts and identify convergence and divergence across expert opinions. Prior to participation, all experts provided consent regarding the collection, processing, and use of personal data for research purposes.

2.1.2. *Semi-structured expert interviews*

The Delphi process included a semi-structured online interview, followed by two rounds of online questionnaires. The interviews were conducted remotely using an online meeting platform that enabled audio recording and automated transcription. The semi-structured interview guide (Supplementary material 1, Table S1) was distributed to the experts in advance to allow familiarization with the thematic areas. During each interview, one member of the coordination team introduced the predefined themes. Following the interviews, the automatically generated transcripts were manually reviewed to correct transcription errors. The finalized transcripts constituted the qualitative dataset, which was further analyzed. The interview process began with an opening question, "*How would you define a noise footprint, and what do you believe its primary purpose should be*?" (Question 1, Supplementary material 1, Table S1), designed to elicit foundational perspectives on the concept and its scope. These initial responses were synthesized into formal statements, constructing a shared conceptual understanding of the noise footprint (Supplementary material 1, Table S2). The synthesized findings were later presented to participants as part of the controlled feedback provided between questionnaire rounds, allowing them to cross-check that their contributions had been accurately represented while remaining anonymous to other panelists.

2.1.3. *Delphi questionnaire iterative rounds and consensus assessment*

This stage involved two sequential rounds of online questionnaires assessing the level of agreement among participants on two aspects of the noise footprint: its conceptual definition and the metrics suitable for its future quantification. In the first round, participants evaluated, using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree), a set of statements on the definition derived from the interview analysis, and separately rated a list of 14 candidate noise metrics (1 = Not useful at all to 5 = Extremely useful). Participants were provided with a table of acoustic metric definitions to support a shared understanding across disciplines (Supplementary material 1, Table S3). Additionally, they were asked to provide open-ended comments on each statement. These qualitative inputs were subjected to thematic analysis to extract additional insights. As suggested in the RAND methodological guidance (Fitch et al., 2001; Khodyakov et al., 2023) qualitative comment analysis can help describe the most and least common perspectives and track ongoing disagreements. For this research, consensus was assessed using a percentage-agreement criterion, which is one of the most widely applied approaches in Delphi research for determining convergence of expert opinion (Diamond et al., 2014). To this end, a 75% agreement threshold was prespecified and communicated to participants in advance (Khodyakov et al., 2023). Statements meeting or exceeding the 75% agreement level were retained and those falling below this threshold were excluded from subsequent rounds. Responses were grouped into agreement (ratings 4 and 5) and disagreement (ratings 1 and 2), with the midpoint (3) treated as a neutral position, following established Delphi practice (van der Maaden et al., 2015). In the second round, participants were provided with controlled feedback in the form of a statistical summary of the first-round results. For the metrics, the same 75% threshold was used. Ratings of metrics with clearly low first-round agreement were eliminated (Jünger et al., 2017), while the remaining metrics were re-rated using the same scale. The 75% agreement threshold was applied exclusively to the ratings of the eight independent expert panelists, while the coordination team did not participate in voting throughout the Delphi iterations.

2.1.4. Thematic analysis

The interviews were recorded and transcribed verbatim to generate the dataset. Thematic analysis was employed, a qualitative methodology in the psychological and social sciences designed to systematically identify, analyze, and report thematic patterns within a dataset (Braun and Clarke, 2006). The qualitative data utilized for the thematic analysis included the transcribed semi-structured interviews and the full collection of open-ended comments provided by participants during the Delphi questionnaire rounds. The analysis employed a theoretical thematic analysis approach, driven deductively by the three Research Questions (RQ1-RQ3). The thematic analysis was undertaken by the coordination team, and the resulting synthesis was returned to participants. This checking process helped ensure that the meanings expressed during the interviews were accurately captured and interpreted by the core group, thereby strengthening the quality and validity of the data. The phases of the coding process are the following:

- *Coding*: Data excerpts (chunks) were assigned descriptive codes, capturing the surface meaning of the expert's comment. These descriptive codes were reviewed and reduced to concise final codes.
- *Searching for themes*: The final codes were grouped based on their relationship with the three RQs.
- *Reviewing and naming themes*: Themes were reviewed against the full dataset to ensure internal coherence. Each theme was assigned an interpretive title that represented the core finding.
- *Reporting*: Coding and theme formation were performed manually.

The entire coding procedure can be viewed in Supplementary material 2.

2.2. Step 2 – SWOT analysis and guideline formulation

The second step of the methodology consisted of a SWOT analysis, conducted by the entire research team (expert and coordination panels), aimed at translating the Delphi outcomes into strategic insights and actionable guidance. Delphi has been integrated with strategic planning tools like SWOT analysis (Bošnjaković and Santa, 2025), resulting in a Delphi-SWOT hybrid that is particularly valuable for developing robust strategies in complex and data-deficient scenarios (Tavana et al., 2012). SWOT analysis is a strategic planning tool that identifies internal strengths and weaknesses, and external opportunities and threats related to an organization or project. This process aids in developing strategies that leverage strengths, address weaknesses, capitalize on opportunities, and mitigate threats (Puyt et al., 2023; Weihrich, 1982). The hybrid Delphi-SWOT methodology has been applied across fields like sustainable growth in the bioeconomy (Papadopoulou et al., 2025) and policy development for material utilization (Auer and Rauch, 2021), enhancing objectivity and consensus of strategic factors.

3. Results

Table 2 provides a structured overview of the data inputs, analytical procedures and resulting outputs associated with each research question.

3.1. Definition of the noise footprint

This section presents the definitions of the noise footprint that achieved consensus through the Delphi process, together with points of disagreement identified through the thematic analysis of expert interviews and comments.

3.1.1. Delphi consensus results on the noise footprint definition

From the expert interviews conducted in the initial steps of the Delphi process, eight distinct statements were generated, reflecting conceptualizations of the noise footprint (also in Supplementary material 1). These statements, captured a wide range of perspectives, including technical measurement approaches, life cycle–based formulations, spatial representations, population-based metrics and multidimensional conceptualizations integrating source–receiver dynamics (Fig. 2). Analytical results for all statements are provided in Supplementary material 1, Table S4.

Following the first-round evaluation, two statements (statements 1 and 6 in Fig. 2) reached the predefined consensus threshold (≥75% agreement): (a) the noise footprint as a structured, life cycle-based measure of noise impact (statement 1, 75% consensus) and (b) the idea of a noise footprint as a decision-making tool (statement 6, 87.5% consensus). These two conceptualizations reflect complementary perspectives on the noise footprint from a product standpoint and were retained as the conceptual foundation of the framework.

Specifically:

Statement 1.

The noise footprint is:

“A structured, life cycle-based measure of noise impact linked to specific activities and defined by spatial and temporal scales. It involves all noise generated across a supply chain, applicable to products, industries, countries or people.”

Statement 6.

The noise footprint is:

“A decision-making tool designed to prioritize actions based on noise impact outcomes. Its design and effectiveness depend on its intended purpose, influencing what aspects it captures.”

The remaining six statements did not reach consensus but provided valuable insight into areas of conceptual divergence, which are analyzed in the following subsection.

3.1.2. Emission-based inventory and impact-based noise footprint

Thematic analysis of the expert comments revealed varying views on whether the focus should lie on the source (the noise emitted) or the receiver (the impact on people and ecosystems). Participants noted that an emission-based approach provides technical practicality and maintains a clear connection to a product's physical life cycle, as the emission inventory is independent of geographic context. At the same time, they acknowledged that the resulting impact depends on the presence and location of receivers. As one expert expressed:

Table 2
Overview of data sources, analytical procedures and outputs by research question.

Research Question	Input data	Data generated	Data analysis	Results
RQ1	Semi-structured interview excerpts; written comments from the Delphi iterative rounds.	Formulated noise footprint definition statements derived from interview synthesis; qualitative comments from Delphi questionnaires.	Consensus-building on definition statements through Delphi rounds (≥75% agreement threshold); thematic analysis of all qualitative comments.	Consensus-based working definitions of the noise footprint (emission-based and impact-based formulations).
RQ2	Semi-structured interview excerpts; written comments from the Delphi iterative rounds.	List of proposed noise indicators/metrics; qualitative comments from Delphi questionnaires.	Consensus-building on preferred noise footprint metrics through Delphi rounds (≥75% agreement threshold); Thematic analysis of all qualitative comments to identify methodological requirements and constraints.	Identification of the preferred metric and key methodological requirements for quantitative implementation.
RQ3	Semi-structured interview excerpts; written comments from the Delphi iterative rounds.	Qualitative comments addressing operationalization, compensation and trade-off mechanisms.	Thematic analysis of all qualitative material, structured deductively.	Thematic identification of operational pathways

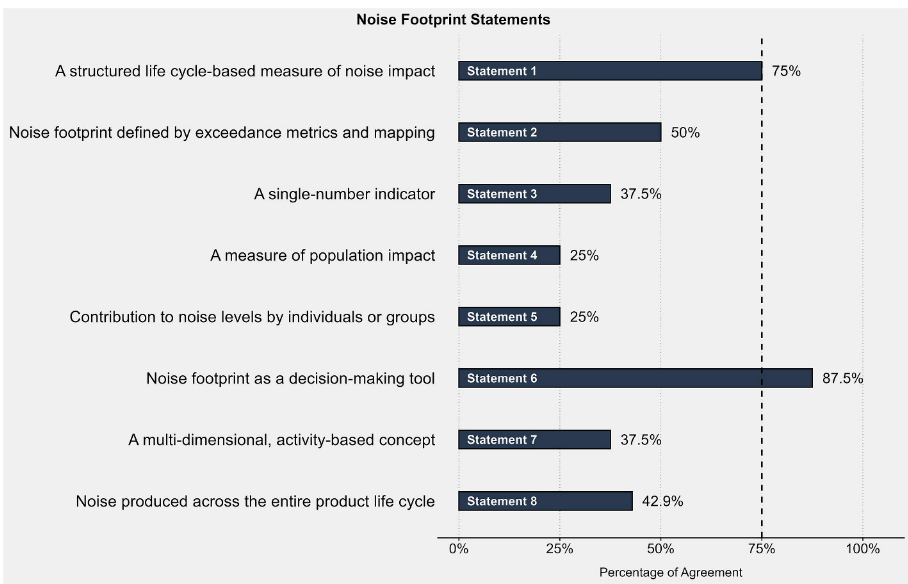

Fig. 2. Delphi results on noise footprint statement.

"… I believe that the noise footprint should be something related to the source, regardless of the people exposed to the noise produced during the Life Cycle. I understand that emitting noise in the middle of nowhere is not harming anyone is different than operating a noisy source in urban context …".

According to the experts, for a noise footprint to be effective it would be "…*easier and less subjective to focus on the emission aspects*…" than to focus on the impacts. Nevertheless, regardless its practicality, the participants indicated the risk that an "…*emission-based is probably more practical, but could lead to unintended consequences more easily, targeting emission reductions that have no impact*…". A purely emission-based metric lacks environmental relevance, as it may prioritize noise reductions in areas where no harm is occurring. An additional comment was:

"I believe the impact-based approach is superior...the terms 'interactions between emitted noise and sensitive receivers, including humans and ecosystems' really gets at the heart of the matter...Without the human-ecosystems perspective, the emission-based approach becomes simply architectonic, missing the mark on urban epidemiology and non-human populations."

Upon acknowledging these views, the panel's coordination group adopted a dual-pathway conceptualization, indicating that the structural identity of the noise footprint is shaped by the source–receiver interplay. To be both scientifically robust and methodologically coherent, the approach should begin with a source-based inventory and, provided that a robust methodological framework for converting noise emissions into impact indicators is established, extend to receiver-based impact characterization. In this sense, progression from inventory to impact is not primarily constrained by data availability, but by the maturity and acceptance of characterization models capable of translating noise emissions into impact indicators. Utilizing the themes and insights that emerged from the comments, the coordination team synthesized the retained statements into two working definitions representing the noise footprint.

Specifically:

Definition A. Emission-Based Noise Footprint.

"The Noise Footprint is a life cycle emission-based indicator that aggregates the sound energy output of interconnected sources within products, processes, or activities. It operates at the inventory level of LCA, serving as a decision-making tool within environmental policy, guiding prioritization of actions, allocation of responsibility and strategic management of noise impacts across sectors and scales."

Definition B. Impact-Based Noise Footprint.

"The Noise Footprint is an impact-based life cycle indicator that quantifies the potential harm caused by noise exposure from products, processes, or activities. It incorporates the spatial and temporal factors to model interactions between emitted noise and sensitive receivers, including humans and ecosystems."

These working definitions were presented to the experts for feedback in the second Delphi round. Experts argued that purely emission-based metrics can be misleading because they aggregate noise events that are geographically and temporally separated:

"...[an emission-based noise footprint] could end up quantifying impacts that happen in temporally or spatially disparate times and locations... When aggregated as a single value... [it] may make impacts appear larger than they are, being spread out in time and space."

At the same time the experts questioned the scientific reliability of long-term harm modelling as expressed through an impact-based noise footprint, suggesting that an inventory-level metric would be more practical for comparing industrial processes:

"...I have some doubts about the ability to quantify the potential harm in years or decades for a large variety of sound sources. I imagine that a midpoint indicator could instead be a single aggregated expression of the inventory indicators... that can be used to compare two processes or activities."

The expert consensus indicated that both definitions are capable of capturing the requirements of a noise footprint, in complementary ways. While the impact-based approach provides the necessary environmental relevance, the emission-based approach offers the "straightforward" computability required for supply-chain comparisons. Consequently, the proposed framework adopts two possible levels of resolution, allowing the noise footprint to function at both the inventory and impact levels depending on the assessment's objective and feasibility, given the higher complexity of impact-based modelling.

3.2. *Conceptual requirements for a noise footprint measure*

The following sections present the conceptual and methodological boundaries of the emerging noise footprint construct as identified through expert consensus. Drawing on the outcomes of the Delphi process and thematic analysis, they outline the key requirements and guiding principles that will inform the future development of noise footprint calculation.

3.2.1. *Expert consensus on noise footprint measure*

As shown in Fig. 3, none of the noise indicators reached the predefined 75% agreement threshold in the first Delphi round. Sound Power Level (L_w) and acoustic energy using as an example Joule (J), the SI unit of energy, received the highest levels of agreement, each reaching 71.4%. The indicators Sound Pressure Level (SPL), the equivalent continuous sound level L_{eq} and the nighttime noise indicator L_{night} also achieved relatively higher levels of agreement compared with the remaining metrics. For each indicator, only responses rated as 'Very useful' or 'Extremely useful' were considered as agreement. Although no indicator achieved the 75% consensus threshold in Round 1, those receiving the highest number of such ratings were retained for Round 2 in order to reduce the number of items while preserving those with relatively strong support. The results of the second-round expert ratings indicate that the Sound Power Level (L_w) achieved the target consensus threshold of 75%, while acoustic energy (J) reached a lower level of agreement at 62.5%. Analytical results for all metrics across both rounds are provided in Supplementary material 1, Table S5.

3.2.2. *Expert perspectives on the quantitative assessment of a noise footprint*

The thematic analysis of interviews and Delphi questionnaire comments revealed three major themes regarding the methodological and quantitative requirements of a noise footprint. Specifically, a) emission-based metric requirements, b) impact-based metric requirements and c) system boundary conditions and spatiotemporal resolution.

The first theme concerned the emission-based metric requirements. Methodological risks were identified regarding the standard logarithmic unit, with one participant noting: "...*If 'noise level' means dB...dB(A), it is incompatible with LCA...*". Once a full life-cycle perspective is adopted, for example in the case of a product noise footprint, dB-based metrics become unsuitable as decibels are non-additive. A life-cycle inventory

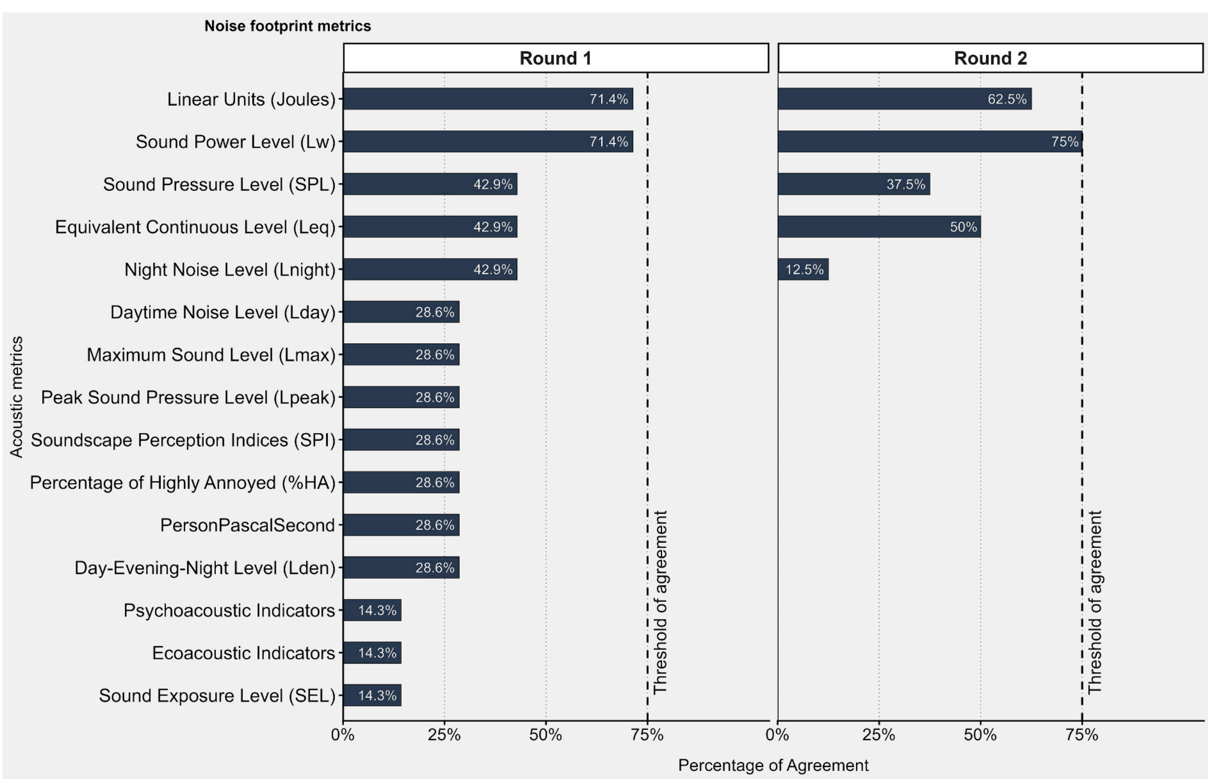

Fig. 3. Delphi consensus round 1and 2 for the noise footprint metric.

requires an additive physical quantity, requiring a metric that operates beyond the limitations of decibel-based indicators (e.g., a source-based energy metric) (Torija et al., 2018; Torija and Self, 2018). Experts further emphasized that a suitable noise footprint metric must satisfy two fundamental requirements. It should be aggregable across life-cycle processes, and it should incorporate both noise level and duration relative to the functional unit. As one expert noted"…*Crucial is an indicator that (1) can be aggregated over life cycle processes and (2) that includes both the noise level and the time attributed to a functional unit. A metric like dB does not satisfy (1) and (2). A metric like number of persons affected does satisfy (1) but not (2). Only metrics like energy or pressure can be used for this…*". In this context, conventional decibel-based indicators were considered unsuitable because they do not support additive aggregation across life-cycle stages and do not inherently account for the temporal dimension. Metrics like "number of people affected" is insufficient on their own as they capture aggregation but not exposure intensity or duration. This perspective further supports the use of source-based energy metrics and pressure-based exposure metrics as candidate foundations for future noise footprint quantification.

Additionally, participants highlighted that the temporal assessment is necessary to avoid constant source misinterpretation and avoid source miscalculations…*It should be multiplied by the hour of the activity of the source or something like that otherwise it looks like the sound source is permanent…* A major concern identified within the emission-based metric requirements theme is the possibility to incorporate finer spatiotemporal scales of valuation allowing perception assessment …*the inventory-based approach would allow for a more microscopic assessment of the noise footprint…whether it's an individual, a vehicle, a train, or even a barking dog or temporary construction site…there might be space in this approach to introduce people's perception…* The general idea revolving around the emission-based aspect of the noise footprint is to focus on the source of noise utilizing cumulative sound power levels…*focus on the source, and the sound power level emitted by the source…require a modelling part…a cumulative sound power level would make sense…some sort of cumulative sound power model…*agreeing with the results of the Delphi questionnaire rounds.

Regarding the impact-based metric requirements, the experts noted that the choice of metric is unavoidably linked to the specific effect under study, emphasizing that "*not all decibels are equal*" and highlighting the need for standardization to allow for cross-study comparisons: "*...How you measure it depends on how you understand its effects…it might be L_{night} if you're looking at the effect on sleep… not all decibels are equal…how can we compare things on an equivalent level?... you need everyone to use the same metrics so you can combine results from different studies…*". Metrics such as L_{night} are considered appropriate when assessing sleep disturbance, while other indicators may be required for annoyance or awakenings. Participants also proposed the development of composite or layered indicators with categorized impacts. Suggested formulations included multiplying the number of impacted individuals by duration of exposure, drawing analogies to carbon equivalents in environmental assessments…*impacted people could be analogous to carbon equivalents in environmental assessments…impact itself could be categorized into different effects, such as annoyance, sleep disturbance, or awakenings, and perhaps a combined metric could be developed to account for all these factors… using a clear metric like "number of people woken up" would be very effective for communication…*This approach allows for a more finely resolved understanding of the burden of noise on human health.

The experts suggested caution regarding a single-number indicator and evolve into a layered indicator capable of integrating multiple factors. While attractive for decision-making, single-number indicators were viewed as potentially insufficient to capture the diversity of effects. *…However attractive single indicators are, they usually fall short in really describing the range of effects…*with an additional challenge to integrate perceptual dimensions, including the distinction between desired and undesired sounds…*I like the "single-number indicator". It seems interesting but I don't see how this indicator could easily incorporate perception "desired and undesired sounds"…* Additionally, the receptors of noise were addressed, indicating that human well-being should be the major area of concern…*humans should be prioritized…people in sensitive locations like hospitals and educational centers…but also biodiversity and overall environmental health should be considered…I appreciate the notion that exposure would be aggregated across humans, animals, and environment…*

The third theme concerned the identification of assessment boundaries and the specification of spatial and temporal resolution. The experts stressed that noise is inherently local and time-dependent and therefore cannot be meaningfully quantified without explicit boundary conditions. To avoid miscalculating noise propagation, the experts suggested that the spatial scale be defined by the "…*radius of influence…*". This signifies the "…*spatial scale that represents the radius of impact of an activity or process, the area over which its effects are felt…*". While some experts argued that the spatial scale should be a priority noting that one must "…*first decide on the spatial scale, and only then focus on the temporal scale…*", others highlighted a tension regarding this hierarchy, asserting that the duration of the noise is equally essential as it "…*differs per process across the life cycle…*" and prioritize the temporal scale with day and night specifications. Finaly, the energy and pressure assessed over Life Cycle scale was addressed…*If you speak about the source, it's expressed in energy, and if it's about the receptor, it's expressed in pressure. Those are the things that can be aggregated in some way over a life cycle, over different places, over different moments in time…* Nevertheless, …*noise is a very temporal and localized phenomenon and activity…*indicating that a dedicated risk-assessment step is required to identify the resulting impacts across the life cycle and to attribute them appropriately along a supply chain.

3.3. Operationalizing the noise footprint as a decision-support tool, including compensation and trade-off mechanisms

The thematic analysis of interviews and Delphi questionnaire comments revealed three major themes for addressing noise through a tradeoff system: a macro-level approach centered on compensation-based tradeoffs, a micro-level approach focused on restorativeness, quiet access and subjective experience and finally the limitations of noise related offset mechanisms.

Experts elaborated on the potential for a compensation mechanism at the macro-level:

"…if the noise footprint of a given activity exceeds a certain threshold, the industry or activity might need to compensate the people living in the area… the concept of noise footprints could help manage the trade-offs between economic activity and environmental impact…".

A related theme emerged regarding the technical preconditions and limitations of offset mechanisms at the micro-level. Specifically, experts evaluated whether the noise footprint metric could facilitate tradeoffs by offsetting direct exposure with access to quiet and restorative areas. This approach suggests an indicator accounting for both negative impacts of noisy areas and the positive benefits of quiet spaces, as one expert described:

"…I would use a sound pressure level but in order to measure the emissions or some kind of an offset to the sound pressure level based on the quietness resource or accessibility to a quiet resource by the exposed population…if you just have L_{den} then you really just have a noise map… develop the normalized difference equation…using two units exposure and restorativeness…you end up with a normalized unit that can be mapped…".

The difficulty of creating a reliable "offset" metric was emphasized by the challenge of measuring the actual utilization of restorative environments…*we would need a metric like "resourced people per hour", meaning the number of people who benefit from the quiet environment over time. However, creating or even ensuring access to such spaces is extremely challenging…I don't think this approach works…my initial feeling is that noise cannot be offset in this way…the effectiveness of such spaces depends on how many people use them, and that is difficult to measure…* These insights indicate that while the noise footprint measure can provide a quantitative basis for analysis, its application as a decision-support tool reveals challenges across different scales. Overall, the experts recognized the opportunity for a compensation or trade-off mechanism guided by a noise footprint framework. Nevertheless, they emphasized the difficulty of reliably quantifying the use and benefit of restorative environments. The development of such a mechanism is therefore identified as an open challenge.

4. Discussion - strategic implications, synthesis and moving the field forward

The findings of this research should be interpreted as a conceptual framework and research agenda rather than as validation of a mature assessment methodology. To understand how the noise footprint can be defined and applied in practice, the study addressed the three interconnected research questions. RQ1 sought to establish a conceptual definition, revealing a dual structure for the noise footprint that bridges sound source-based energy output and receiver-based impact. RQ2 examined the quantitative characteristics required for assessment. Although the broader logic of the framework moves beyond receiver-based decibel metrics, the expert consensus highlighted sound power level (L_W) as an appropriate source-based descriptor. While L_W is expressed in decibels, it is physically grounded, traceable to energy and convertible into additive quantities. Finally, RQ3 addressed operationalization, highlighting the potential for the noise footprint to act as a decision-support tool through compensation and trade-off mechanisms.

A SWOT analysis was conducted to evaluate the internal and external factors affecting the noise footprint's development presented in Table 3.

Table 3
Noise footprint framework SWOT analysis.

Strengths	Weaknesses
Builds on established parallels with carbon footprinting, making it intuitive for policymakers and stakeholders	High uncertainty in long-term cumulative effects
Supports responsibility allocation across agents, rather than attributing impacts solely to end users	High dependency on local context and spatiotemporal variables makes calculation difficult
Enables supply chain attribution supporting targeted mitigation actions, aligning noise with sustainability accounting practices	Simplified emission focus may overlook critical epidemiological data
Can offer a link between physical noise assessments and soundscape perception	Responsibility for offsetting may fall to different actors, with a loss of accountability
Incorporates “restorativeness” and quiet space access as offset mechanisms	
Can enable integration of exposure inequality and noise justice analysis	
Opportunities	**Threats**
Moves beyond site-specific noise assessments	
Could support integration of noise into broader sustainability assessments alongside carbon and water footprint and air pollution raising public awareness	Integrating noise into broader sustainability assessments may be methodologically difficult and therefore delay the adoption of the metric in standard policy and even discourage non-expert users
Advances in open data, open modelling and computing now make noise footprint approaches technically and economically accessible	
Opportunities to use this tool to explore environmental inequalities and support noise-justice initiatives	Unlike carbon, noise is a byproduct of all activity, making it harder to isolate and regulate
Creates a link between physical noise exposure and perceptual soundscape policy	Risk of misuse as a purely communicative tool without methodological usefulness
Ability to assess non-human receptors (ecosystems) and indoor environments	Risk of “noise washing,” where entities use footprint reporting to appear sustainable without reducing exposure
Potential to complement EU Environmental Noise Directive reporting with life-cycle insights	
Enables scenario analysis for urban planning, infrastructure design and mobility transitions	

4.1. *Internal factors: strengths and weaknesses of the noise footprint*

Several methodological attributes define internal Strengths and Weaknesses of this framework, particularly its capacity to move beyond site-specific noise assessments. One of its key strengths lies in its conceptual alignment with established environmental footprint approaches and most notably the carbon footprint. This parallel provides a familiar structure for policymakers and stakeholders, offering a solid knowledge base from which to anticipate methodological challenges and avoid pitfalls that carbon accounting has encountered over the years. At the same time, it highlights the intuitive nature of the noise footprint as a decision support instrument. Additionally, the noise footprint will be able to support responsibility allocation across multiple agents, rather than attributing impacts solely to end users. As with carbon, responsibility is understood as shared between individual-level actions and collective political responsibility (Schübel, 2023). Similar logic applies to noise. While individuals contribute directly to noise production, particularly through transport-related choices (Ranpise and Tandel, 2022), noise exposure is also heavily shaped by infrastructural design, land-use planning and regulatory decisions that lie largely beyond individual control (Aletta et al., 2020). The framework also enables supply chain attribution, allowing targeted mitigation actions along the full life cycle of a product system. Such insights can inform policy instruments that link responsibility allocation with incentives for improved noise management, including emerging mechanisms such as nature-based credits or soundscape-oriented compensation schemes. Importantly, the noise footprint can bridge physical noise assessments with perceptual soundscape approaches, supporting the integration of concepts such as restorativeness, quiet area access and soundscape quality into offsetting or compensation strategies.

Despite these strengths, several weaknesses must be acknowledged. First, the long-term cumulative effects of noise are not as well established as those of other environmental burdens, introducing uncertainty into life-cycle-based assessments. Second, noise impacts are highly dependent on local context and spatiotemporal conditions (Cucurachi et al., 2017), making calculation and comparison across settings inherently challenging. Third, an overly simplified emission-based focus risks overlooking critical epidemiological evidence, particularly when exposure–response relationships vary across populations and environments. Finally, responsibility for offsetting may become fragmented across different actors, potentially leading to diluted accountability if governance mechanisms are not clearly defined.

4.2. *External factors: opportunities and threats of the noise footprint*

An opportunity that emerged regards the use of the noise footprint in broader sustainability assessments, strengthening its position among established environmental burdens. Recent research grouped traditional impact categories, such as global warming, together with noise-specific impact indicators, including the highly annoyed people (HAP) and highly sleep-deprived people (HSDP) metrics demonstrating that noise impacts can be quantified and incorporated within an LCA framework (Sultana et al., 2025). A robust noise footprint requires capturing the complex interplay between the source emissions and the receiver exposure. Advances in open data, open modelling and computing can make noise footprint calculations technically and economically accessible (Nygren et al., 2024). Microscopic noise modelling approaches provide a more advanced noise source analysis by using individual speeds to capture traffic jams and acceleration (Mascolo et al., 2025). On the receiver side, agent-based modelling replaces static populations with dynamic "agents" following 24-h activity plans to better represent actual exposure during daily mobility (Galassi Luquezi et al., 2025). Together, these developments can support the methodological foundation of the noise footprint and enable scenario analysis for urban planning, infrastructure design and mobility transitions. Additional opportunities relate to complementing existing noise legislation, such as the EU Environmental Noise Directive, by providing life cycle and supply chain insights. This integration is timely, as noise pollution is reaching near epidemic proportions (Europe, 2023). The noise footprint also offers potential for exploring environmental inequalities and supporting noise justice initiatives. The ethical dimension of attributing responsibility for noise pollution is central here, as spatial inequities in exposure often disproportionately affect low income or marginalized communities (Trudeau et al., 2023). Embedding justice principles would strengthen the footprint's legitimacy and help prevent misapplication. Socioeconomic disparities can be quantitatively assessed by a suite of life cycle–based methods. The socio-economic dimensions of sustainability can be examined through Social Life Cycle Assessment (S-LCA) and Whole Life Costing (WLC) or Life Cycle Costing (LCC). S-LCA follows the ISO LCA framework to assess potential social impacts across the life cycle (e.g., per working hour) (Dunuwila et al., 2025), whereas WLC applies life cycle thinking to systematically evaluate the costs and benefits of a product or service over time (Yousfi et al., 2025). By linking sustainability to economic outcomes, WLC highlights the real implications of investment decisions. Within this broader monetized perspective, health-related impacts for example expressed as DALYs, can also be converted into monetary terms by assigning a currency value to each lost year of healthy life (Arendt et al., 2020). By monetizing such health burdens, the noise footprint can indicate long-term health impacts as economic costs. This allows the framework to reveal social costs highlighting when a product system, infrastructure, or service imposes burdens that should not be shifted onto affected communities.

Additionally, noise related compensation could take non-acoustic forms, such as investments in community amenities or health-promoting infrastructure, highlighting the broader social cost dimension of noise. A concrete example of noise-related compensation can be found in airport management, where aircraft noise imposes substantial external costs on surrounding communities, including reduced property values and diminished quality of life (Sebastian et al., 2025). In such contexts, economic compensation schemes are frequently implemented to address these impacts and internalize noise-related externalities (Cui et al., 2024). Another opportunity lies in integrating perceptual dimensions, marking a significant shift away from purely decibel-based assessments, towards a more human-centered approach to sound environment management and well-being. Compensation and trade-off mechanisms, in this sense, could be interventions (Aletta et al., 2024) that bring a noise polluted sound environment closer to a target soundscape, with the distance between the two being measurable through Soundscape Perception Indicators (SPIs). Incorporating psychoacoustic metrics and SPIs (Mitchell et al., 2024), adds a qualitative layer that accounts for human perception. In practice, SPIs could be used to evaluate whether the quantitative results of the noise footprint align with the desired acoustic quality of a specific location. Psychoacoustic indicators, such as loudness, sharpness, roughness and tonality, provide additional quantitative measures reflecting how sound is processed by the auditory system rather than how it is physically measured (Engel et al., 2021). Together, these approaches offer promising pathways for enriching the quantitative foundation of a future noise footprint framework.

Alongside these opportunities, several threats have been identified. Integrating noise into broader sustainability assessments may be methodologically challenging, potentially slowing the adoption of the metric in standard policy and discouraging non expert users. This threat is reinforced by the physical characteristics of noise, since, unlike carbon, noise is an inherent byproduct of almost all human activity, which makes it more difficult to isolate, quantify and regulate. There is also a risk that the metric could be misused as a purely communicative device without real methodological substance or even lead to forms of "noise washing" where organizations report a footprint to appear sustainable without meaningfully reducing exposure.

4.3. Positioning the noise footprint

A central strategic question emerging from this work concerns the "value added" of the noise footprint relative to existing tools such as noise mapping, annoyance models and LCIA methods. The Delphi results indicate that its distinctiveness lies in its ability to unify dispersed assessment traditions under a single conceptual umbrella. Unlike traditional noise mapping, which remains site-specific and primarily exposure-driven, the noise footprint explicitly embeds responsibility, life-cycle thinking and supply-chain attribution. This shift enables organizations to quantify not only the noise exposure their products or activities produce locally, but also the noise burdens embedded throughout their production systems.

It should be noted that the definitions and methodological requirements developed through this research align most naturally with a product-related noise footprint, as the results point towards a life cycle–based perspective. While other forms of noise footprints, such as personal or land-based variants are conceivable, the current evidence indicates that a product-level framework is the most appropriate starting point. A footprint can adopt a life cycle approach if (a) the function of the investigated product or service can be clearly specified (allowing a suitable reference unit to be defined), (b) an appropriate system boundary can be meaningfully set (e.g., cradle-to-gate or cradle-to-grave), (c) inputs and outputs can be quantified for the main stages and activities along the supply chain, and (d) these inventoried, quantified flows can be linked to impacts through characterization. Typically, product footprints can be assessed using an LCA approach, but from a broader perspective footprints are not always LCA-compatible and an LCA is not always necessary for footprint analysis (Fang and Heijungs, 2015; Fang and Heijungs, 2014). As this framework is currently aligned with LCA-compatible structures making it more suitable for product-level applications, a broader urban or territorial noise-governance needs to be elaborated.

The Sound Power Level (L_W) was identified as a suitable metric for quantifying the noise footprint. Nevertheless, it should be noted that its use requires careful consideration of modelling assumptions, aggregation rules and exposure-response relationships to avoid over-simplification. To support comparability across the different sources and sectors encountered along a life cycle, L_W is treated as a common inventory-level currency, analogous to the aggregation of energy or mass flows in life cycle assessment. Standardized determination following established procedures such as ("ISO 3744,", 2025) provides a harmonized baseline for this purpose, although full standardization of measurement assumptions across all industries remains an area for future methodological development. The use of L_W is already rooted in established practice, for instance in sound power declarations for machinery and in the noise-related information provided on product energy labels. The choice of frequency weighting also needs consideration, as A-weighted sound power relates more closely to human audibility, while linear levels retain the spectral content relevant to other health effects and even to impacts on wildlife. A single value of L_W does not retain the spectral characteristics of a source (tonality, low-frequency content) or its temporal characteristics (impulsiveness, intermittency), yet these properties influence the resulting impact (Hongisto et al., 2019; Oliva et al., 2017). The panel noted that emission should be weighted by activity duration, so a source active only part of the time is not treated as continuous. A single overall value can nevertheless be sufficient to construct the inventory when complemented by qualitative descriptors of these characteristics, with the corresponding adjustments introduced at the assessment stage in line with established rating practice ("BS 4142:2014 + A1", 2019; "ISO 1996-1,", 2016). Where spectral and temporal data are available, preserving them in the inventory allows a more detailed impact assessment, since sources of equal overall sound power but differing spectral distribution or time structure produce different impacts. Additionally, a further opportunity identified in the Delphi (Table 3) is the ability of the noise footprint to extend assessment towards non-human receivers. To this end, L_W can serve as the physical characterization of the source prior to any receiver-specific weighting, onto which species-appropriate adjustments can be applied as they become available.

The proposed framework is best understood as a structured indicator with two complementary levels of resolution rather than competing alternatives. The emission-based level operates at the inventory stage, offering a practical, objective and computable means of identifying hot spots of acoustic energy across a product's life cycle, independent of receiver context; this makes it well-suited to supply-chain comparison and design decisions where exposure data are unavailable. The impact-based level extends the inventory towards harm by incorporating exposure and receiver sensitivity, providing environmental relevance at the cost of greater modelling complexity. The progression from emission to impact is therefore governed less by data availability than by the maturity of characterization models capable of translating noise emissions into reliable impact indicators. As such models advance, the framework can incorporate impact-based assessment while preserving a full supply-chain perspective.

4.4. Limitations and future work

This study has several limitations, which also point to important directions for future research. As an exploratory consensus-building exercise, the proposed framework reflects the perspectives of a panel assembled for its expertise at the intersection of environmental acoustics and Life Cycle Assessment (LCA). While this composition was intentional and well aligned with the objectives of the study, it cannot be assumed to include all possible perspectives within the broader scientific community. Confirmation bias is an inherent risk in expert participatory studies. In this research, however, anonymity was maintained at all stages, removing the possibility of participants influencing one another. Overall, the framework provides a valuable foundation for initiating a wider scientific discussion on the concept of a noise footprint and its operationalization. Realizing this will require a coordinated multidisciplinary effort, developing mathematical formulations, characterization approaches and empirical case studies across the diversity of noise sources and effects. Finally, the impact-based pathway requires further methodological development before it can be applied in practice. A central challenge is translating noise exposure into a measure of damage. One possible approach would be to account for the number of people exposed above a given sound level along with the duration of their exposure within a dedicated risk-analysis step, in the same way that population exposure is handled in life cycle impact assessment (Huijbregts et al., 2000). Established concepts such as the lowest observed adverse effect level (LOAEL) and the significant observed adverse effect level (SOAEL) could serve as reference points for defining when a receiver is considered affected. It should be stressed that a single, objective noise-based threshold is not feasible, as it can vary across noise sources, receptors and time (Department for Environment, Food and Rural Affairs (Defra), 2010; World Health Organization, 2009). In practice, this would depend on data describing actual exposure, which are not always available at a satisfactory level. The inherent challenge of confidently accounting for "the number of people affected" is further amplified when it extends to "the number of people benefited". This is the case with compensating for noise exposure through access to quiet or restorative environments, which remains an open question rather than an established component of the framework.

5. Conclusions

This research established a conceptual foundation for the noise footprint through a modified Delphi process supported by thematic analysis and a subsequent SWOT assessment. The study clarifies the structural identity of the noise footprint and provides a consensus-based framework capable of guiding its development, application and future expansion. At the product level, the noise footprint is a life cycle–oriented measure that captures source–receiver dynamics and traces noise across supply chains. Rather than a single fixed metric, it is a structured measure with two possible levels of resolution: an emission-based core inventorying the sound energy output of interconnected sources, and an impact-based extension derived from that core by incorporating who or what is exposed. While the present framework concerns product systems, it remains extensible to other footprint types, including a personal footprint, as methodological maturity increases. The framework also highlights the need for careful integration of trade-off and compensation mechanisms. Overall, this work provides the conceptual groundwork for a coherent noise footprint framework and identifies the strategic considerations necessary for its responsible implementation and future refinement.

CRediT authorship contribution statement

Angelos Tsaligopoulos: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Francesco Aletta:** Conceptualization, Funding acquisition, Supervision, Methodology, Writing – review & editing. **Gianluca Maracchini:** Conceptualization, Supervision, Methodology, Writing – review & editing. **Francesco Asdrubali:** Writing – review & editing, Validation, Resources. **Pierre Aumond:** Writing – review & editing, Validation, Resources. **Claudio Guarnaccia:** Writing – review & editing, Validation, Resources. **Jack Harvie-Clark:** Writing – review & editing, Validation, Resources. **Reinout Heijungs:** Writing – review & editing, Validation, Resources. **Bryce T. Lawrence:** Writing – review & editing, Validation, Resources. **Alessio Mastrucci:** Writing – review & editing, Validation, Resources. **Antonio J. Torija:** Writing – review & editing, Validation, Resources. **Simone Torresin:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2026.108629.

Data availability

The data supporting this study are provided in Supplementary material 1 and 2

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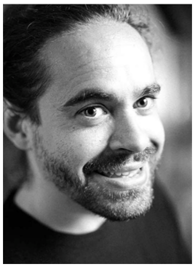

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