Aggregating the noise footprint of a heat pump across its supply chain: insights from a panel of experts

Angelos Tsaligopoulos[a*] | Francesco Aletta[b] | Gianluca Maracchini[a] | Simone Torresin[a]

[a] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano, 77, 38123 Trento (TN)

[b] UCL Institute for Environmental Design and Engineering, The Bartlett, University College London, Central House, 14 Upper Woburn Place, WC1H 0NN London, United Kingdom

* Corresponding author: a.tsaligopoulos@unitn.it

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Quantifying noise emissions across supply chains presents a significant challenge within environmental assessment. This study investigates how experts in environmental acoustics and Life Cycle Assessment conceptualise the aggregation of noise across a product's life cycle into a total noise footprint, using a heat pump as an example. This is achieved through a thematic analysis of qualitative responses gathered via an open-ended questionnaire administered to a panel of eight experts. The analysis establishes five structural requirements for noise footprint aggregation: (1) inventory metrics must be linear and physically additive; (2) calculations must be modular to accommodate phase-specific source mechanics; (3) exposure modelling must be spatially explicit, separating human and ecological receivers; (4) distinct types of environmental harm cannot be directly combined; and (5) aggregation must proceed through a transparent, multi-step sequence from cumulative energy to spatial impact. Ultimately, these expert-derived constraints establish essential criteria for evaluating, standardizing, and operationalizing future noise footprint methodologies.
Keywords: noise footprint, aggregation, life cycle assessment LCA, heat pump

Aggregare l'impronta acustica di una pompa di calore lungo la supply chain: il contributo di un panel di esperti

Quantificare le emissioni sonore lungo le catene di fornitura rappresenta una sfida complessa nell'ambito della valutazione ambientale. Questo studio analizza come esperti in acustica ambientale e Life Cycle Assessment concettualizzano l'aggregazione del rumore generato durante l'intero ciclo di vita di un prodotto in un'impronta acustica totale, utilizzando una pompa di calore come caso esemplificativo. L'indagine è stata condotta tramite un'analisi tematica delle risposte qualitative raccolte attraverso un questionario a risposta aperta somministrato a un panel di otto esperti. L'analisi ha permesso di definire cinque requisiti strutturali per l'aggregazione dell'impronta acustica: (1) gli indicatori dell'inventario devono essere lineari e fisicamente sommabili; (2) i calcoli devono essere modulari per adattarsi ai meccanismi di emissione specifici di ciascuna fase; (3) la modellazione dell'esposizione deve essere spazialmente esplicita, distinguendo i recettori umani da quelli ecologici; (4) i diversi tipi di danno ambientale non possono essere combinati direttamente; e (5) l'aggregazione deve seguire una sequenza trasparente e multi-fase, procedendo dall'energia cumulativa all'impatto spaziale. Nel complesso, questi vincoli definiti dagli esperti stabiliscono i criteri essenziali per valutare, standardizzare e rendere operativa la metodologia dell'impronta acustica nelle sue future applicazioni.
Parole chiave: impronta acustica, aggregazione, valutazione del ciclo di vita LCA, pompa di calore

1 | Introduction

Noise is a persistent pollutant affecting human and environmental health, attributed to processes, infrastructure, activities, personal choices and products [1]. Traditionally, noise has been treated as a local issue and addressed through noise control techniques applied near the source. Noise has reached near epidemic proportions and is increasingly regarded as a major sustainability concern [2]. Addressing it at a greater scale requires a shift in perspective, drawing linkages among processes and product systems from which it originates. The noise produced in association with a product can be treated as one connected chain across its life cycle, in which each step is linked to the next because the output of one becomes the input of another [3].

The noise footprint framework offers a means of establishing such a connection. It addresses the noise generated across every phase of a product system's life cycle, from raw material extraction to end-of-life, attributed along the supply chain rather than at a single site. It is a structured indicator with two levels of resolution: an emission-based inventory of the sound energy generated by sources linked within the product system, and an impact-based extension incorporating the exposure of receivers, both human populations and non-human ecological receptors [3].

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Establishing the framework's conceptual foundation was a necessary first step. However, its operationalisation raises a further question regarding the way that aggregation should be carried out. In life cycle assessment (LCA), aggregation refers to the summation of a flow across the unit processes of a product system, so that the contributions of individual phases are combined into a single figure per functional unit. A distinct, optional aggregation step is conducted at the end of impact assessment, combining results across impact categories and areas of protection into a single score. In this research, aggregation is the combination of phase-specific noise into a single value representing the product's total noise footprint.

This is an accounting construct for attributing responsibility, rather than a claim that noise from different phases physically coexists or accumulates. Summing noise across phases that differ in source, setting, duration and receiver is not straightforward, and the conditions under which it remains meaningful and defensible must be established. The research question (RQ) is therefore: how do experts in environmental acoustics and LCA conceptualise the requirements for aggregating noise into a total noise footprint across the life cycle of a product?

This study addresses that question using a heat pump as a reference case, chosen because its supply chain spans geographically and acoustically diverse phases, from raw material extraction to domestic operation, making the difficulties of summing across them explicit. Beyond its illustrative value, this case is exceptionally timely given the large-scale deployment of heat pumps across Europe, where noise emissions are receiving increased research focus [4]. The contribution is the specification of the conditions that noise aggregation across a supply chain must satisfy to produce a total noise footprint. These conditions are grounded in expert reasoning about a concrete product rather than inferred by analogy with established life cycle assessment practice and are intended to inform the subsequent formalisation of the framework.

1.1 | Heat pump noise supply chain overview

Evaluating the environmental sustainability of heat pump technologies requires a comprehensive understanding of their entire supply chain and life cycle. LCA frameworks analyse heat pump systems across sequential phases, from initial raw material extraction, multimodal transportation, component manufacturing, assembly, installation, operation, maintenance, and end-of-life processing. By quantifying resource inputs, energy demand, and waste outputs, research can evaluate impact categories, like climate change, marine ecotoxicity, particulate matter formation, and ozone depletion [5]. Comparative evaluations across air-source, ground-source, water-source, and hydrogen-powered heat pumps show that while green hydrogen options offer lower carbon footprints, the operation and maintenance phase remains the dominant contributor to overall carbon emissions for conventional electric heat pumps, owing to grid electricity mix dependencies. Yet while life cycle assessments extensively track chemical emissions and climate change metrics expressed in carbon equivalents, physical stressors such as noise emissions remain largely absent from standardized life cycle supply chain frameworks [6].

Standardized sound metrics for heat pumps are currently restricted to product compliance during the use phase. Harmonized standards such as EN 12102-1:2022 define the declared sound power level (L_wA in dB(A)) required for EU Ecodesign and Energy Labelling compliance, drawing on established ISO airborne sound-power and sound-intensity testing methodologies (e.g., ISO 3740 and ISO 9614 series). While these frameworks ensure standardized, comparable noise declarations for operational space heating and cooling units across energy registries, such as the European Product Registry for Energy Labelling (EPREL) [7], comparable noise data remain missing for all other life cycle phases. Operation therefore remains the only phase with a standardized, product-level emission metric.

The most studied noise-related phase of a product such as a heat pump is the use phase. Experimental approaches to heat pump noise assessment involve real-life operating conditions and continuous year-long acoustic monitoring at residential sites, assessing the working cycles of heat pumps [8]. Results indicate that the noise emitted by an air source heat pump into the surrounding environment is generated primarily by two major mechanical components, the compressor and the fan, and by vibrations of the enclosure, producing both broadband and tonal components. The tonal components typically occur at the blade-passing frequency and its higher-order harmonics [9]. Laboratory-based psychoacoustic investigations consistently show that human response to heat pump noise depends strongly on spectral characteristics, temporal structure, and contextual masking, rather than on energetic indicators alone [10]. Further experimental evidence shows that as background sound levels increase, heat pump noise becomes less dominant within the acoustic scene, leading to reduced annoyance and increased pleasantness [8]. This implies that heat pump noise is likely to be perceived more critically in acoustically quiet environments, such as rural areas, than in already noisy urban contexts.

Noise-related studies across the other life-cycle phases present marked data asymmetry. Noise data exist for individual phases, but almost exclusively as occupational-hygiene or community assessments and are not assembled into a heat pump life cycle. In the raw material extraction phase, occupational noise is a recognized mining hazard. In non-coal mines in China extracting metal ores (copper, iron, gold) and industrial minerals (limestone, silica, granite), 31.9% of individual noise exposures exceeded 85 dB(A), with median levels of 89.1 dB(A) for excavation workers, 88.7 dB(A) for mill operators and 87.0 dB(A) for crusher operators [11]. Nevertheless, these are worker-exposure data and not emission inventories. The processing phase, involving operations such as smelting, likewise carries a documented occupational noise risk. Task-specific median exposures range from 80.2 dB(A) for sand cleaning to 90.8 dB(A) for falling sand and 90.1 dB(A) for cutting and grinding, with smelting at 82.7 dB(A), levels classified as an intolerable occupational risk [12]. Transportation

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is the best-developed noise-LCA phase, supported by mature road-traffic emission and propagation models (IMAGINE) and characterisation methods [13-15].

Installation noise is documented only at the level of individual tools and tasks, with sound pressure levels reported per implement [16] rather than as emissions attributable to the installation of a specific product, so the acoustic burden of fitting a heat pump cannot be derived from existing data. At end-of-life, dismantling and material recovery are documented through worker exposure studies, with recycling workers exceeding occupational (85 dB(A)) and community (70 dB(A)) noise limits [17], but no emissions are attributed to the recovery of individual products.

1.2 | The aggregation problem in the noise/LCA literature

Integrating noise into life cycle impact assessment (LCIA) presents a fundamental aggregation challenge. As decibels are logarithmic ratio quantities, noise levels from distinct life cycle phases cannot be summed arithmetically [18]. Overcoming this limitation requires additive, energy- or pressure-based quantities. Characterisation factors have been developed on the basis of linear sound power in watts across archetypal exposure scenarios [19], and an exposure indicator expressed in person·Pa·s has been introduced to quantify cumulative human sound pressure exposure over time [20]. Impacts whose severity depends on where they occur are not unique to acoustics. In Life Cycle Impact Assessment (LCIA), established frameworks already account for location without requiring a separate flow to be defined for every site. One example is the AWARE method for water scarcity footprints, in which the same volume of water is assessed differently according to the availability of water in the region where it is withdrawn [21].

2 | Methodology

This study utilizes qualitative material collected during an earlier consensus-building study on the definition and conceptual requirements of the noise footprint, reported in full elsewhere [22]. The panel comprised eight experts from six countries (Italy, United Kingdom, France, the Netherlands, Germany and Austria), affiliated with universities (n = 6), an international research institute (n = 1) and an acoustic consultancy (n = 1). Four experts held expertise in both environmental acoustics and life cycle assessment, while the remaining four specialised in one of the two domains. Their expertise covered environmental acoustics, noise policy and regulation, soundscape, psychoacoustics, environmental footprints, LCA, quantitative sustainability and industrial ecology [22]. Participants remained anonymous to one another throughout, and all provided consent for the collection and use of their data for research purposes.

For the purposes of the present study, we analysed a specific subset of this material to address a separate research question. In an applied exercise, experts were invited to consider how noise contributions arising across the life-cycle stages and supply chain of a heat pump could be aggregated into an overall noise footprint. As shown in Fig. 1, a cradle-to-gate system boundary comprising six phases of the heat pump life cycle was adapted to guide participants towards reasoning about a total noise footprint. This set-up was chosen because it derives from a comparative life cycle assessment of air-source, ground-source, water-source and hydrogen-based heat pump technologies and therefore represents a real-case rather than a hypothetical supply chain. The UK heat pump market is import-dependent, with the supplier mapping placing the main manufacturing in China and South Korea alongside several European countries, and the final point of distribution a warehouse in London. Multiple supply chain scenarios were compared in that study to establish which sourcing route offers the lowest environmental impact and the greatest energy security for the UK [6]. The phases adopted here were raw material extraction (Phase 1), transportation of raw materials (Phase 2), transportation by cargo ship (Phase 3), storage in warehouse (Phase 4), assembly and installation (Phase 5), and operation and maintenance (Phase 6).



Fig. 1 – Life cycle phases contributing to the total noise footprint of a heat pump, adapted from [6]

Fasi del ciclo di vita che contribuiscono all'impronta acustica totale di una pompa di calore, adattato da [6]

The three questionnaire questions addressed successive levels of assessment: emission within each phase, impact within each phase, and aggregation across phases.

Q1 (emission, per phase): When assessing the noise generated during each phase, which is the best way to measure or estimate the noise produced?

Q2 (impact, per phase): For each phase, what would be the best way to summarise the overall impact of noise?

Q3 (aggregation, across phases): Thinking about the entire life cycle, how should the total noise footprint be assessed or summarised across all phases?

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The first two questions were answered per life-cycle phase from a fixed set of options, with an open "Other, please specify" alternative and the third was open-ended. For Q1 the options were the sound power level generated by machines, vehicles and equipment (e.g. L_W), the cumulative noise energy generated by the same sources (e.g. joules), and the sound pressure level commonly used in regulatory contexts (e.g. L_{den}, L_{eq}). For Q2 the options were the number of people exposed and the duration of their exposure (e.g. person·Pa·s), the percentage of Highly Annoyed persons (%HA), and affected animals·year. The qualitative material analysed in the present study comprised three types of text: (i) specifications entered in the "Other" field for Q1; (ii) specifications entered in the "Other" field for Q2; and (iii) free-text responses to Q3. The fixed-choice responses to Q1 and Q2 were not included in this analysis. The analysis focused on statements addressing whether, how and under what conditions noise contributions from separate life-cycle phases could be combined. The material was subjected to thematic analysis, a qualitative method widely used in the psychological and social sciences to identify and interpret patterns of meaning within a dataset. Responses were coded deductively in relation to the research question [23], with the analysis focusing on reasoning patterns and on the constraints that experts consider must be satisfied for aggregation to be meaningful.

3 | Results

Through thematic analysis of the expert responses, five core themes were identified regarding the structural requirements for aggregating a noise footprint across the heat pump supply chain. The first theme establishes that the aggregated quantity must be linear and physically additive. The second demonstrates that calculations must be phase-specific to account for varying source dynamics. The third highlights that sound emissions convert into potential impacts only when evaluated alongside receivers and spatial context. The fourth addresses the fundamental difficulty of combining endpoints that express distinct types of harm. Finally, the fifth theme outlines how aggregation must proceed through a structured, multi-step process. Themes and sub-themes are represented in Fig 2. The expert responses are reported here as given, and are examined critically against the life cycle assessment literature in Section 4.

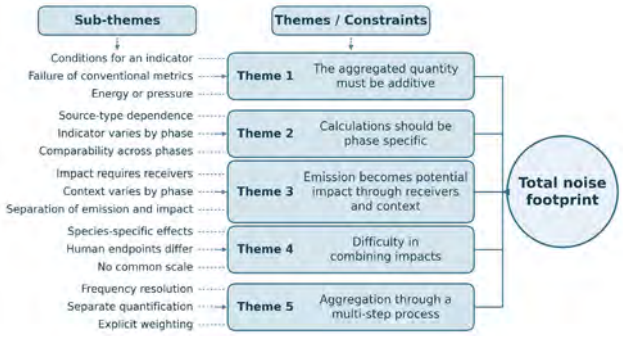


Fig. 2 – Themes and sub-themes
Temi e sotto-temi

3.1 | The aggregated quantity must be additive

The aggregated quantity must be linear and physically additive and must carry both level and duration relative to the functional unit. Experts identified the properties an indicator must hold before any summation across the life cycle can be attempted. One respondent set out two conditions explicitly, requiring "*... an indicator that (1) can be aggregated over life cycle processes...*" and one that "*... includes both the noise level and the time attributed to a functional unit...*". Measured against these conditions, the conventional units were considered inadequate: "*... dB does not satisfy [aggregability] and [level and time]...*", while the "*... number of persons affected does satisfy [aggregability] but not [level and time*]...". What remains are physical quantities that behave linearly, since "*... Only metrics like energy or pressure can be used for this...*". The constraint identified here is that the aggregated quantity must be linear and physically additive and must carry both level and duration relative to the functional unit.

3.2 | Calculations should be phase specific

Rather than applying one approach uniformly, experts differentiated between phases according to the nature of the sources within them. Assessment was held to depend on whether sources are fixed or in motion: "*... For static operations... you could use SWL... For moving sources you use integrated sound level-based metrics...*". The same differentiation extended to impact, with annoyance considered appropriate only where prolonged human exposure occurs, so that "*... Phase 5 (Assembly and installation) and 6 (Operation and maintenance) would be annoyance according to ISO 15666...*". The prospect of reconciling these differences was itself questioned: "*... Not sure how you can combine these different emissions in a single metric or compare between phases...*". The resulting constraint is that each life-cycle phase must be assessed using methods tailored to its source characteristics, exposure patterns, and receiver context. Cross-phase comparability – and therefore the validity of any aggregation – cannot be assumed.

3.3 | Emission becomes potential impact only through receivers and context

Exposure must be characterised per phase, with contextual weighting and separate treatment of receiver types, and the independence of emission and impact cannot be presumed. Experts held that emitted noise acquires impact only where receivers are present, since "*... Noise has an impact only if there are sensitive receivers close by...*". The magnitude of that impact was treated as conditional on the circumstances of each phase, "*... Depending on the context of each phase (time of day, competing sound sources, etc.)...*", and on which receivers are exposed, as it is "*... Impossible to choose between human or other animal impacts, as it depends on the exposure of*

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each, which is different in every context...". One respondent extended this to question the separation on which the inventory step relies: *"... I am not sure we can separate noise production and impact in two different things...*". The constraint identified here is that exposure must be characterised separately for each life-cycle phase and receiver type, taking contextual factors into account.

3.4 | Difficulty in combining Impacts

Experts emphasized that combining endpoints that express distinct types of harm into a single score is methodologically challenging and not necessarily useful. Because endpoints differ fundamentally, even within the same Area of Protection (e.g., human health, ecosystem quality and resource depletion), a universally accepted basis for weighting and balancing them against one another remains elusive.

Where impacts were considered, experts distinguished between effects that are not interchangeable. The relevant outcomes were seen to differ by receiver, spanning *"... health, annoyance, sleep disturbance... in the case of wildlife, the ability to feed, nest, or reproduce...*", and to differ in kind even among human receivers, since "... *some of these activities may also harm hearing health, which is clearly a different type of impact...".* Conversion to a common damage unit was raised but not endorsed, as *"... Unless you convert all impacts to DALYs... And then the DWs would change...",* and the underlying difficulty was stated directly: *"... I can't think how you can balance impact across those categories...*". The core constraint is that combining these endpoints lacks a standardized methodology, rendering any aggregated figure of limited practical value.

3.5 | Aggregation through a multi-step process

Aggregation must proceed through inventory, spectral resolution, spatial modelling and weighting, with the weighting between specific impacts stated explicitly.

One expert proposed a sequence rather than a single operation. The procedure begins from the inventory, where "... *The first step would be the cumulative noise energy in joules...",* with that energy resolved spectrally by assigning it *"... to different ranges in the frequency spectrum...*". It then requires transferring the accumulated energy *"... to a spatially explicit context...*", within which the "... *number of humans exposed... and... area of nonhuman habitat exposed...*" are estimated separately for each phase. These quantities are finally *"... used as a weighting criterion to characterize the noise exposure...*", resolving a question the total must answer: "... *Is the noise exposure a human health problem, or is it a habitat loss problem?...".* The constraint identified here is that aggregation must proceed through inventory, spectral resolution, spatial modelling and weighting, with the weighting between impact types stated explicitly.

4 | Discussion

This study examined how experts conceptualize the aggregation of noise emissions and impacts across the life cycle of a heat pump into a total noise footprint. The experts articulate the structural conditions that any total must satisfy. These conditions define the boundaries within which aggregation is possible and identify where it may be mathematically invalid or conceptually incoherent.

4.1 | Emission-level constraints

The expert panel's first constraint requires the aggregated metric to be linear and physically additive. Meeting this condition requires careful re-examination of how elementary flows are defined in LCA. In LCA, elementary and product flows are distinct quantities. An elementary flow is material or energy that crosses the boundary between the product system and the environment without human transformation, either drawn from it as a resource or released into it as an emission (ISO 14040:2006). A product flow, by contrast, describes products entering from or leaving to another product system, as when copper travels from the extraction site to the smelter and on to the factory. These flows are compiled in the inventory table, which lists the quantity of every elementary flow entering and leaving the product system, obtained by summing each flow across all unit processes. Sound energy released to the environment satisfies the definition of an elementary flow, since such flows may be energy as well as material. The challenge lies not in whether noise qualifies, but in the quantity used to express it.

Logarithmic decibel descriptors cannot be summed across the processes of a product system, and inventory accounting must instead be carried out in linear energy or pressure terms [19]. This has been operationalised through an indicator expressed in person·Pa·s, which describes the exposure of people to sound over a period and is therefore intrinsically additive over both level and duration [20]. The term related to the exposed population in this indicator does not derive from the product system but from the exposure scenario assumed, so comparisons between product systems are only meaningful if the same scenario is applied to each.

Sound must accordingly enter the inventory as a summable energy flow rather than as a level [24], a requirement consistent with the additivity and consistency principles of inventory analysis [25]. Without a linear, time-explicit inventory, aggregation across the phases of a supply chain cannot be performed defensibly.

4.2 | Phase-specific constraints

Building on the second constraint regarding phase-specific calculations, the variety of noise sources across the supply chain requires a modular framework rather than a uniform assessment scheme. Each phase of a supply chain activates

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its own set of noise sources, from extraction machinery and industrial plant to freight vehicles, hand tools and the operating unit itself, all serving a function within the delivery of the product. The variety across these sources requires a common acoustic currency at the inventory stage, and sound power level provides it, as established through expert consensus in the earlier study [22]. The distinction drawn between static and moving sources like transport [14] does not therefore call for different inventory descriptors, since sound power characterises the emission of any source irrespective of its motion. What differs is everything that follows, how the emitted energy reaches a receiving context, and which receivers occupy that context.

Capturing this complexity requires that the framework be modular. A mine, a warehouse, a vehicle in transit and a dwelling are not variants of a single situation, and the handling of each phase must be configured to the facility and setting in which its sources operate. Such process-differentiated treatment is consistent with wider practice in life cycle assessment, where inventory-to-impact modelling choices vary by category rather than following a single universal scheme [26,27]. Modularity is therefore not a matter of convenience but a condition for the framework to accommodate the diversity of a real product system.

4.3 | From emission to potential impact

In line with the third constraint, that emissions convert into potential impacts only through receivers and spatial context, the noise footprint must bridge source energy with localized exposure pathways. Noise becomes an environmental burden only where receivers are present. Exposure must therefore be spatially explicit, receiver-specific and context-dependent, shaped by time of day, competing sources and restoration potential. Human and wildlife exposure cannot be collapsed into a single category without loss of biological meaning. This requirement is not unique to acoustics. The same difficulty arises for water consumption, where a cubic meter withdrawn in an arid basin deprives other users far more than the same volume withdrawn where water is plentiful, so the impact cannot be derived from the quantity alone. Life cycle impact assessment addresses this by assessing the impact separately for each watershed, according to the water remaining once the demands of other users and ecosystems have been met [21]. Adjusting the assessment to location in this way is now established practice for impact categories whose severity depends on the receiving environment [28]. Noise presents the same structure as a given emission produces very different consequences depending on who is nearby and when.

Determining the actual impact at a specific place and time requires transitioning from a supply-chain perspective to a risk-based framework. While LCA evaluates global, potential environmental burdens across a product's full supply chain, risk assessment predicts local, site-specific health and safety hazards against defined exposure thresholds. LCA estimates impacts using generic assumptions about where emissions occur and who is exposed, rather than measurements from the specific locations involved, summing exposures across places and moments that do not necessarily overlap. Its results are therefore expressed as potential impacts, indicating the harm an emission could cause. Conversely, risk assessment examines a defined situation, establishes the actual exposure of a specific population, and compares it against thresholds of known effect to judge real-world harm in that setting [29].

Unlike a greenhouse gas, where 1 kg of CO_2 exerts the same radiative forcing regardless of location, a source's sound power output carries no environmental harm on its own. Sound only converts into a noise impact when local exposure pathways, background sound levels, and human or ecological receivers are introduced to convert sound power into sound pressure at the point of exposure. Attempts to incorporate noise into LCA struggle precisely because LCIA models rely on generic exposure scenarios that detach the source emission from these necessary local conditions [20]. Because a noise footprint framework must bridge source emissions with meaningful exposure conditions, site-specific risk assessment methodologies provide the necessary foundation to inform how these impacts should be modelled.

4.4 | Combining impacts

The fourth constraint emphasizes the difficulty of combining distinct impact endpoints. Combining endpoints across areas of protection is an optional step in LCA and is not routinely performed. The experts' reluctance to combine impacts reflects a difficulty that life cycle assessment has not resolved for any impact category. Damage to human health is expressed in disability-adjusted life years, which combine years lost to early death with years lived in poorer health, the latter scaled by a disability weight representing how severe each condition is judged to be. Damage to ecosystems is expressed differently, most often as the fraction of species potentially disappearing from an area over time. These describe different things and share no common unit and bringing them together requires weighting whose basis is a value judgement rather than a measurement [30]. ISO 14044 accordingly states that weighting shall not be used in comparative assertions disclosed to the public.

For noise, the difficulty is already visible in existing work. Cucurachi et al. (2019) express noise damage in Disability Adjusted Life Years (DALY) [31], covering human receivers only, while Middel and Verones (2017) express the effect of underwater noise on cetaceans as a potentially disappeared fraction of species [32]. A framework covering an entire supply chain may therefore need to accommodate both types of endpoint. More generally, even within human-health assessment, aggregation relies on weighting choices that may vary and cannot be regarded as neutral. A total

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noise footprint expressed as a single figure would therefore embed normative judgements about the relative importance of different forms of harm. These judgements should be made explicit and justified rather than concealed within the calculation.

4.5 | Multi-step aggregation

To satisfy the final constraint requiring a structured, multi-step process, the noise footprint framework must adopt a transparent, sequential impact pathway. Any total metric is necessarily the outcome of an aggregation procedure. What matters here is the explicit specification, modularity, and transparency of the pathway, not the existence of one. The multi-step sequence proposed by one expert, specifically aggregating cumulative acoustic energy, conducting spectral analysis, accounting for spatial context, and applying explicit weighting between areas of protection, mirrors the established impact pathway used in LCA. The structure follows separate steps to account for how the emission travels, who is exposed to it, and how that exposure harms them [33]. Existing frameworks for incorporating noise into LCA follow the same approach, constructing the assessment from explicit models of source emissions and sound propagation [15].

Maintaining frequency-resolved energy rather than collapsing sound into a single A-weighted metric preserves critical acoustic data, as human audibility and health effects are spectrum-dependent [20]. Furthermore, evaluating noise within its specific spatial context is essential because identical emissions result in different impacts depending on receiver density and environmental sensitivity [28]. Finally, the value-based weighting phase must remain explicit and transparent rather than embedded invisibly within the calculation [34].

This multi-step, modular architecture is not merely a methodological preference, it is crucial for actionable communication. A single aggregated value hides its underlying drivers, making it impossible to discern whether a high noise footprint originates from high source power, extended operational duration, or high population exposure in a specific life-cycle stage. A modular, step-by-step reporting structure ensures that each intermediate phase remains transparent, traceable, and open to independent evaluation.

The constraints identified in this research represent the conditions that any noise aggregation procedure across a supply chain must satisfy in order to produce a defensible total. They were derived from a panel of eight experts, a size consistent with expert thematic analysis, where depth of reasoning determines the value of the material. Applying them to product systems with different acoustic structures, such as electric vehicles, where noise emission shifts from a fixed installation to a moving source, or in conditions where the dominant receivers may be non-human, would establish whether they hold generally or require adaptation to the product under assessment.

5 | Conclusions

When asked how noise contributions across a heat pump's supply chain should be aggregated into an overall noise footprint, experts did not converge on a single, universal metric, but rather established the fundamental structural conditions that any defensible total must satisfy. First, inventory aggregation requires a linear, physically additive quantity that explicitly integrates sound power levels with operational duration relative to the functional unit. Second, the assessment must remain modular, tailoring acoustic metrics to specific life-cycle phases to accommodate varying source dynamics and receiving environments rather than applying a uniform scheme. Third, exposure must be spatially explicit, maintaining separate impact assessments for human health and other ecological receivers. Fourth, the calculation must follow a transparent, multi-step pathway, progressing from cumulative inventory and spectral resolution to spatial modelling, in order to ensure every step remains traceable. Ultimately, these constraints establish a robust architectural benchmark for evaluating and standardizing future operationalizations of the noise footprint.

Conclusioni

Nel valutare l'aggregazione dell'impronta acustica di una pompa di calore lungo la sua catena di fornitura, gli esperti non hanno concordato su un singolo indicatore universale, ma hanno piuttosto stabilito le condizioni strutturali fondamentali che qualsiasi metrica totale deve soddisfare. In primo luogo, l'aggregazione a livello di inventario richiede una grandezza lineare e fisicamente sommabile, che integri esplicitamente il livello di potenza sonora con la durata operativa rispetto all'unità funzionale. In secondo luogo, la valutazione deve mantenere una struttura modulare, adattando le metriche acustiche alle specifiche fasi del ciclo di vita per considerare le diverse dinamiche delle sorgenti e i differenti contesti di ricezione, evitando schemi uniformi. In terzo luogo, la modellazione dell'esposizione deve essere spazialmente esplicita, mantenendo distinte le valutazioni d'impatto sulla salute umana da quelle su altri recettori ecologici. In quarto luogo, il calcolo deve seguire un percorso trasparente e articolato in più fasi, progredendo dall'inventario cumulativo e dalla risoluzione spettrale fino alla modellazione spaziale, così da garantire la tracciabilità di ogni passaggio. Infine, questi vincoli costituiscono un solido riferimento metodologico per valutare e standardizzare le future applicazioni operative del concetto di impronta acustica.

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