forum acusticum 2026
8-12 September · Graz, Austria

MEASURING THE NOISE FOOTPRINT OF PRODUCTS: A PROVISIONAL FRAMEWORK

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This paper is a revised version of the authors' submitted manuscript that was peer-reviewed by at least two anonymous reviewers.

Abstract

Noise pollution is a critical yet historically underrepresented environmental pressure in global sustainability assessments. To address this gap, this research introduces the concept of the Noise Footprint (NF) and establishes its foundational calculation methods. The NF is designed to capture complex source–receiver dynamics across entire product supply chains through a structured indicator offering two possible levels of resolution. First, the emission-based noise footprint (NF_E) acts as a core inventory metric, objectively quantifying the total acoustic energy output from sources across all supply chain phases. Second, the impact-based footprint (NF_I) translates this raw emitted energy into localized environmental and human impacts by accounting for propagation and exposure severity. The NF measure offers a robust, modular tool to formally integrate noise pollution into sustainability assessments.

Keywords: *Noise footprint, supply chain, sustainability*

1. Introduction

Even though the term "noise footprint" has been used in environmental acoustics literature since the 1970s, its definition and assessment methodologies remain fragmented [1]. So far, the noise footprint functions less as a defined metric and more as a buzzword signaling concern about noise [2]. In global literature it mostly appears as a loose synonym for noise pollution, and in its spatial sense as a literal imprint, mainly in aviation and underwater environments, where it is often visualized through noise mapping [3].

Unlike carbon, noise is an immaterial pollutant with localized effects and a strong dependence on the surrounding environment. It is undeniable that noise does not persist in the environment after emission, but its effects persist beyond the time and point of exposure. To this end, associating noise with its impacts is not always a straightforward task. Cucurachi et al. [4] presented a method to connect acoustic emissions from any source to their potential impacts. In their framework, they utilized the sound energy emitted by the source, translating it into the sound pressure reaching a receiver location and multiplying it by the affected population and the severity of the timing. This approach results in total human exposure to noise pollution, expressed in person-Pa * s. Additionally, they modeled a consumption-based noise footprint for Switzerland's private mobility using a life cycle approach and linear acoustic inventories (Joules). Utilizing the CNOSSOS-EU framework [5] for sound power

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calculations, the authors quantified the resulting human health impacts, specifically annoyance and sleep disturbance, in Disability-Adjusted Life Years (DALYs) [6]. An additional approach can be found in the LIME2 framework [7], which evaluates the human health damage caused by an increase in road traffic noise in Japan. Itsubo and Inaba modeled a theoretical scenario where 1,000 extra vehicles were added to the national road network. They calculated how much this extra traffic increased the physical noise level (ΔLA_{eq}) and identified the population exposed to this change. Existing LCA noise frameworks, such as those proposed by Cucurachi et al. [4] and the LIME2 model, rely on a marginal approach. By incorporating ambient background noise derived from noise maps into their fate or exposure calculations, these models assess the relative change in the sound environment.

A noise footprint must be able to quantify and communicate the impact generated by human activities in order to enable comparison, guide mitigation actions and support policy and behavioral change toward reducing noise. The suggested indicator has two possible levels of resolution. An emission-based core (NF_E) inventories the sound energy output from sources across these phases, indicating how 'loud' a product system is. The impact-based extension (NF_I) derives from those emissions and quantifies potential environmental impacts at an intermediate point in the cause-effect chain, before final damage occurs. The framework inventories and characterizes the noise of all sources within a supply-chain phase, without yet allocating that noise to a single product. The goal of this research is to present a scalable framework for quantifying the noise footprint, including an early suggestion to interpret its potential impact.

2. Emission-based noise footprint

NF_E concerns the inventorying of noise sources within each phase. Inventorying compiles the acoustic emissions of all sources within a phase, expressed as sound energy. The Sound Power Level (L_W) of each source is a commonly reported parameter that can be used for this purpose; for instance, the EPREL (European Product Registry for Energy Labelling) database, the EU's central register where manufacturers submit products' energy labels, also includes A-weighted L_W values as part of those labels [8]. However, decibel-based quantities are not additive, making them unsuitable for aggregation. The Sound Power Level expressed in dB(A) is obtained using eq. 1.

$$L_W = 10 \log \frac{W}{W_0} \tag{1}$$

Where:

L_W is the sound power level in decibels

W is the sound power in watts produced by the source

W_0 is the reference sound power of 1 pW (10^{-12} W)

To achieve additivity, the reported decibel levels must be back transformed into sound power measured in watts (eq. 2).

$$W = W_0 \cdot 10^{\frac{L_W}{10}} \tag{2}$$

The level of detail in the L_W data significantly influences the analytical depth of the noise footprint. While an overall L_W value is sufficient for a baseline inventory, achieving higher spectral resolution in accordance with the ISO 3740 series on the determination of L_W of noise sources [9] is preferable. For instance, 1/3 octave band analysis enables deeper assessment [10].

Another critical aspect of the inventory is the duration of noise production. Duration in this context refers to the working cycles of the noise-emitting activities within each phase. Once the sound power in watts is determined, multiplying it by this time period results in the total acoustic energy measured in joules [4]. The emission-based noise footprint is thus described as the sum of the acoustic energy, calculated using the following (eq. 3).

$$\mathrm{NF}_{E,k} = \sum_{s=1}^{S_k^{\mathrm{all}}} \sum_{f=1}^{F} \left(W_0 \cdot 10^{L_{W,k,s,f}/10} \cdot \tau_{k,s} \right) \tag{3}$$

where:

k = supply chain phase

s = noise source within phase k

S_k^{all} = total number of active sources in phase k

f = frequency band

F = total number of frequency bands

W_0 = reference sound power, 10^{-12} W

$L_{W,k,s,f}$ = sound power level of source s, band f, phase k, in dB

$\tau_{k,s}$ = operating duration of source s in phase k, in seconds

Contextual descriptors of spatial and temporal characteristics can also be included in the inventory of noise sources. NF_E informs on the acoustic energy emitted during a specific phase, expressed in joules. As a result, future users can compare the most noise-producing phases of a supply chain.

3. Characterizing noise

To characterize noise means to move beyond its description from the inventory and quantify its potential impact by linking propagation and exposure [11]. This characterization is built upon the cause-and-effect chain of Fate, Exposure and Effect. The Fate Factor (FF) models the physical journey of noise after its release, describing how it spreads and attenuates from the source to the receiver. Between Fate and Effect stands the Exposure Factor (XF), which represents the duration of exposure to the receiver. Finally, the Effect Factor (EF) represents the severity of the impact resulting from that exposure [4]. For this research, noise characterization is achieved via the inclusion of Fate, Exposure and Effect factors to expand upon the inventory data described at the emission (NF_E) level.

3.1 Impact-based noise footprint

NF_I utilizes inventory data. The fate (FF), effect (EF) and exposure (XF) factors are combined into a single impact contribution per phase (k) and source (s) resulting in a dimensionless quantity (Eq. 4).

$$NF_{I,k,s,f} = \underbrace{\frac{W_{k,s,f}}{W_0}}_{\text{emission (inventory)}} \cdot \sum_p \left[\underbrace{10^{(D_{k,s,f} - A_{k,s,f} + EF_{p,k,s,f})/10}}_{\text{Fate \& Effect (FF, EF)}} \cdot \underbrace{\frac{\tau_{p,k,s}}{T_0}}_{\text{Exposure (XF)}} \right]$$

(4)

where:

$W_{k,s,f}$ = sound power of the source, in watts

W_0 = reference sound power, 10^{-12} W

$D_{k,s,f}$ = directivity correction, in dB

$A_{k,s,f}$ = total path attenuation, in dB

p = period (day, evening, night)

$EF_{p,k,s,f}$ = effect factor for period p, in dB

$t_{p,k,s}$ = operating duration of source s in phase k, in seconds. For the use phase, accumulated over the product's service life

T_0 = reference period, one year (31,536,000 seconds)

As shown in Eq. 4, the impact contribution combines three parts. The emission term ($W_{k,s,f}/W_0$) is the inventory, depending only on the source. The bracketed exponential groups propagation, directivity (D) and attenuation (A), with the effect weighting (EF), all in the decibel domain. The exposure term (τ/T_0) is the operating duration normalized by the reference period T_0 (Eq. 5). It is kept outside the exponent because a duration cannot be added to decibel quantities and it produces a dimensionless time fraction. Using one year as T_0 provides a consistent, universal reference across products and supply chains. For the use phase, where the product is itself the noise source, τ should reflect the product's service life. The operating duration is therefore the everyday usage accumulated across the product's lifespan.

$XF_{k,s} = \frac{\tau_{k,s}}{T_0}$ (5)

It should be noted that noise is not a substance that accumulates in a body, so its exposure factor cannot be an intake fraction, as in traditional LCA dealing with chemical pollutants. Since noise exposure is inherently temporal, XF is addressed through duration. Population exposure has been deliberately left out at this stage, to be introduced in later future research. At this point the exposure factor a property of the source–receiver relationship, independent of how many receivers are present, so that the same footprint applies regardless of location before population is considered.

The Fate Factor converts the inventory L_W into the sound pressure level at the receiver (L_P). To keep it compatible with the linear summation in Eq. 4, the pressure level is expressed as a linear ratio (Eq. 6).

$FF_{k,s,f} = 10^{L_{P,k,s,f}/10}, L_{P,k,s,f} = L_{W,k,s,f} + D_{k,s,f} - A_{k,s,f}$ (6)

$D_{k,s,f}$ is the directivity correction in dB, accounting for the angular radiation pattern of the source. Standard assumptions can be used, for example 0 dB for an omnidirectional source and +3 dB for a hemispherical one. $A_{k,s,f}$ is the total path attenuation in dB, including geometrical spreading and, where relevant, enclosure and barrier attenuation, consistent with methods such as ISO 9613-2. For a point source in free field, the geometrical spreading with propagation distance d is given by Eq. 7.

$A_{div}(d) = 20 \cdot \log_{10}(d) + 11$ (7)

$EF_{k,s,f}$ is the Effect Factor expressed as dB corrections to be entered in Eq. 4, thus quantifying the severity of the impact through a scenario-based approach. Here, scenarios represent alternative configurations of the product system, used to evaluate how variations in technology, context, or behavior influence environmental outcomes [12]. Within this framework, scenarios explicitly account for the area of protection (human or ecosystem health), specific noise characteristics (tonality, impulsiveness, or low-frequency content) and time-of-day.

The NF assessment employs a modular, scenario-based approach where scenarios define the context of impact and are operationalized through the EF. Because acoustic emissions affect human and ecosystem health, two primary areas of concern are considered. Based on global literature and legislative guidelines, specific acoustic characteristics require targeted evaluation. For the human health scenario, these primarily include impulsive noise, tonal noise and low-frequency noise [13]. In parallel, the ecosystem health scenario addresses major acoustic impacts affecting wildlife, similar to masking, disruption and distraction due to noise. These categorizations are supported by bioacoustics principles such as the Acoustic Adaptation Hypothesis [14] as well as the alteration of predator-prey dynamics, where acoustically distracted prey become easier targets [15].

A major consideration for the EF is the time of day when receivers are exposed. A well-established approach is the Environmental Noise Directive (2002/49/EC), which segments the 24-hour cycle into day (07:00–19:00), evening (19:00–23:00) and night (23:00–07:00) periods. Standard legislative practices often apply penalties of 5 dB for the evening and 10 dB for the night. Such penalties are usually empirical, but they also derive from large-scale community surveys that correlate time-dependent noise exposure directly to annoyance and sleep disturbance [16]. Acoustic character penalties in the Effect Factor are based on BS 4142:2014+A1:2019 (Methods for rating and assessing industrial and commercial sound), published by the British Standards Institution. The standard specifies corrections for distinctive acoustic features, applied as arithmetic additions to the rating level. Tonality is penalized by 2 dB (just perceptible), 4 dB (clearly perceptible) or 6 dB (highly perceptible). Impulsivity is penalized by 3 dB (just perceptible), 6 dB (clearly perceptible) or 9 dB (highly perceptible).

3.2 Phase-level and cross-phase Noise Footprint

All linear impact contributions are summed, and the logarithm is applied. The expression generates the phase-level footprint NF_k when summed over the sources and frequency bands of a single-phase k, allowing identification of the noisiest phases (Eq. 8).

$$\mathrm{NF}_k = 10 \cdot \log_{10}\left(\sum_{s,f} \mathrm{NF}_{I,k,s,f}\right) \quad (8)$$

Additionally, given that an appropriate allocation has been achieved, a Noise Footprint (NF) across phases can be calculated (Eq. 9). It should be noted that this is a life cycle accounting construct representing responsibility attribution, not a claim that noise from different phases physically coexists or accumulates.

$$\mathrm{NF} = 10 \cdot \log_{10}\left(\sum_{k}\sum_{s,f} \mathrm{NF}_{I,k,s,f}\right) \quad (9)$$

4. Discussion and future considerations

The resulting NF_k and NF, as defined in equations 8 and 9, represent scenario-adjusted aggregations of noise exposure across the life cycle of a product. However, in their current form, they remain relative indicators expressed in decibel units without a direct reference for interpretation. To enable interpretation and communication, this impact can be expressed relative to a common baseline. Road traffic noise is globally recognized as the primary source of noise pollution and a major driver of human and animal health deterioration [17], supported by extensive epidemiological data from the World Health Organization [18]. Furthermore, numerous studies have identified road traffic noise as a significant cause of ecosystem degradation affecting wildlife [19]. A Road Traffic Noise equivalent (RTN_{eq}) metric can be introduced. A key requirement for defining such an equivalence is the selection of an impact metric, similar to annoyance and sleep disturbance. The choice of metric determines how different noise impacts are compared to road traffic references. Psychoacoustics and the ISO soundscape approach can assist this procedure. By comparing specific noise types (impulsive, tonal, or low frequency or different meanings attached to sources) against the road traffic baseline, a relative weighting factor can be established. Future work is required to define explicit equivalence relationships and determine whether RTN_{eq} should be expressed as an equivalent level (dB). In analogy to Global Warming Potentials, future developments of the framework may introduce characterization factors to explicitly convert different noise characteristics into traffic-equivalent impacts.

One of the most complex challenges in attributing noise across a product system is addressing the time-lag inherent in global supply chains. Acoustic emissions do not occur simultaneously across a life cycle, requiring a time-explicit or dynamic approach to the inventory [20]. Raw material extraction, distribution and end-of-life processes are typically modeled as part of large-scale economic activities that continuously supply multiple product systems. As such, only an allocated share of these activities is attributed to the product under study[21]. In the present NF formulation this allocation step is not yet applied, and the cross-phase NF of Eq. 9 remains a conceptual target.

Looking forward, the noise footprint framework opens the door to exploring acoustic trade-offs. Stakeholders could balance direct noise exposure against positive acoustic outcomes, such as compensating through pleasant soundscapes [22]. This should be applied for unavoidable noise burdens within a product's supply chain by facilitating soundscape enhancement in other impacted locations similarly to planting trees in the case of carbon uptake.

5. Conclusions

In conclusion, establishing NF is an achievable and necessary step toward noise mitigation across product supply chains. By distinguishing between physical acoustic energy emissions (NF_E) and impacts (NF_I), this framework allows stakeholders to pinpoint the noisiest supply chain phases and appropriately address their specific burdens. As methodologies for quantifying the effects of noise on human and environmental health continue to advance, this framework will adapt and integrate these developments. Finally, NF provides the tool needed to incorporate noise pollution into broader sustainability assessments.

6. Acknowledgments

This work was funded by HEAD-Genuit-Stiftung as part of the "Noise Footprint" project (P-23/01-W).

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